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<https://doi.org/10.2298/FUPCT1901011B>**CONSTRAINING SCALAR-TENSOR GRAVITY MODELS
BY S2 STAR ORBITS AROUND THE GALACTIC CENTER[†]***UDC 04.50.Kd, 04.80.Cc, 04.25.Nx, 04.50.-h***Vesna Borka Jovanović^{1,2}, Predrag Jovanović², Duško Borka¹,
Salvatore Capozziello^{3,4,5}, Stefania Gravina³, Anna D'Addio³**¹Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences,
University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia²Astronomical Observatory, Volgina 7, P.O. Box 74, 11060 Belgrade, Serbia³Dipartimento di Fisica "E. Pancini", Università di Napoli "Federico II",
Compl. Univ. di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy⁴Istituto Nazionale di Fisica Nucleare (INFN), Sez. di Napoli,
Compl. Univ. di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy⁵Gran Sasso Science Institute, Viale F. Crispi, 7, I-67100, L'Aquila, Italy

Abstract. *The aim of our investigation is to derive a particular theory among the class of scalar-tensor(ST) theories of gravity, and then to test it by studying kinematics and dynamics of S-stars around a supermassive black hole (BH) at Galactic Center (GC). We also discuss the Newtonian limit of this class of ST theories of gravity, as well as its parameters. We compare the observed orbit of S2 star with our simulated orbit which we obtained theoretically with the derived ST potential and constrained parameters. Using the obtained best-fit parameters we calculated orbital precession of S2 star in ST gravity and found that it has the same direction as in General Relativity (GR) but causes much larger pericenter shift.*

Key words: *modified theories of gravity, black holes, methods: analytical, methods: numerical*

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Corresponding author: Vesna Borka Jovanović

Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia
E-mail: vborka@vinca.rs

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1. INTRODUCTION

Modified theories of gravity have been proposed as alternative approaches to Newtonian gravity in order to cure shortcomings of Newtonian gravity and GR, but without introducing dark matter and dark energy (Capozziello and de Laurentis, 2012; Nojiri and Odintsov, 2011). A huge number of alternative gravity theories have been proposed (see e.g. review papers Capozziello and de Laurentis, 2011; Capozziello and Faraoni, 2011; Clifton et al., 2012 and the book Clifton, 2006). All these theories have to be also checked by astronomical observations taken on different astronomical scales, from the Solar System, binary pulsars, elliptical and spiral galaxies to the clusters of galaxies and cosmological scales (Capozziello and de Laurentis, 2011; Capozziello and Faraoni, 2011; Capozziello, 2002; Capozziello et al., 2003; Carroll et al., 2004; Iorio, 2010; Sotiriou and Faraoni, 2010; Leon and Saridakis, 2011; Capozziello et al., 2014).

Extended theories of gravity (Capozziello and de Laurentis, 2011; Capozziello and Faraoni, 2011) are alternative theories of gravity developed from the similar starting points investigated first by Einstein and Hilbert, but instead of the Ricci curvature scalar R , one assumes a generic function f of the Ricci scalar R . Using extended theories of gravity in our previous papers, we tried to explain different astrophysical phenomena such as the orbital precession of S2 star (Capozziello et al., 2014; Borka et al., 2012; Borka et al., 2013; Zakharov et al., 2014; Borka et al., 2016; Borka Jovanović et al., 2016), the fundamental plane of elliptical galaxies (Borka et al., 2016; Borka Jovanović et al., 2016), the baryonic Tully-Fisher relation of gas-rich galaxies (Capozziello et al., 2017) and also to give the mass constraints for graviton (Zakharov et al., 2016; Zakharov et al., 2019).

S-stars are bright stars which move around the centre of our Galaxy where the compact radio source Sgr A* is located (more about this can be found in references Ghez et al., 2000; Schödel et al., 2002; Ghez et al., 2008; Gillessen et al., 2009a; Gillessen et al., 2009b; Genzel et al., 2010; Gillessen et al., 2012; Meyer et al., 2012; Gillessen et al., 2017; Hees et al., 2017; Chu et al., 2018). The progress in monitoring bright stars near GC has been made (Gillessen et al., 2017; Hees et al., 2017; Chu et al., 2018), but the current astrometric limit is still not sufficient to unambiguously confirm the deviations of the S2 star orbit from the Keplerian one. We expect that future observations of S-stars will be more precise with astrometric errors several times smaller than currently are.

Some models of extended gravity and, in particular, generic models containing ST and higher-order curvature terms are described in Capozziello et al. (2015). In this study, we consider possible signatures for an ST theory within the Galactic Central Parsec, not tested at these scales yet. Using the gravitational potential that we derived from the modified theories of gravity (D'Addio et al., 2018; Gravina et al., 2018), we compare the simulated and observed orbits of S2 star. In this way, we are able to investigate the orbital precession of S2 star, the deviations from the Keplerian orbit, the stellar kinematics around supermassive BH at GC, as well as constraining parameters of the derived potential.

This paper is organized as follows: in § 2 we explain the theoretical foundation of ST gravity, in § 3 we describe our two-body numerical simulations, § 4 is devoted to the obtained results and discussion, and finally, in § 5 we point out the main results of our study.

2. SCALAR-TENSOR THEORY OF GRAVITY AND ITS PARAMETERS

In ST theory of gravity, both the metric tensor g and the fundamental scalar field ϕ are involved. This theory of gravity contains two arbitrary functions of the scalar field: the coupling $F(\phi)$ and the interaction potential $V(\phi)$. $F(\phi)$ underlines a non-minimal coupling between the scalar field and the geometry, and $V(\phi)$ implies a self-interaction of the field. More about the general scalar-tensor Lagrangian see in Capozziello et al. (1996).

We take the most general action in four dimensions of a theory of gravity where a scalar field is non-minimally coupled with the geometry of the form (Capozziello and de Ritis, 1993; Capozziello and de Ritis, 1994):

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

and choose a specific form for $F(\phi) = \xi \phi^m$, $V(\phi) = \lambda \phi^n$, where S_M is the matter action, ξ is a coupling constant, λ gives the self-interaction potential strength, m and n are arbitrary parameters. We take a rather general choice for arbitrary functions $F(\phi)$ and $V(\phi)$, which is in agreement with the existence of a Noether symmetry (Capozziello et al., 1996; Capozziello and de Ritis, 1993; Capozziello and de Ritis, 1994). Also, several ST physical theories (e.g. induced gravity) admit such a form for $F(\phi)$ and $V(\phi)$.

We investigated a few different cases for $h_{00} = 0.5\Phi$, where Φ is the Newtonian-like potential.

In the case of spherical symmetry and for a point distribution of matter, the linearized equations have the solutions as follows (Gravina, 2017; D’Addio, 2017). In case $n \neq 0$ and $n \neq 2m$, the solution is:

$$h_{00} \simeq \frac{\kappa^2 M}{4\pi\xi\varphi_0^m r} - \frac{\lambda}{2\xi} \varphi_0^{n-m} r^2 - \frac{\kappa^2 m^2 M}{3(1-m^2\varphi_0^{m-1}\xi)} \frac{e^{-pr}}{4\pi r}. \quad (2)$$

In case $n = 2m$, the solution is:

$$h_{00} \simeq \frac{\kappa^2 M}{4\pi r} \left[\frac{3-3m^2\varphi_0^{m-1}\xi - m^2\xi\varphi_0^m}{3\xi\varphi_0^m(1-m^2\varphi_0^{m-1}\xi)} \right] - \frac{\lambda\varphi_0^m}{2\xi} r^2. \quad (3)$$

In case $n = 1$, the solution is:

$$h_{00} \simeq \frac{\kappa^2 M}{4\pi r} \left[\frac{3-3m^2\varphi_0^{m-1}\xi - m^2\xi\varphi_0^m}{3\xi\varphi_0^m(1-m^2\varphi_0^{m-1}\xi)} \right] - \frac{\lambda\varphi_0^{1-m}}{2\xi} r^2. \quad (4)$$

The ST gravitational potential in the weak field limit can be written in the following form (D’Addio et al., 2018; Gravina et al., 2018):

$$U_{ST} = \frac{\mathcal{G} M}{\xi\varphi_0^m r} - \frac{\lambda}{4\xi} \varphi_0^{n-m} r^2 - \frac{\mathcal{G} m^2 M}{3(1-m^2\varphi_0^{m-1}\xi)} \frac{e^{-pr}}{r}, \quad (5)$$

where φ_0 is a positive real number (close to 1), p is the function of the ST gravity parameters ξ, λ, m, n :

$$p = \sqrt{\frac{\lambda n \varphi_0^{n-1} (2m - \lambda n)}{3(m^2 \xi \varphi_0^{m-1} - 1)}}, \quad (6)$$

and \mathcal{G} is related to the gravitation constant G_N :

$$\mathcal{G} = - \left[\frac{3(1-m^2\varphi_0^{m-1}\xi)\xi\varphi_0^m}{3-\xi(3m^2\varphi_0^{m-1}+m^2\varphi_0^m)} \right] G_N. \quad (7)$$

3. SIMULATED S2 STAR ORBITS IN ST AND NEWTONIAN POTENTIAL

In order to constrain the parameters observationally, we simulated the orbits of S2 star in the modified gravitational potential, and then we compared the results with the set of S2 star observations obtained by a New Technology Telescope (NTT) and a Very Large Telescope (VLT).

As S2 star is one of the brightest among S-stars, with the short orbital period and the smallest uncertainties in determining the orbital parameters, it is a good candidate for this study. We draw orbits of S2 star in the ST and Newtonian potential. For that purpose, we performed two-body simulations in the modified ST gravity potential: $U_{ST}(r) = C_1 \cdot \frac{1}{r} + C_2 \cdot r^2 + C_3 \cdot \frac{e^{-pr}}{r}$, with $C_1 = C_1(\xi, m)$, $C_2 = C_2(\xi, \lambda, m, n)$, $C_3 = C_3(\xi, m)$, $p = p(\xi, \lambda, m, n)$, and in the Newtonian potential: $U_N(r) = \frac{-GM}{r}$.

The equations of motion in ST gravity are:

$$\dot{\vec{r}} = \vec{v}, \mu \ddot{\vec{r}} = -\vec{\nabla} U_{ST}(\vec{r}), \quad (8)$$

where $\mu = M \cdot m_S / (M + m_S)$ is the reduced mass in the two-body problem.

One example of the comparison between the orbit of S2 star in the Newtonian and ST potential is given in Fig. 1. Our results show that there is a positive precession (as in GR), and after a number of periods, the prograde shift results in rosette-shaped orbits.

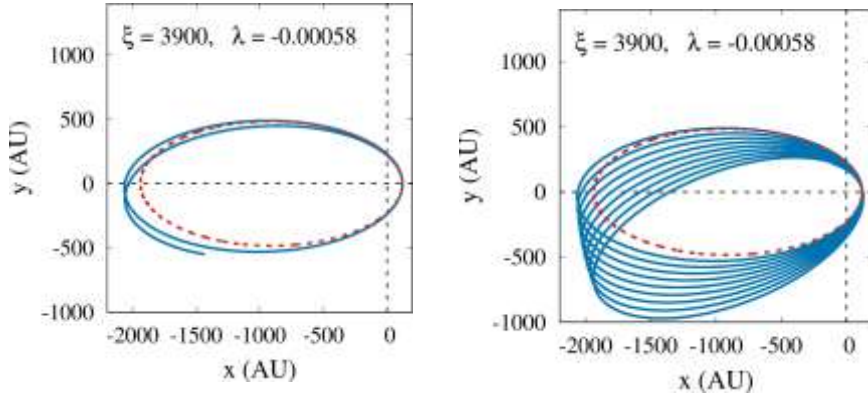


Fig. 1 Comparison between the orbit of S2 star in the Newtonian potential (red dashed line) and the ST potential (blue solid line) for parameters $(m,n) = (1,3)$ and $(\xi,\lambda) = (3900,-0.00058)$ during time $t = 2T$ and $10T$, where T is a Keplerian period.

We compare the obtained theoretical results for S2-like star orbits in the ST potential with the available set of observations of S2 star. The observations, collected between 1992 and 2008 at the European Southern Observatory (ESO) with an optical telescopes

NTT and VLT, are publicly available as supplementary online data to the electronic version of Ref. (Gillessen et al., 2009).

For comparing the astrometric observations with the fitted orbit, our method of calculation is the following:

1. we calculate the positions of S2 star in the orbital plane (the true orbit) by numerical integration of the equations of motion;
2. then we project the true orbit to the observer's plane (the apparent orbit);
3. we estimate the discrepancy between the simulated and the observed apparent orbit by the reduced χ^2 (Borka et al., 2013).

From the comparison of the observations and the fitted orbit of S2 star around the GC, it can be clearly seen that the precession exists. In Fig. 2 we present one part of the orbit near the apocenter where the orbital precession is obvious.

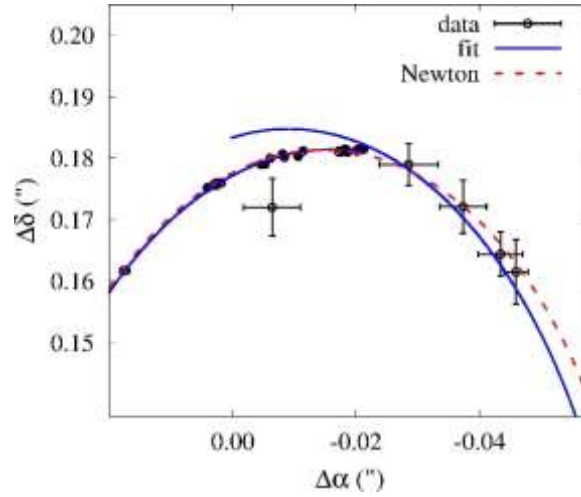


Fig. 2 Comparison of the NTT/VLT astrometric observations (black circles) and the fitted orbit in ST modified gravity (blue solid line) of S2 star around the Galactic Center, for ST gravity parameters $(m,n) = (1,3)$ and $(\xi,\lambda) = (3900,-0.00058)$. The Newtonian orbit is added with a red dashed line.

4. RESULTS AND DISCUSSION

4.1. Constraints on ST gravity parameters

For constraining the ST gravity parameters, we choose some values for (m,n) , vary the parameters (ξ,λ) over some intervals, and then search for those solutions which for the simulated orbits in ST gravity give at least the same or better fits ($\chi^2 \leq 1.89$) than the Keplerian orbits. Then, we repeat the procedure for different combinations $(m,n) \rightarrow [1,10]$. Some maps of the reduced χ^2 over the parameter space (ξ,λ) of ST gravity, for different combinations of m and n , are shown in Figs. 3-6. The calculated χ_{min}^2 values and the corresponding best fit values ξ_{-min} and λ_{-min} are given in Table 1. The readers

should pay attention here that χ^2_{min} is the minimal value, but the parameters ξ_{-min} , λ_{min} are not minimal but the best fit values which correspond to χ^2_{min} .

As it can be seen from Figures 3-6, as well as from Table 1, different combinations of m and n parameters give different best fit values for ξ and λ , but they will not significantly affect the resulting orbital precession, as it will be shown below.

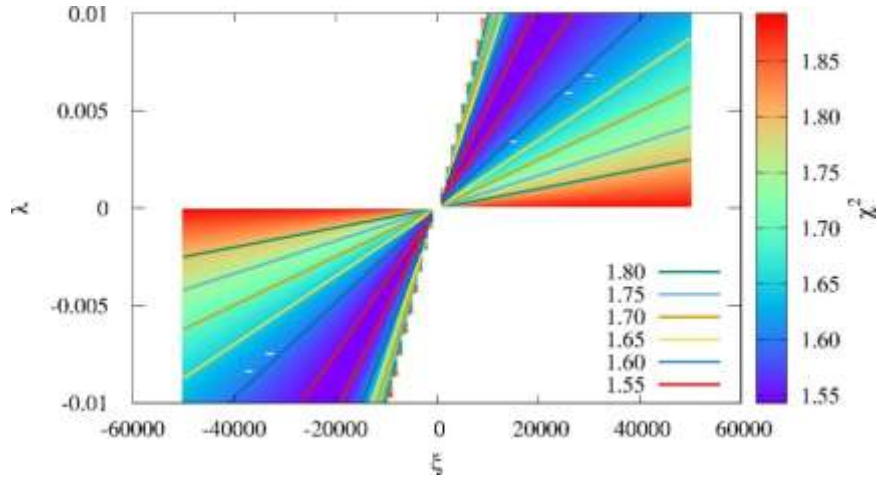


Fig. 3 The map of the reduced χ^2 over the parameter space (ξ, λ) of ST gravity in the case of NTT/VLT observations of S2 star which give at least the same or better fits ($\chi^2 \leq 1.89$) than the Keplerian orbits. The figure represents the case for $(m, n) = (1, 1)$. A few contours are presented for specific values of the reduced χ^2 given in the bottom right part of the figure.

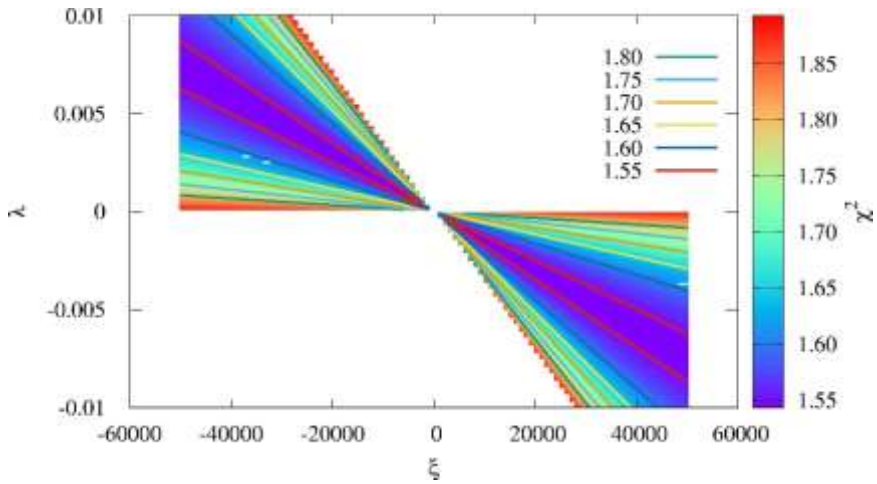


Fig. 4 The same as Fig. 3, but for the case $(m, n) = (1, 3)$.

4.2. Orbital precession estimates in ST gravity

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

$$V(r) = U_{ST} - U_N; U_N = \frac{-GM}{r}. \quad (9)$$

The obtained perturbing potential is of the form:

$$V(r) = \frac{-GM}{r} \frac{\xi m^2 \varphi_0^m}{3 - \xi(3m^2 \varphi_0^{m-1} + m^2 \varphi_0^m)} - \frac{\lambda}{4\xi} \varphi_0^{n-m} r^2 - \frac{6m^2 M}{3(1 - m^2 \varphi_0^{m-1} \xi)} \frac{e^{-pr}}{r}. \quad (10)$$

and it can be used for calculating the precession angle according to Eq. (30) in Ref. (Adkins and McDonnell, 2007):

$$\Delta\theta = \frac{-2L}{GMe^2} \int_{-1}^1 \frac{z \cdot dz}{\sqrt{1-z^2}} \frac{dV(z)}{dz}, \quad (11)$$

where r is related to z via: $r = \frac{L}{1+ez}$. By differentiating the perturbing potential $V(z)$ and by substituting its derivative and $L = a(1 - e^2)$ into (11), we can obtain the value for the precession angle. Some calculated values are given in Table 1 from (Gravina et al., 2018).

The precession of the S2 star orbit is in the same direction with respect to GR and produces a prograde shift that results in rosette-shaped orbits. The pericenter advances by 2.5° per orbital revolution, while in GR the shift is 0.18° .

Table 1 Best fit values for ST gravity parameters, for different combinations of m and n (we take $\varphi_0 = 1$).

m	n	χ_{min}^2	ξ_{-min}	λ_{-min}
1	1	1.5434350	13000	0.0058
1	3	1.5434440	43000	-0.0064
1	4	1.5434426	43000	-0.0024
2	1	1.5434345	16000	0.0095
2	2	1.5434352	15000	0.0067
2	3	1.5434474	-1000	-0.0006
3	1	1.5434336	1000	0.0008
3	2	1.5434383	1000	0.0005
3	3	1.5434352	15000	0.0067
3	4	1.5434383	1000	0.0005
4	1	1.5434317	4000	0.0041
4	2	1.5434478	-1000	-0.0006
4	3	1.5434348	21000	0.0100
4	4	1.5434353	15000	0.0067
10	10	1.5434353	-15000	-0.0067

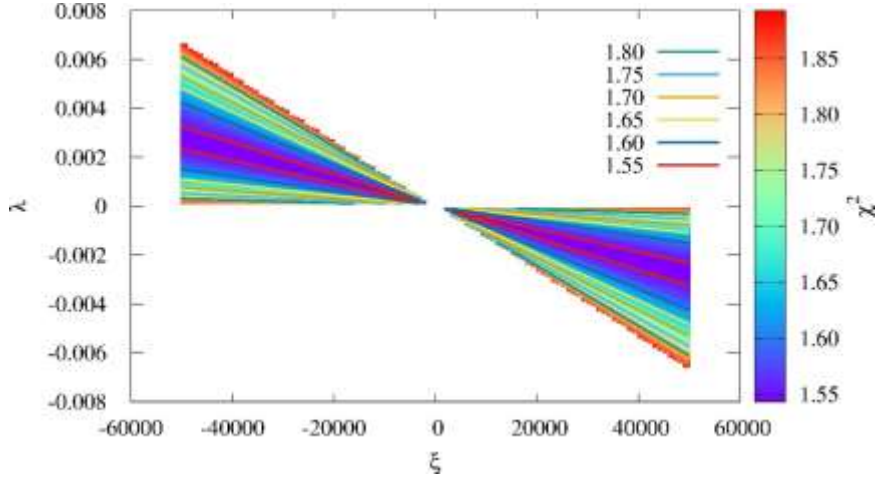


Fig. 5 The same as Fig. 3, but for case $(m, n) = (1, 4)$.

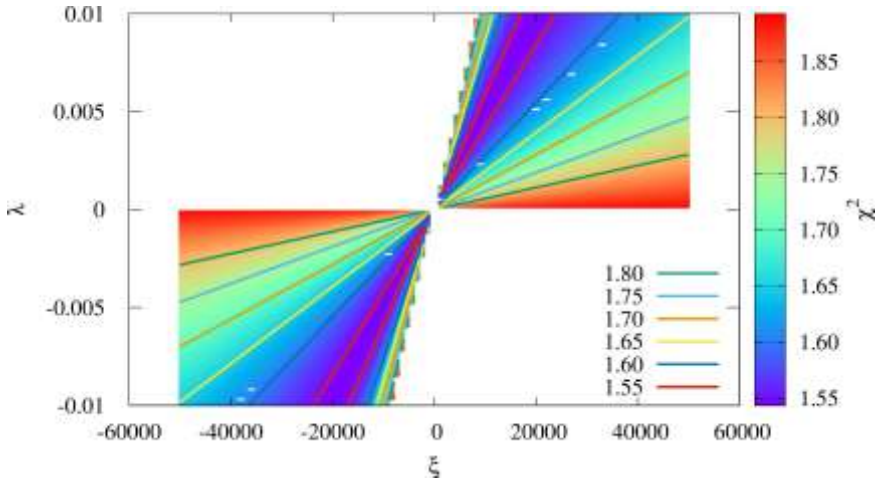


Fig. 6 The same as Fig. 3, but for case $(m, n) = (3, 4)$.

5 CONCLUSIONS

As S2 star is one of the brightest among S-stars, with a short orbital period and the smallest uncertainties in the orbital parameters, we find that it is a good candidate for this study. First, we obtained the parameter space (ξ, λ) of ST modified gravity for which the fits are the same or better than in the Keplerian case. We then calculated the orbits for the best fit parameters of ST gravity and compared them with the observations. In that way, our results allowed us to test the ST theory at galactic scales.

In this paper, we derived a particular theory among the class of ST theories of gravity. We tested this gravity theory by studying the dynamics of S2 star around a supermassive BH at GC. For 15 combinations of m and n parameters, we obtain the values of ξ and λ

for which the S2 star orbits in ST gravity better fit astrometric observations than the Keplerian orbit. We obtained much larger orbital precession for the best fit parameter values of S2 star in ST gravity than the corresponding value predicted by GR. The precession of the S2 star orbit has a positive direction, as in GR. Also, we discussed the Newtonian limit of this class of ST theories of gravity. We believe that the approach we proposed here can be used to constrain different modified gravity models from the stellar orbits around GC (see also De Laurentis et al., 2018a; De Laurentis et al., 2018b; Dialektopoulos et al., 2019).

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OGRANIČAVANJE SKALAR-TENZORSKIH GRAVITACIONIH MODELA POMOĆU ORBITA S2 ZVEZDE OKO GALAKTIČKOG CENTRA

Cilj našeg istraživanja je da izvedemo konkretnu teoriju među klasom skalar-tenzorskih (ST) teorija gravitacije, i zatim da je testiramo proučavajući kinematiku i dinamiku S-zvezda oko supermasivne crne rupe u centru naše galaksije. Takođe razmatramo njutnovsku granicu za ovu klasu ST teorija gravitacije, kao i njene parametre. Poredimo posmatranu orbitu S2 zvezde sa našom simuliranom orbitom koju smo dobili pomoću teorijski izvedenog ST potencijala, iz čega određujemo njegove parametre. Koristeći dobijene parametre koji najbolje fituju posmatranja, računamo orbitalnu precesiju S2 zvezde u ST gravitaciji, i nalazimo da ima isti smer kao u opštoj teoriji relativnosti, ali prouzrokuje mnogo veći pomeraj pericentra.

Ključne reči: teorije modifikovane gravitacije, crne rupe, metode: analitičke, metode: numeričke