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[1,2]B.T. Shukirgaliyev, [1,2]T.P. Panamarev, [4]A.Zh. Naurzbaeva, [1,4]M.T. Kalambay, [1]M.A. Makukov, [1]E.Y. Vilkoviskij, [3,1]Ch.T. Omarov, [2,5,6]P.P. Berczik, [2]A. Just, [2,5,7]R. Spurzem

[1] Fesenkov Astrophysical Institute, Kazakhstan;
[2] Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Germany;
[3] National Center of Space Research and Technology, Kazakhstan;
[4] Al-Farabi Kazakh National University, Kazakhstan;
[5] National Astronomical Observatories of China and Key Laboratory for Computational Astrophysics, China;
[6] Main Astronomical Observatory, National Academy of Sciences of Ukraine, Ukraine;
[7] Kavli Institute for Astronomy and Astrophysics at Peking University, China
bekdaulet.s@gmail.com, mukhagaly@gmail.com

EFFECT OF GAS ACCRETION DISC PROFILE ON ORBITAL PARAMETERS OF THE ACCRETED STARS

Abstract. The results of studies of the effect of the gas disk and its profile on the dynamics of active galactic nuclei are presented. The study was conducted with a numerical model of galactic nucleus based on phiGRAPE+GPU comprising three subsystems – a central supermassive black hole, gaseous accretion disc, and compact stellar cluster. The evolution of the compact stellar cluster is modeled with direct integration (N-body simulation), while the black hole and gaseous disc are represented phenomenologically: the black hole is introduced as an external potential (fixed in space but variable in time due to black hole mass growth), and the gaseous disc is introduced as spatial time-independent density distribution. We examined and compared with each other orbital parameters of accreting stars for model of the galactic nucleus with gas disc of constant and variable thickness, as well as without gas. It was found that in the presence of a gaseous disk almost half of the accreted particles interact strongly with the gas and are captured by the disc before accretion, while more than 85% of particles are affected to some extent by the disc prior to accretion. This suggests that interaction of the stellar cluster with the gas disk in the galactic nucleus might lead to the formation of stellar disk in the central part of the nucleus.

Key words: active galactic nuclei (AGN), supermassive black hole (SMBH), accretion gas disk(AGD), computational astrophysics, N-body simulations.

The physical nature of active galactic nuclei (AGN) our day is far from a complete understanding, that is why the development of AGN theory still remains one of the most urgent problems of astrophysics. According to modern concepts, activity of galactic nuclei is due to the accretion of matter onto supermassive (up to several trillion solar masses) black holes, which are, apparently, in all the centers of galaxies [1]. Released in the course of this accretion the gravitational energy is the source that lies at the heart of an extremely powerful radiation observed from the AGN.

Active galactic nuclei can be seen as consisting of three subsystems: the central supermassive black hole (SMBH), the accretion gas disk (AGD), which is formed due to the conservation of angular momentum of accreting matter, and compact spherically symmetric stellar clusters [2].

In previous studies [3-6] by means of numerical simulation we have been investigated the interaction of star cluster with an accretion disk and its impact on the dynamics and evolution of active galactic nuclei. Indeed, dissipative effects from the gas disk leads to loss of energy of stars in the central cluster and, under certain conditions, to the accretion of some stars onto the black hole.

In these studies, we used two phenomenological gas disk model. The first gas disk had Keplerian rotation, constant height and was defined in a constant in time density distribution:

$$\rho(R,z)=\frac{2-\alpha}{2\pi\sqrt{2\pi}}\frac{M_d}{hR_d^3}\left(\frac{R}{R_d}\right)^{-\alpha} exp\left[-\beta_s\left(\frac{R}{R_d}\right)^s\right]\exp\left(-\frac{z^2}{2h^2R_d^2}\right), \quad (1)$$

where $\alpha = 3/4$ (corresponds to the outer boundary of the disk according to the Novikov-Thome model [6]), $R^2 = x^2 + y^2$, R_d - disk radius, $\beta_s = \left[\Gamma\left(1+\frac{2-\alpha}{s}\right)\right]$ ($\Gamma(x)$ - gamma function, s was taken to 4, then $\beta_s = 0.70$), M_d - disk mass, h defines the half-thickness of disk: $h_z = hR_d$.

The second, a more realistic model of the gas disk is a modification of the first model with the introduction of a linear increase of the half-thickness of disk in the domestic sector. This modification was based on the physical properties of the inner accretion disk, which are described by the Shakura-Syunyaev approach [8].

$$h_z = hR_d\left(\frac{R}{R_{crit}}\right). \quad (2)$$

The transition point from linear half-thickness to the constant was determined by equating the expression for the velocity of sound in the case of self-gravity of disk $c_s^2 = 4\pi G h_z \Sigma$, and in case of its absence $c_s^2 = 2h_z^2 GM_{bh} R^{-3}$. Then $R_{crit} = 0.0257314$ in the dimensionless system of units N-body [8], which we use everywhere in the future.

Accretion disk properties were recorded with reduced mass μ_d with analytical density distribution according to equation (1) with the values of the parameters $\alpha = 3/4$ and $s = 4$ and $h = 10^{-3}$. There was an implication of Keplerian rotation of the disc in the potential of a supermassive black hole, neglecting the gravitational influence of the disc and pressure gradients inside the disc [3]. Read more about the gas disk models - [5].

The black hole was also defined phenomenologically as a Newtonian potential. Star cluster was modeled by direct integration of interaction of individual stars with each other (N-body simulations), as well as with the gas disk and black hole. If the star falls in a region with radius of less than R_{accr} (accretion radius), then it is considered as accreted - its mass is added to the mass of the black hole and the star itself is removed from the system. As the source code phiGRAPE+GPU [10] it was used for the numerical simulation, which uses parallel computation technologies (CUDA and MPI). This code was added to our module, describing dissipative interaction of stars with gas. Evolution of the system begins with the status given by Plummer model. A more detailed description of the numerical model can be found in [3,4,6].

In [5] there was a comparison of the results obtained using two gas disk models, i.e. we investigated the influence of the disk profile on the process of accretion of stars in the black hole (see. the dotted line in Fig. 2). There were considered stars that are accreting due to the effect of the gas disk, that is, stars with small eccentricity (it was believed that the stars, accreting when $e \approx 1$, that is, in orbits close to hyperbolic, fall into the capture area of the black hole as a result of random spans). It was found that in the first model accreting when rotated in one direction with disk the stars form on the diagram "eccentricity - orbit inclination angle to the plane of the disc" a close group with nearly circular orbits lying substantially in the disc plane and the counter-rotating stars have any inclination values and eccentricity when accretion. In the disk model with a variable thickness the co-and counter-rotating stars accrete at all angles of inclination of the orbit, but about 70% of all captured SMBH stars at the time of capture were very close to a circular orbit and were in the plane of the disk. Furthermore, in the second disk model impulse momentum is transferred to the black hole in a larger amount than in the first.

This paper presents the results of further studies of the effect of the gas disk on the dynamics of active galactic nuclei, namely, discussing the orbital parameters of accreting stars, which were captured by SMBH for two relaxation time (t=2t_{rel}), since initial time, for the three models: with "old" (with constant thickness) and the "new" (with variable thickness) gas disks, and also without the disc. In all launches rating system was 32 thousand, accretion radius was assumed to be 0.0003R_d.

Results and discussion

Results of the study of orbit eccentricity of accreting stars are shown in Figures 1-3. Figure 1 shows the cumulative distribution of the particles on the eccentricities of their orbits at the time of accretion for the three models, the ordinate axis represents the ratio of the number of stars, accreting eccentric, less than given to the number of accreted stars.

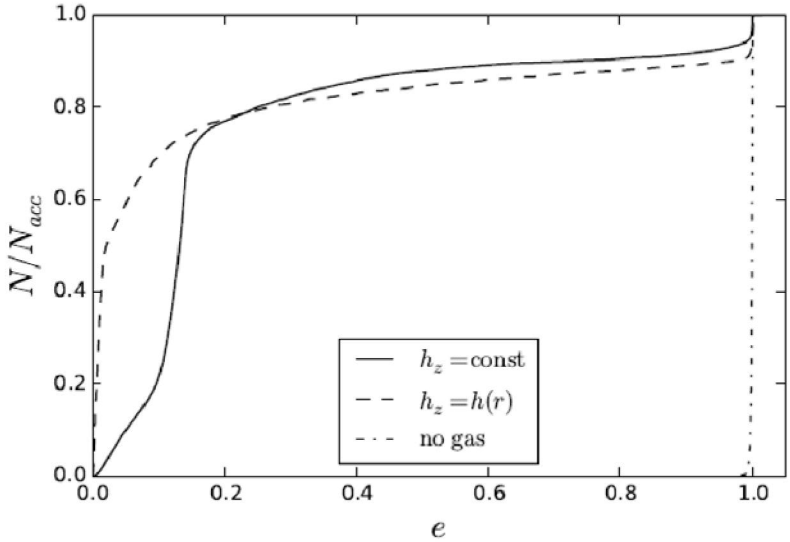

Figure 1 - The cumulative distribution of the particles on the eccentricities of their orbits at accretion time for the model without gas disk (dot-and-dash line), model with a disc of constant thickness (solid line) and model with disk of variable thickness (dashed line). On the vertical axis it is presented the ratio of the number of stars that accrete with an eccentricity of less than given, to all the accreted stars

Figures 2-3 show bar graphs of eccentricities of the orbits of accreted stars. To enable a more detailed analysis, the histogram are given in linear and logarithmic form, and separately there is a graph for the model without the gas disk with smaller intervals of the partition area of the eccentricity values. As can be seen from the figures, in the absence of the gas disk stars accrete in orbits close to hyperbolic, i.e., fall into the capture area of the black hole as a result of random spans. Gas disk greatly affects the distribution of eccentricities of accreted particles: in the model with the "new" disk about 50% of stars accrete in nearly circular orbits, in the model with the "old" disk the particles mainly accrete in more elongated orbits.

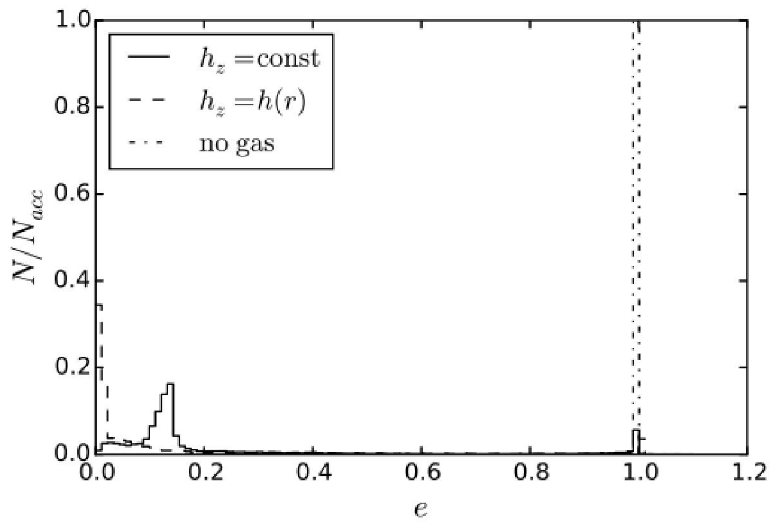

Figure 2 - Distribution of the eccentricities of the orbits of stars at the time of accretion for the three models in the linear (A) and logarithmic (B) scales. Designations are the same as in Figure 1.

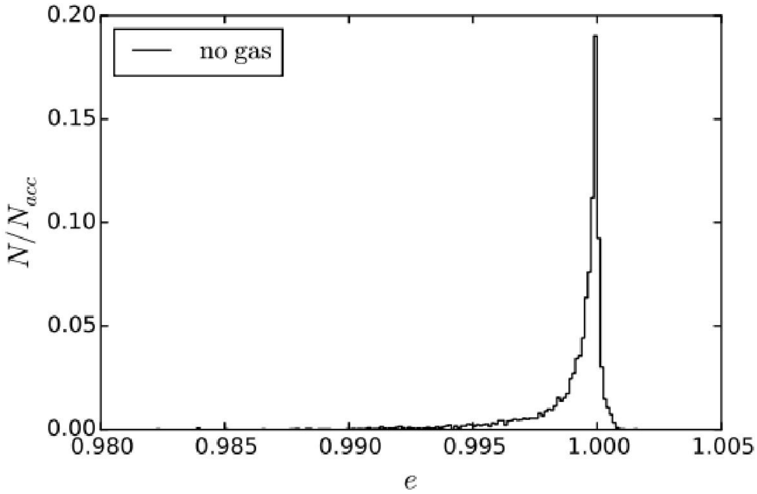

Figure 3 - Distribution of the eccentricities of the orbits of stars at the time of accretion for model without gas disk with a smaller than in Figure 2 the intervals partition area of the eccentricity values.

Figure 4 shows the cumulative distribution of the particles on the orbits inclination angles to the plane of the gas disk at the time of accretion. It can be seen that by using the "old" disc model the inclination angles of almost 50% of the accreted particles occupy an area between 00 and 100, in addition, almost half of the accreted particles, while in the reverse rotation of the disk. When using the "new" model of the disk about 45% of stars accretes onto the black hole rotating in the disk plane and in the same direction with it, the share of the counter-rotating at the time of accretion of particles is smaller than for the disc model with a constant thickness. This is because the thickness of the disc in the "old" model is larger than the radius of accretion which leads to inhibition of many stars with a reverse rotation in center of a disc, including stars nearly perpendicular to the disk plane. In the case of the improved disk model, dense gas around the central black hole is almost exclusively in the plane of the equator, which allows a lot of stars in the central part of the time to the evolved to the direction of rotation of the disc.

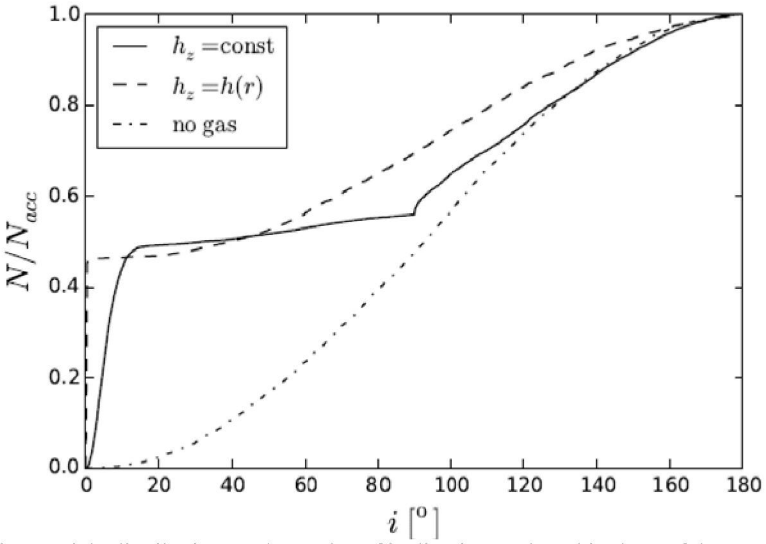

Figure 4 - The cumulative particle distribution on the angles of inclination to the orbit plane of the gas disk at time of accretion for the three models. Designations are the same as in Figure 1.

Figures 5 and 6 show the distribution of the accreted particles on the plane eccentricity - orbit inclination angle for the "old" and "new" disk models, respectively. There are clearly visible particles that were captured before the gas disk accretion: a flat cloud in the area ~0.10 ÷ ~100 to drive at constant thickness, and cloud in the area <10 for disc of variable thickness. This cloud in Figure 6 corresponds to the 45% of particle of figure 4 which accreted, revolving in the disk plane.

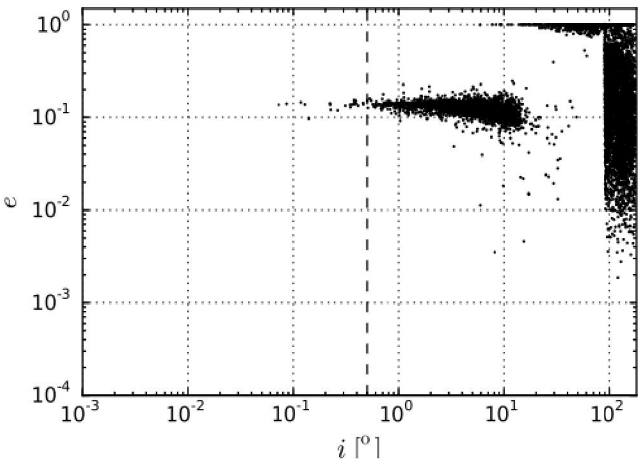

Figure 5 - Distribution of the accreted particles in the plane of the orbit inclination angle - eccentricity for model with gas disk of constant thickness. Each point represents a single particle. The dotted line corresponds to the inclination angle of the orbit equal to opening angle in the model of accretion disk with variable thickness.

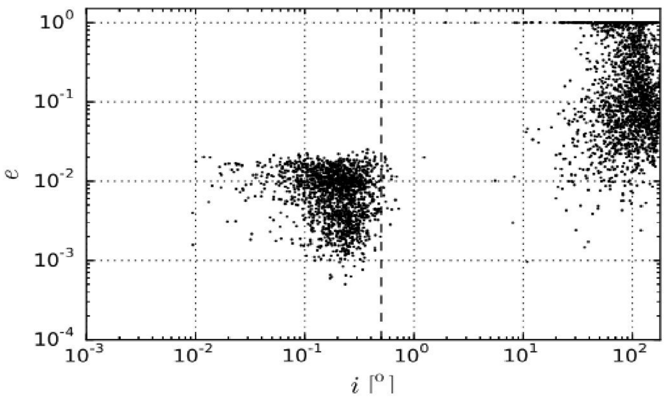

Figure 6 - Distribution of accreted particles in the plane of the orbit inclination angle - eccentricity for model with gas disk of variable thickness. Designations are the same as in Figure 5.

We also analyzed the distribution of the lengths of the semi-major axis of the particles orbits at time of accretion. Figure 7 shows the cumulative distribution of the particles on values of semi-major axes of their orbits, and in Figures 8-10 - the distribution of particles in the diagram length of semi-major axis - orbit inclination angle for the three models.

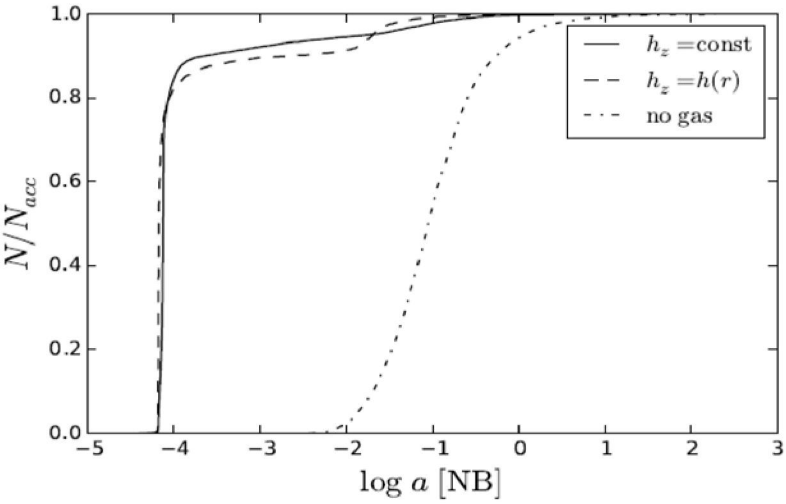

Figure 7 - Cumulative distribution of the particles according to the values of semi-major axes of their orbits. Designations are the same as in Figure 1

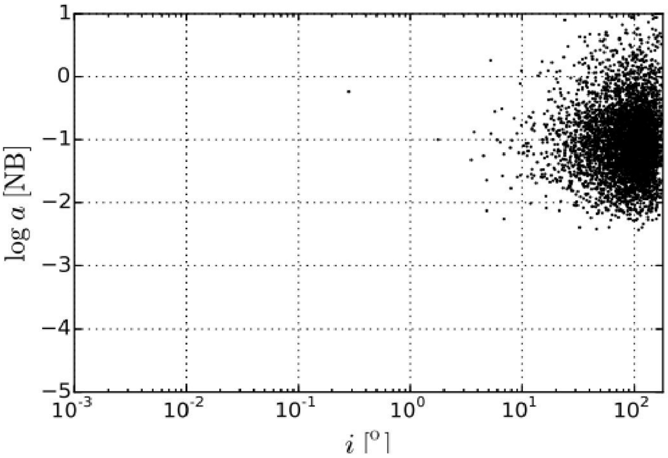

Figure 8 - Distribution of particles in the diagram length of semi-major axis - angle of inclination of the orbit for the model without the gas disk

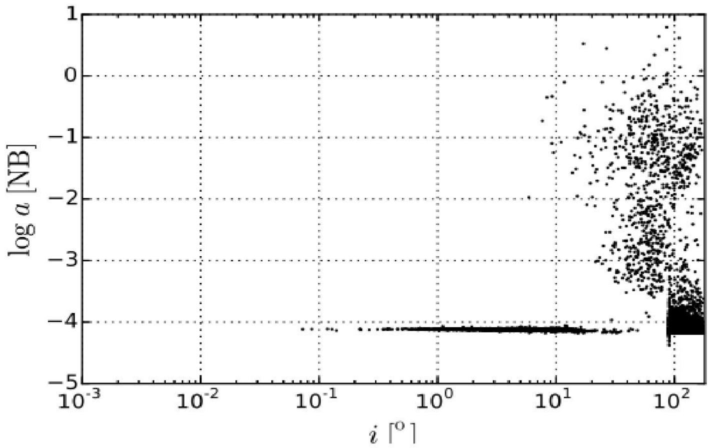

Figure 9 - Distribution of particles in the diagram the length of semi-major axis - the angle of inclination of the orbit to the plane of the accretion disk for model with disk of constant thickness

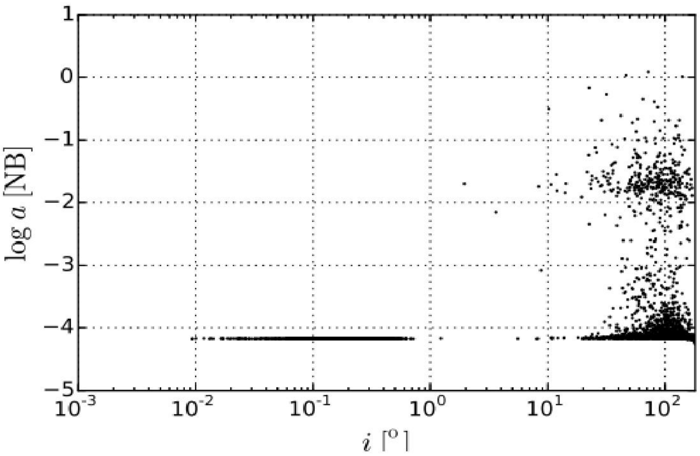

Figure 10 - Distribution of particles in the diagram the length of semi-major axis - angle of inclination of the orbit to the plane of the accretion disk for model with disk of variable thickness

In figure 8, which presents diagram for the model without the gas disk, we see particles accreted according to the theory of the loss cone [11]. The diagrams for the other two models, we can also see these particles accreted without interaction with gas disk, but there is also a "particle disk", ie particles captured by disc before accretion are represented in these diagrams as thin "clouds" in their lower part.

Conclusions

Analysis of the results allows to formulate a conclusion that in the presence of the gas disk, almost half of the accreted particles worked was closely with the gas and was captured by the disk before accretion. The proportion of particles accreted on the loss cone theory (without the effect of the disc), for model with gas disk is very small - 5.10%. The fact that more than 85% of the particles before accretion has undergone a greater or lesser degree of influence on the part of the disc leads to the idea that the interaction of the stellar cluster with gas disk in the galactic nuclei may contribute to stellar accretion disk in the central part of the nucleus and make the star cluster is axially symmetric. The results of further research will be published in our next work. Preliminary results can be found in [12].

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[1,2]Б.Т. Шукиргалиев, [1,2]Т.П. Панамарев, [4]А.Ж. Наурзбаева, [1,4]М.Т. Қаламбай, [1]М.А. Макуков, [1]Э.Я. Вильковиский, [3,1]Ч.Т. Омаров, [2,5,6]П.П. Берцик, [2]А. Юст, [2,5,7]Р. Шпурцем

[1] В.Г. Фесенков атындағы астрофизикалық институт, Атматы, Қазақстан;
[2] Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Germany;
[3] Ұлттық ғарыштық зерттеулер мен технологиялар орталығы, Алматы, Казахстан;
[4] Әл-Фараби атындағы Қазақ Ұлттық Университеті, Алматы, Казахстан;
[5] National Astronomical Observatories of China and Key Laboratory for Computational Astrophysics, China;
[6] Бас Астрономиялық Обсерватория, Украина Ұлттық Ғылыми Академиясы, Украина;
[7] Kavli Institute for Astronomy and Astrophysics at Peking University, China

АККРЕЦИЯЛЫҚ ГАЗДЫ ДИСК ПІШІНІНІҢ АККРЕЦИЯЛАНУШЫ ЖҰЛДЫЗДАРДЫҢ ОРБИТАЛЫҚ СИПАТТАМАСЫНА ӘСЕРІ

Түйіндеме. Осы жұмыста газды диск және оның пішінінің галактикаларының динамикасына әсерін зерттеу нәтижелері көрсетілген. Зерттеулер phiGRAPE+GPU кодының негізінде іске асырылған белсенді ядролы галактика үлгісі үш құраушыдан – орталық аса үлкен массалы қара құрдымнан, аккрециялық газ дискісі және ықшам жұлдыздық кластерден құралған деп жүргізілді. Жұлдыздық кластер эволюциясы тікелей әдіспен (N-body simulations) интегралданады, ал қара құрдым мен газды диск феноменологиялық түрде берілген – қара құрдым сыртқы (кеңістікте қозғалмайтын, алайда қара құрдым массасының өсуі салдарынан өзгеретін) потенциял түрінде, ал газды диск уақыт бойынша өзгермейтін газ тығыздығының кеңістікте таралуымен берілген. Қалыңдығы тұрақты және өзгермелі, және де диск жоқ болғандағы галактика ядроларының моделдері үшін аккрецияланушы жұлдыздардың сипаттамаларын өзара салыстыру қарастырылды. Газды диск бар болған жағдайда аккрецияланган бөлшектердің жартысы дерлік газбен тығыз байланысады және аккрецияға дейін дискпен қарпылады, аккрецияға дейін 85% бөлшектер диск тарапынан қандай да болсын әсерге ұшырайды. Бұл галактика ядроларындағы жұлдыздық жүйе мен газды дисктің әсерлесу нәтижесінде ядроның орталық бөлігінде жұлдыздық аккрециялық диск пайда болады деген ойға алып келеді.

Тірек сөздер: Галактикалардың белсенді ядролары (ГБЯ), аса массалы қара құрдым (АМҚҚ), аккрециялы газды диск (АГД), есептеуіш астрофизика, N-дене есебі.

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[1,2]Б.Т. Шукиргалиев, [1,2]Т.П. Панамарев, [4]А.Ж. Наурзбаева, [1,4]М.Т. Қаламбай, [1]М.А. Макуков, [1]Э.Я. Вильковиский, [3,1]Ч.Т. Омаров, [2,5,6]П.П. Берцик, [2]А. Юст, [2,5,7] Р. Шпурцем

[1]Астрофизический институт им. В.Г. Фесенкова, Казахстан;
[2] Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Germany;
[3] Национальный центр космических исследовании и технологии, Казахстан;
[4] Казахский Национальный Университет им. Аль-Фараби, Казахстан;
[5] National Astronomical Observatories of China and Key Laboratory for Computational Astrophysics, China;
[6] Главная Астрономическая Обсерватория, Национальной Академии Наук Украины, Украина;
[7] Kavli Institute for Astronomy and Astrophysics at Peking University, China

ВЛИЯНИЕ ПРОФИЛЯ АККРЕЦИОННОГО ГАЗОВОГО ДИСКА НА ОРБИТАЛЬНЫЕ ПАРАМЕТРЫ АККРЕЦИРУЕМЫХ ЗВЕЗД

Аннотация. В работе представлены результаты исследования влияния газового диска и его профиля на динамику активных ядер галактик. Исследование проводилось на основе реализованной с помощью кода phiGRAPE+GPU численной модели галактического ядра, состоящей из трех подсистем – центральной сверхмассивной черной дыры, аккреционного газового диска и компактного звездного кластера. Эволюция звездного кластера интегрируется прямым методом (N-body simulations), а черная дыра и газовый диск заданы феноменологически – черная дыра задана в виде внешнего потенциала (неподвижного в пространстве, но изменяемого со временем вследствие роста массы черной дыры), а газовый диск задан в виде пространственного распределения плотности, не зависящего от времени. Рассматривались и сравнивались между собой орбитальные параметры аккрецирующих звезд для моделей ядра галактики с газовым диском постоянной и переменной толщины, а также без диска. Выявлено, что в присутствии газового диска почти половина аккрецированных частиц тесно взаимодействует с газом и захватывается диском перед аккрецией, более 85% частиц до аккреции претерпевает то или иное влияние со стороны диска. Это наводит на мысль, что взаимодействие звездного кластера с газовым диском в галактическом ядре может привести к возникновению звездного аккреционного диска в центральной части ядра.

Ключевые слова: активные ядро галактик (АЯГ), сверхмассивная черная дыра (СМЧД), аккреционный газовый диск (АГД), вычислительная астрофизика, задача N тел.