Publ. Astron. Obs. Belgrade No. 98 (2018), 129 - 135 *Progress Report*

STELLAR KINEMATICS AROUND GALACTIC CENTER

S. GRAVINA[1], S. CAPOZZIELLO[1,2,3], D. BORKA[4] and V. BORKA JOVANOVIĆ[4]

[1]*Dipartimento di Fisica "E. Pancini", Università di Napoli "Federico II", Compl. Univ. di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy*
E–mail: st.gravina@studenti.unina.it, capozzie@na.infn.it

[2]*Istituto Nazionale di Fisica Nucleare (INFN) Sez. di Napoli, Compl. Univ. di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy*

[3]*Gran Sasso Science Institute, Viale F. Crispi, 7, I-67100, L'Aquila, Italy*

[4]*Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia*
E–mail: dusborka@vinca.rs, vborka@vinca.rs

Abstract. In this paper we discuss the deviations between the observed and Keplerian orbit of S2 star around the Galactic Center (GC), using the gravitational potential that we derived from the modified theories of gravity. S2 star is one the brightest among S-stars, with the short orbital period, and also with the smallest uncertainties in determining the orbital parameters. So we use it as a good candidate for investigating the precession of the orbit, deviations from the Keplerian orbits, as well as stellar kinematics around supermassive black hole at GC.

1. INTRODUCTION

The different anomalous astrophysical and cosmological phenomena like the cosmic acceleration, the dynamics of galaxies and gas in clusters of galaxies, the galactic rotation curves, etc. did not find satisfactory explanations in terms of the standard Newton-Einstein gravitational physics, unless exotic and still undetected forms of matter-energy are postulated: dark matter and dark energy. Alternative approaches using well-motivated generalization and extensions of General Relativity (GR) are proposed in order to try to explain these phenomena without using dark matter and dark energy. In this perspective, star kinematics and dynamics around the Galactic Centre could be a useful test bed to probe the effective gravitational potentials coming from the theory.

S-stars are the young bright stars which move around the centre of our Galaxy (Ghez et al. 2000, Ghez et al. 2008, Genzel et al. 2010) where the compact radio source Sgr A* is located. S2 is one of the bright S-stars moving around Sgr A* source in the center of our Galaxy. A Keplerian orbit could be determined for the S2 (a star with one of the shortest orbital period of 16 years), after passing the periapse. This star can now be traced in its motion around the Galactic Center with the smallest uncertainties in determining the orbital parameters and a complete phase coverage. No other star has so far been reported covered by data with more than ∼40% of its orbit. The astrometric limit is constantly improving from around 10 mas, during the first part of the observational period, currently reaching less than 1 mas. This limit is still not sufficient to definitely confirm that S2 star orbit really deviates from the Newtonian case. However, some recent studies (Gillessen et al. 2009a, Gillessen et al. 2009b, Meyer et al. 2012, Gillessen et al. 2017, Boehle et al. 2016) provide evidence that the orbit of S2 star is not closing. The orbital precession can occur due to relativistic effects, resulting in a prograde pericentre shift or due to a possible extended mass distribution, producing a retrograde shift. Both prograde relativistic and retrograde Newtonian pericentre shifts will result in rosette shaped orbits. We consider a possible application of modified gravity within Galactic Central Parsec, in order to explain the observed precession of S2 star orbit, in particular the Newtonian limit of a class of scalar-tensor (ST) theories of gravity, where a scalar field is nonminimally coupled to the geometry. For more details about S2 star see Genzel et al. (2010) and Gillessen et al. (2012).

Here we study a possible application of ST theories of gravity within Galactic Central Parsec, in order to explain the observed precession of orbits of S2-star. This investigation is a continuation of our previous studies where we considered different extended gravities, such as power law $f(R)$ gravity (Borka et al. 2012, Zakharov et al. 2014), $f(R,\phi)$ gravity implying Yukawa and Sanders-like gravitational potentials in the weak field limit (Borka et al. 2013, Capozziello et al. 2014, Borka et al. 2016, Zakharov et al. 2016).

2. THEORY

Extended Theories of Gravity have been proposed like alternative approaches to Newtonian gravity in order to explain galactic and extragalactic dynamics without introducing dark matter. In the case of $f(R)$ gravity, one assumes a generic function f of the Ricci scalar R (in particular, analytic functions) and searches for a theory of gravity having suitable behavior at different astrophysical and cosmological scales: for short distances, Solar system, spiral galaxies, galaxy clusters and cosmology. See reviews in: Capozziello & Faraoni 2010, Capozziello & De Laurentis 2011, Nojiri & Odintsov 2011, Capozziello & De Laurentis 2012, Clifton et al. 2012.

The ST theories of gravity are theories, in which both the metric tensor $g_{\mu\nu}$ and a fundamental scalar field ϕ are involved (Capozziello et al. 1996). In our investigation we take the action of the form:

$$S = S_M + \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}[F(\phi)R + \frac{3}{2\phi}g^{\mu\nu}\phi_{,\mu}\phi_{,\nu} - V(\phi)]. \tag{1}$$

where the coupling $F(\phi)$ and the potential $V(\phi)$ are generic functions of the scalar field ϕ, and κ is a coupling constant.

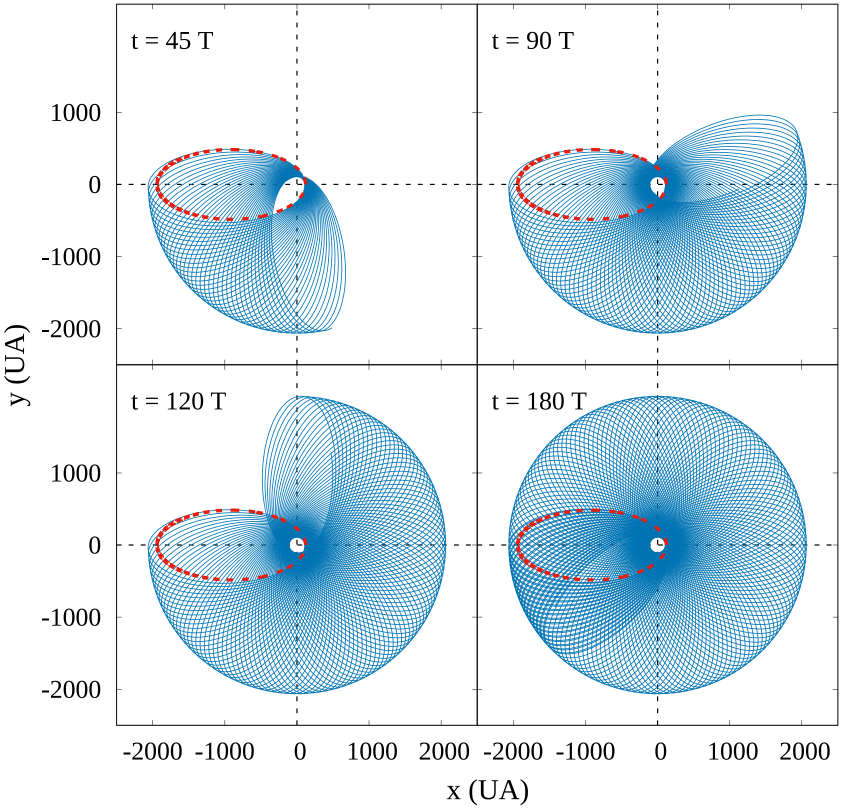

Figure 1: Comparison between the orbit of S2 star in Newtonian potential (red dashed line) and ST potential (blue solid line) for parameters (m,n) = (2,2) and (ξ,λ)=(-9000, 0.005) during the time t = 45, 90, 120 and 180 T.

3. RESULTS AND DISCUSSION

The ST gravitation potential in the weak field limit can be written in the form:

$$U_{ST} = \frac{\widetilde{G}}{\xi\varphi_0^m}\frac{M}{r} - \frac{\lambda}{4\xi}\varphi_0^{n-m}r^2 - \frac{\widetilde{G}m^2M}{3(1-m^2\varphi_0^{m-1}\xi)}\frac{e^{-pr}}{r}, \tag{2}$$

where M is central mass, and p is function of the ST gravity parameters ξ, λ, m and n:

$$p = \sqrt{\frac{\lambda n\varphi_0^{n-1}(2m-\lambda n)}{3(m^2\xi\varphi_0^{m-1}-1)}}, \tag{3}$$

and $\widetilde{G}$ is related with a gravitation constant G_N through relation:

$$\tilde{G} = -\left[\frac{3(1-m^2\varphi_0^{m-1}\xi)\xi\varphi_0^m}{3-\xi(3m^2\varphi_0^{m-1}+m^2\varphi_0^m)}\right]G_N. \tag{4}$$

The parameters λ, ξ, m and n define the specific form of function $F(\phi)$ and interaction potential $V(\phi)$, since before starting the linearization of field and scalar

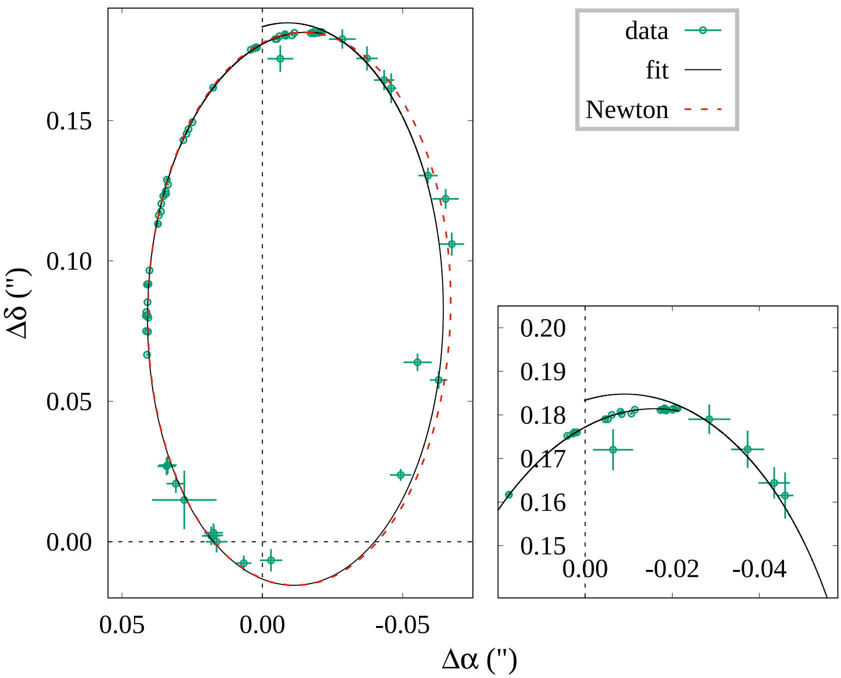

Figure 2: Comparison of the observations and the fitted orbit of S2 star around the Galactic Center, for (m,n)=(2,2) and (ξ,λ)=(-9000, 0.005). *Left*: S2 orbit in the modified gravity (black solid line) and Newtonian orbit (red dashed line). The VLT astrometric observations are presented by green circles. *Right*: Zoom of the orbital part showing the precession.

field equations, we choose a specific form for the up to now arbitrary functions, that is $F(\phi) = \xi\phi^m$, $V(\phi) = \lambda\phi^n$, where ξ is a coupling constant, λ gives the self-interaction potential strength, m and n are arbitrary parameters. Our aim is to determine these parameters using astrometric data for S2 star orbit. We are simulating orbit of S2 star in the ST modified gravity potential by numerical integration of equations of motion:

$$\dot{\vec{r}} = \vec{v}, \qquad \mu\ddot{\vec{r}} = -\vec{\bigtriangledown} U_{ST}(\vec{r}) \tag{5}$$

where $\mu = M_{BH} \cdot m_S/(M_{BH} + m_S)$ is the reduced mass in the two-body problem due to the mass M_{BH} of the central black hole and the mass m_S of the S2 star.

We put in advance the parameters m and n. The initial values for true position (x_0, y_0) and orbital velocity $(\dot{x}_0, \dot{y}_0)$ of S2 star at the epoch of the first observation are specified and the positions (x_i, y_i) and velocities $(\dot{x}_i, \dot{y}_i)$ of S2 star along its true orbit are calculated for all observed epochs by numerical integration of equations of motion in the ST gravity potential. The reduced χ^2 of fit is estimated according the following expression:

$$\chi^2 = \frac{1}{2N - \nu} \sum_{i=1}^{N} \left[\left(\frac{x_i^o - x_i^c}{\sigma_{xi}} \right)^2 + \left(\frac{y_i^o - y_i^c}{\sigma_{yi}} \right)^2 \right], \tag{6}$$

where (x_i^o, y_i^o) are the observed values of the true positions, (x_i^c, y_i^c) are the calculated values, and σ_{xi}, σ_{yi} are the variances.

At the end, we kept the value of ξ and λ which resulted with the smallest value of minimized reduced χ^2. More detailed description about fitting procedure is given in Borka et al. (2013).

We have made a comparison of VLT observations and theoretically fitted orbit of S2 star around the Galactic Center. We calculated the S2 orbit in the modified gravity potential of a ST Theory. Comparison between the orbit of S2 star in Newtonian potential and ST potential for parameters (m, n) = (2,2) and (ξ,λ)=(-9000, 0.005) during the time t = 45, 90, 120 and 180 T (T - orbital period) is shown in Fig. 1. Comparison of the observations and the fitted orbit of S2 star around the Galactic Center is shown in Fig. 2, and from the zoomed part of the figure it can be clearly seen that the precession exists.

In order to calculate orbital precession in ST modified gravity we assume that ST potential does not differ significantly from Newtonian potential and we derived the perturbing potential:

$$V(r) = U_{ST} - U_N; \qquad\qquad U_N = -\frac{GM}{r}. \tag{7}$$

The obtained perturbing potential is of the form:

$$V(r) = -\frac{GM}{r}\frac{\xi m^2\varphi_0^m}{3-\xi(3m^2\varphi_0^{m-1}+m^2\varphi_0^m} - \frac{\lambda}{4\xi}\varphi_0^{n-m}r^2 - \frac{\widetilde{G}m^2M}{3(1-m^2\varphi_0^{m-1}\xi)}\frac{e^{-pr}}{r}. \tag{8}$$

Table 1: Precession angle for different values of m and n gravity parameters.

m	n	$\Delta\theta(^\circ)$
1	1	2.5
1	4	2.5
1	10	2.7
2	1	2.5
2	2	2.5
2	6	2.5
3	4	2.2
4	2	2.5
4	4	2.8
10	10	2.5

The particular form of the chosen Lagrangian among the class of ST theories of gravity induces the precession of S2 star orbit in the same direction with respect to GR and produces a prograde shift that results in rosette-shaped orbits. In the case when the simulated revolution of S2 star is in positive mathematical direction (counter clockwise), the simulated precession of S2 star orbit has positive mathematical direction too, and vice versa. The pericenter advances by 2.5° per orbital revolution, while in GR the shift is 0.18°.

4. CONCLUSIONS

In this paper orbit of S2 star has been investigated in the framework of the ST gravity potentials. Using the observed positions of S2 star around the Galactic Centre we constrained the parameters of these gravity potentials.

We obtained the values for parameters ξ and λ for different parameters m and n when S2 star orbit in ST gravity better fits astronomy data than Keplerian orbit.

The precession of S2 star orbit obtained for the best fit parameter values has the positive direction, as in GR.

We obtained much larger orbital precession of the S2 star in ST gravity than the corresponding value predicted by GR.

The approach we are proposing can be used to constrain the different modified gravity models from stellar orbits around Galactic Centre.

Acknowledgment

This work is supported by Ministry of Education, Science and Technological Development of the Republic of Serbia, through the project 176003 "Gravitation and the Large Scale Structure of the Universe", and by Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy, iniziative specifiche TEONGRAV and QGSKY. The authors also acknowledge the support by Bilateral cooperation between Serbia and Italy 451-03-01231/2015-09/1 "Testing Extended Theories of Gravity at different astrophysical scales", of the COST Action CA15117 (CANTATA), supported by COST (European Cooperation in Science and Technology), and ERASMUS+ Programme (for higher education student and staff mobility) between Dipartimento di Fisica, Università degli studi di Napoli "Federico II" and Vinča Institute of Nuclear Sciences, University of Belgrade.

References

Boehle, A. et al.: 2016, *Astrophys. J.*, **830**, 17.
Borka, D., Jovanović, P., Borka Jovanović, V., Zakharov, A. F.: 2012, *Phys. Rev. D*, **85**, 124004.
Borka, D., Jovanović, P., Borka Jovanović, V., Zakharov, A. F.: 2013, *Journal of Cosmology and Astroparticle Physics*, **11**, 050.
Borka, D., Capozziello, S., Jovanović, P. and Borka Jovanović, V.: 2016, *Astropart. Phys.*, **79**, 41.
Capozziello, S., de Ritis, R., Rubano, C., Scudellaro, P.: 1996, *La Rivista del Nuovo Cimento*, **19**, 1.
Capozziello, S. & Faraoni, V.: 2010, *Beyond Einstein gravity: A Survey of gravitational theories for cosmology and astrophysics*, Fundamental Theories of Physics, Vol. 170, Springer, New York.
Capozziello, S. & De Laurentis, M.: 2011, *Physics Reports*, **509**, 167.
Capozziello, S. & De Laurentis, M.: 2012, *Ann. Phys.*, **524**, 545.
Capozziello, S., Borka, D. Jovanović, P., Borka Jovanović, V.: 2014, *Phys. Rev. D*, **90**, 044052.
Clifton, T., Ferreira, P. G., Padilla, A., Skordis, C.: 2012, *Physics Reports*, **513**, 1.
Genzel, R. et al.: 2010, *Rev. Mod. Phys.*, **82**, 3121.
Ghez, A. M. et al.: 2000, *Nature*, **407**, 349.
Ghez, A. M. et al.: 2008,*Astrophys. J.* **689**, 1044.
Gillessen, S. et al.: 2009a, *Astrophys. J.*, **707**, L114.

Gillessen S. et al.: 2009b, *Astrophys. J.*, **692**, 1075.
Gillessen, S. et al.: 2012, *Nature*, **481**, 51.
Gillessen, S. et al.: 2017, *Astrophys. J.*, **837**, 30.
Meyer, L. et al.: 2012, *Science*, **338**, 84.
Nojiri, S. & Odintsov, S. D.: 2011, *Physics Reports*, **505**, 59.
Zakharov, A. F., Borka, D., Borka Jovanović, V., Jovanović, P.: 2014, *Adv. Space Res.* **54**, 1108.
Zakharov, A. F., Jovanović, P., Borka, D., Borka Jovanović, V.: 2016, *Journal of Cosmology and Astroparticle Physics*, **05**, 045.