Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 74 (2015) 292 – 296

Physics Procedia

Conference of Fundamental Research and Particle Physics, 18-20 February 2015, Moscow, Russian Federation

Precession of fast S0 stars in the vicinity of supermassive black hole in the Galactic Center

V.I. Dokuchaev[a,b,*], Yu.N. Eroshenko[a,†], K.S. Klimkov[a,‡]

[a]Institute for Nuclear Research of the Russian Academy of Sciences, Prospekt 60-letiya Oktyabrya 7a, Moscow, 117312, Russia
[b]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoye shosse 31, Moscow, 115409, Russia

Abstract

We elaborate the model of the influence of the diffuse dark matter, invisible stars or stellar mass black holes on the motion of the observed fast moving S0 stars [1-4] around the supermassive black hole SgrA* in the Galactic center with a mass $M_{BH} = 4{\cdot}10^6$ $M_\odot$. We will call all this invisible mass as a dark matter. The additional mass perturbs the elliptical orbits of the S0 mass resulting in the so called Newtonian precession of the elliptical orbits. The major aim of our research is the fitting of the published dates on the observed orbital positions of the S0 stars by the theoretically modeling orbit with a power-law profile of the additional (dark matter) mass. Nowadays the observational data provide only the upper limit on the additional mass. In the nearest years the observations of the S0 stars may provide the real weighing of the dark matter inside the orbits of these S0 stars in the Galactic center. This method is a very perspective for the elucidation of the formation and evolution of the dark matter in the Galactic nucleus.

Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

Keywords: Galactic center; black holes; Sgr A*; S-stars

1. Introduction

Since the 1995 the astronomers observe the special group of the S0 stars, moving on the elliptic orbits, which are gravitationally bound with the supermassive black hole SgrA* in the Galactic center. The observed velocities of the S0 (>1000 km/s) stars far exceed a corresponding virial velocity of stars in the central cluster [1-4]. In particular, the

* Corresponding author. Tel.: +7-906-045-8561.
E-mail address: dokuchaev@inr.ac.ru

1875-3892
Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
doi:10.1016/j.phpro.2015.09.243

observed S0-2 star already finished the whole orbital period for the nearly 16 years. It is awaited that the orbit of S0 star may deviate from the ellipse. These deviations may be due to the relativistic Post-Newtonian correction or due to the Newtonian precession because of the deviation of gravitational potential from the corresponding one of the point mass under the influence of the dark matter.

The precise astrometric observations of the S0-2 stars during more than the 20 years provides the possibility of the weighing of the dark matter inside the orbit of the S0-2 star by measuring the Newtonian precession. The possible Newtonian precession of S0 stars was investigated by the different numerical approaches [5-10], and also analytically [11-12]. In the perspective it will be possible to observe also the relativistic precession of this star, which is very important for the verification of the General Relativity.

Note that the Newtonian and relativistic precessions have the opposite signs and may, in principle, compensate the each other. Even in this case it would be possible the both types of precession by specific behavior of the orbit near the periastron and apastron. The relativistic effects are more prominent in the periastron, on the smallest distance from the central black hole. Quite the contrary, the Newtonian precession distorts the pure ellipse mainly near the apastron, on the farthest distance from the black hole. For this reason it is important to measure not only the precession angle (during the one orbital period), but also to reach the most accurate fitting of the whole orbit. This is an additional aim of the performed research.

The preliminary estimations of the possible mass of the dark matter in the Galactic center indicate that the Newtonian precession probably far exceed the relativistic one. For this reason the Newtonian precession of S0 stars due to the presence diffuse dark matter must be investigated first of all.

2. Relativistic precession of the S0-2 star

Finely, we will show that the identification of tiny relativistic effects requires much more data and precision then it was obtained to date. For numerical calculations of the relativistic orbit of the S0-2 star we use the equation of motion in the Kerr metric adopted to the parameters of the supermassive black hole in the Galactic Center (for details see e.g. [13]) with the following two sets of the initial data:

1. The black hole spin parameter $s = 0.65$, the Carter constant of the nonequatorial motion $Q = 400$, the total energy $\gamma = 0.999975$, azimuthal angular moment $\lambda = 20$, periapsis $x_p = 402.12$, apoapsis $x_a = 39596.438$. Start of calculations is from the apocenter with the latitude angle $\theta_0 = \theta_{max}$.

2. $s = 0$, $Q = 400$, $\gamma = 0.999975$, $\lambda = 20$, $x_p = 402.12$, $x_a = 39596.439$. Start of calculations is from the apocenter with the latitude angle $\theta_0 = \theta_{max}$.

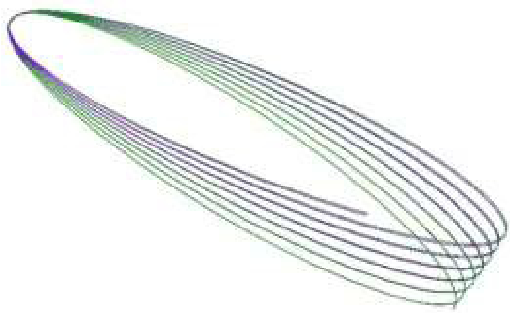

Fig. 1. The superposed orbits of the S0-2star at s = 0 and s = 0.65 practically are the same. The only visible orbital precession is due to the relativistic Mercury perihelion shift effect.

It is clearly seen in the Fig. 1 that the orbits with spin s = 0 and s = 0.65 are practically coincide. So, for the identification of the black hole rotation it is needed the S0 stars with orbits $x_a \ll 10^3$.

3. Newtonian motion of the S0-2 star

The possible cusp of the dark matter around the supermassive black hole SgrA* in the Galactic center will deviate the Newtonian gravitational potential from the Coulomb type $U = -GM_{BH}/r$. In result, the gravitationally bound elliptic orbits would be unclosed. As an representative example we consider this effect for the case of the S0 star which was investigated in most details. The parameters of the Kepler orbit of this star: the eccentricity e = 0.883 ± 0.0034, periapsis $r_p = 0.585$ mpc, apsis $r_a = 9.419$ mpc. The orbital period of the S0-2 star is $T_{S0\text{-}2} = 16.17$ yrs. The corresponding equation of motion of test particles (stars) in the spherically symmetric Newtonian gravitational field [12]:

$$\frac{d\varphi}{dt} = \frac{\lambda}{r^2}, \qquad \frac{dr}{dt} = \sqrt{2[\gamma - U(r)] - \frac{\lambda^2}{r^2}}, \tag{1}$$

where it was used the dimensional quantities: the radial distance is measured in the units of GM_{BH}/c^2. The corresponding dimensional radii are $r_p = 2538.29$, $r_a = 47232.1$, the dimensional total energy is $\gamma = -0.00002 < 0$, the dimensional angular momentum $\lambda = 69$. The total Newtonian potential $U(r) = U_0 + \delta U$ is a sum of the point mass potential of the black hole $U_0 = -GM_{BH}/r$ and a small perturbation δU from the diffuse dark matter with a mass $M_{DM} \ll M_{BH}$. This addition provides, in particular the shift of the apsis. Some information on the diffuse dark matter inside the orbits of the S0 stars may be derived by using the approximate analytical expression for the precession angle [6], but in this work we discuss a more precise method, based on the numerical fitting of the whole orbit of S0-2 star.

We will explore the power-law profile for the dark matter inside the orbit of the S0 star, which provide the small correction δU to the point mass potential U_0:

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\beta}, \tag{2}$$

Where ρ_0, r_0 и β are the free parameters of the model because nowadays the distribution of dark matter is unknown. We put $r_0 = r_a$ and calculate the total mass of dark matter inside the orbit of the S0-2 star:

$$M_{DM} = \frac{4\pi}{3-\beta} \rho_0 r_0^3, \beta < 3. \tag{3}$$

The Newtonian potential for this distribution of dark matter is

$$\delta U = -\frac{GM_{DM}}{r_0} \frac{(3-\beta) - (r/r_0)^{2-\beta}}{2-\beta}, \ \beta < 2, \tag{4}$$

$$\delta U = -\frac{GM_{DM}}{r_0} [1 + \log(\frac{r_0}{r})], \beta = 2. \tag{5}$$

In the dimensional variables we have $U_0 = 1/r$, and equations for δU take the form:

$$\delta U = -\frac{\xi}{r_a}\frac{(3-\beta)-(r/r_a)^{2-\beta}}{2-\beta}, \beta < 2, \tag{6}$$

$$\delta U = -\frac{\xi}{r_a}[1+\log(\frac{r_a}{r})], \beta = 2, \tag{7}$$

where dimensional periapsis $r_a = a(1+e) = 47232.1$, $\xi = M_{DM}/M_{BH} << 1$ is a mass fraction of dark matter with respect to the black hole mass. Below we put some limitation on the possible value of ξ from the numerical fitting of the S0-2 star orbit.

We calculate numerically the orbit of the S0-2 star by using equations (1) and (2) by carrying out the additional coordinate transformation from orbital plane to the viewing plane:

$$X = (x\sin\omega + y\cos\omega)\sin i, \tag{8}$$

$$Y = x(-\cos i\cos\Omega\sin\omega - \cos\omega\sin\Omega) + y(-\cos i\cos\omega\sin\Omega - \sin\omega\sin\Omega), \tag{9}$$

$$Z = y(-\cos\Omega\sin\omega - \cos i\cos\omega\sin\Omega) + x(\cos\omega\cos\Omega - \cos i\sin\omega\sin\Omega), \tag{10}$$

where (x, y) are the coordinates in the elliptic orbital plane. By using the observed values of i, Ω and ω we construct the orbit in the viewing plane. Thereafter we compare the constructed orbit with the observed one by using the standard least square method and find the parameters for the most fitting orbit.

4. Construction of the perturbed orbit of the S0-2 star

We find numerically the S0-2 star Newtonian orbit for $\beta = 1/2$ and for the different values of the dark matter mass fraction $\xi = 5\cdot10^{-3}, 3\cdot10^{-2}, 5\cdot10^{-2}$. The corresponding solutions of the equation of motions equation of motion (1) and (2) are the space coordinates r(t) and φ(t) which give the theoretical orbit, which may be compared with the observational data points. Along the orbit we are choosing the set of points for the comparing with the telescope data. For the every experimental point it was found the nearest theoretical one. Then, it was calculated the distance between them and afterwards it was calculated the sum of the square distances for the different values of dark matter mass fraction ξ.

The best coincidence of the power-law density profile (2) with the observational data for the S0-2 star orbit is achieved at the value of dark matter mass fraction $\xi = M_{DM}/M_{BH} = 3\cdot10^{-2}$.

5. Conclusion

We construct numerically the theoretical orbits of the S0 stars, fast moving in the gravitational field of the supermassive black hole SgrA* in the Galactic center with a mass $M_{BH} = 4\cdot10^6$ $M_\odot$. It is demonstrated that the observed S0-2 and S0-102 stars are still far from the black hole enough to measure the relativistic precession of their orbits (the Post-Newtonian effect of the type the shift of the Mercury perihelion). We construct numerically the theoretical orbits of the S0-2 star with the Newtonian precession due to the perturbative influence of the dark matter inside the star orbit. We find the best coincidence of the theoretical orbits with the observational data by the method of the least squared for the value of the dark matter mass fraction $\xi = M_{DM}/M_{BH} = 3\cdot10^{-2}$. This value of the dark matter fraction is nowadays is the most probable. In the nearest future (in the nearest few years) it would be possible to verify and improve this result.

Acknowledgements

Authors acknowledge V. S. Beskin and E. A. Vasiliev for helpful discussions. The reported study was partially supported by the Research Program OFN-17 of the Division of Physics, Russian Academy of Sciences, and by NSh-3110.2014.2.

References

[1] Ghez A.M., Salim S., Weinberg N.N. et al. Measuring distance and properties of the Milky Way's central supermassive black hole with stellar orbits. *Astrophys. J.* 2008; 689:1044-1062.
[2] Gillessen S., Eisenhauer F., Trippe S. et al. Monitoring stellar orbits around the massive black hole in the Galactic center. *Astrophys. J.* 2009; 692:1075-1109.
[3] Gillessen S., Eisenhauer F., Fritz T.K. et al. The orbit of the star S2 around SgrA* from Very Large Telescope and Keck data. *Astrophys. J.* 2009; 707:L114-L117.
[4] Meyer L., Ghez A.M., Schodel R. et al. The shortest-known-period star orbiting our Galaxy's supermassive black hole. *Science*, 2012; 338:84-87.
[5] Rubilar G.F., Eckart A. Periastron shifts of stellar orbits near the Galactic center. *Astron. Astrophys* 2001; 374:95-104.
[6] Mouawad N., Eckart A., Pfalzner, S. et al. Weighing the cusp at the Galactic centre. *Astron. Nachr*. 2005; 326:83-95.
[7] Gualandris A., Gillessen S., Merritt D. The Galactic centre star S2 as a dynamical probe for intermediate-mass black holes. *MNRAS* 2010; 409:1146-1154.
[8] de Paolis F., Ingrosso G., Nucita A.A. et al. Estimating the parameters of the SgrA* black hole. *Gen. Rel. Gravit*. 2011; 43:977-988.
[9] Borka D., Jovanovic P., Borka Jovanovic V. et al. Constraining the range of Yukawa gravity interaction from S2 star orbits. *JCAP* 2013; 11:050.
[10] Iorio L. Exact expressions for the pericenter precession caused by some dark matter distributions and constraints on them from orbital motions in the solar system, in the double pulsar and in the Galactic center. *Galaxies* 2013; 1:6-30.
[11] Dokuchaev V.I., Eroshenko Yu.N. Weighing of the dark matter at the center of the Galaxy. *JETP Lett.* 2015; 101:777–782.
[12] Landau L.D., Lifshitz E.M. *Mechanics.* New York: Pergamon Press. 1988.
[13] Dokuchaev V.I. Spin and mass of the nearest supermassive black hole. *Gen. Relativ. Gravit*. 2014; 46:1832.