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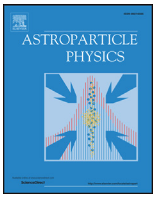

Probing hybrid modified gravity by stellar motion around Galactic Center

D. Borka[a,*], S. Capozziello[b,c,d], P. Jovanović[e], V. Borka Jovanović[a]

[a] Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, Belgrade 11001, Serbia
[b] Dipartimento di Fisica, Università di Napoli “Federico II”, Complesso Universitario di Monte S. Angelo, Edificio G, Via Cinthia, I-80126Napoli, Italy
[c] Istituto Nazionale di Fisica Nucleare (INFN) Sez. di Napoli, Complesso Universitario di Monte S. Angelo, Edificio G, Via Cinthia, I-80126 Napoli, Italy
[d] Gran Sasso Science Institute (INFN), Viale F. Crispi, 7, I-67100L’Aquila, Italy
[e] Astronomical Observatory, Volgina 7, Belgrade 11060, Serbia

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ABSTRACT

We consider possible signatures for the so called *hybrid gravity* within the Galactic Central Parsec. This modified theory of gravity consists of a superposition of the metric Einstein–Hilbert Lagrangian with an $f(R)$ term constructed *à la Palatini* and can be easily reduced to an equivalent scalar–tensor theory. Such an approach is introduced in order to cure the shortcomings related to $f(R)$ gravity, in general formulated either in metric or in metric-affine frameworks. Hybrid gravity allows to disentangle the further gravitational degrees of freedom with respect to those of standard General Relativity. The present analysis is based on the S2 star orbital precession around the massive compact dark object at the Galactic Center where the simulated orbits in hybrid modified gravity are compared with astronomical observations. These simulations result with constraints on the range of hybrid gravity interaction parameter ϕ_0, showing that in the case of S2 star it is between -0.0009 and -0.0002. At the same time, we are also able to obtain the constraints on the effective mass parameter m_ϕ, and found that it is between -0.0034 and -0.0025 AU^{-1} for S2 star. Furthermore, the hybrid gravity potential induces precession of S2 star orbit in the same direction as General Relativity. In previous papers, we considered other types of extended gravities, like metric power law $f(R) \propto R^n$ gravity, inducing Yukawa and Sanders-like gravitational potentials, but it seems that hybrid gravity is the best among these models to explain different gravitational phenomena at different astronomical scales.

1. Introduction

The existence of 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. recently boosted the growth of several long-range modifications of the usual laws of gravitation. These mentioned phenomena 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. A recent approach is to try to explain these phenomena without using new material ingredients like dark matter and dark energy, but using well-motivated generalization and extensions of General Relativity (GR). Several alternative gravity theories have been proposed (see e.g. [1–7] for reviews), such as: MOND [8], scalar–tensor [9–12], conformal [13,14], Yukawa-like corrected gravity theories [15–18], theories of “massive gravity” [19–25]. Alternative approaches to Newtonian gravity in the framework of the weak field limit [26] of fourth-order gravity theory have been proposed and constraints on these theories have been discussed [27–38].

The philosophy is to search for alternative form of gravity, i.e. of the Einstein–Hilbert theory, so that such modifications could naturally explain some astrophysical and cosmological phenomena without invoking the presence of new material ingredients that, at the present state of the art, seem hard to be detected. Besides, this extended approach can be connected to effective theories that emerge both from the quantization on curved spacetimes and from several unification schemes [2–4].

The simplest extension of the Einstein–Hilbert action is based on straightforward generalizations of the Einstein theory where the gravitational action (the Einstein–Hilbert action) is assumed to be linear in the Ricci curvature scalar R. If this action consists in modifying the geometric part considering a generic function

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[*] Corresponding author. Tel.: +381 116455 451; fax: +381 116308 425.
E-mail address: dusborka@vinca.rs (D. Borka).

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$f(R)$, we get so called $f(R)$ gravity which was firstly proposed in 1970 by Buchdahl [39]. Generally, the most serious problem of $f(R)$ theories is that these theories cannot easily pass the standard Solar System tests [40,41]. However, there exists some classes of them that can solve this problem [42]. It can be shown that $f(R)$ theories, in principle, could explain the evolution of the Universe, from a matter dominated early epoch up to the present, late-time self accelerating phase. Several debates are open in this perspective [43–46] but the crucial point is that suitable self-consistent model can be achieved. $f(R)$ theories have also been studied in the Palatini approach, where the metric and the connection are regarded as independent fields [47]. Metric and Palatini approaches are certainly equivalent in the context of GR, i.e., in the case of the linear Einstein–Hilbert action. This is not so for extended gravities. The Palatini variational approach leads to second order differential field equations, while the resulting field equations in the metric approach are fourth order coupled differential equations. These differences also extend to the observational aspects.

A novel approach, that consists of adding to the metric Einstein–Hilbert Lagrangian an $f(R)$ term constructed within the framework of the Palatini formalism, was recently proposed [48–50]. The aim of this formulation is twofold: from one side, one wants to describe the extra gravitational budget in metric-affine formalism, from the other side, one wants to cure the shortcomings emerging in $f(R)$ gravity both in metric and Palatini formulations. In particular, hybrid gravity allows to disentangle the metric and the geodesic structures pointing out that further degrees of freedom coming from $f(R)$ can be recast as an auxiliary scalar field. In such a case, problems related to the Brans–Dicke-like representation of $f(R)$ gravity in terms of scalar–tensor theory (the so called O'Hanlon transformation) are immediately avoided (see [50] for details and the discussion in Section 2). Due to this feature, the scalar–tensor representation of hybrid gravity results preferable with respect to other scalar–tensor representations of gravitational interaction. As byproducts, the appearance of ghosts is avoided and the correct weak field limit of $f(R)$ gravity with respect to GR is recovered. Furthermore, several issues related to the galactic dynamics, the formulation of the virial theorem in alternative gravity, the dark energy behavior seem to be better addressed than in $f(R)$ gravity considered in both metric and Palatini formulations. In summary, the hybrid metric-Palatini theory opens up new possibilities to approach, in the same theoretical framework, the problems of both dark energy and dark matter disentangling the extra degrees of freedom of gravitational field with respect to GR. For a brief review on the hybrid metric-Palatini theory, we refer the reader to [51].

In this perspective, star dynamics around the Galactic Center could be a useful test bed to probe the effective gravitational potentials coming from the theory. In particular, S-stars are the young bright stars which move around the center of our Galaxy [52–57] where the compact radio source Sgr A* is located. For more details about S2 star see references [57,58]. There are some observational indications that the orbits of some of them, like S2, could deviate from the Keplerian case [54,59], but the current astrometric limit is not sufficient to unambiguously confirm such a claim [36,60].

Here we study a possible application of hybrid modified gravity within Galactic Central Parsec, in order to explain the observed precession of orbits of S-stars. This paper is a continuation of previous studies where we considered different extended gravities, such as power law $f(R)$ gravity [29,38], $f(R, \phi)$ gravity implying Yukawa and Sanders-like gravitational potentials in the weak field limit [36,37]. Results obtained using hybrid gravity point out that, very likely, such a theory is the best candidate among those considered to explain (within the same picture) different gravitational phenomena at different astronomical scales.

More details about hybrid gravity you can find in [47,48,50,51]. It is shown in [50,51] that this type of modified gravity is coherently addressing the Solar System issues, and motivations for addressing them are discussed in details in [51].

The modified theory of gravity needs to be constrained at different scales: at laboratory distances, at Solar system, at galaxies, at galactic clusters and at cosmological scales. Obtaining constraints at any of these scales is a fundamental issue to select or rule out models. In particular, it is important to investigate gravity in the vicinity of very massive compact objects because the environment around these objects is drastically different from that in the Solar System framework. The S2 star orbit is a unique opportunity to test gravity at the sub-parsec scale of a few thousand AU. For example, gravity is relatively well constrained at short ranges (especially at sub-mm scale) by experimental tests, however for long ranges further tests are still needed (see Figs. 9 and 10 from [61] for different ranges). It is worth stressing that a phenomenological approach can be useful in this context. In particular, the motion of S2-star is a suitable tool to test alternative gravity. For the reasons that we will discuss in detail below, hybrid gravity is a reliable paradigm to describe gravitational interaction without considering dark energy and dark matter. Specifically, the massive compact object inside the Galactic Center is surrounded by a matter distribution and deviations of S2-star motion from the Keplerian orbit are observed in detail. These deviations can be triggered both by the masses of the surrounding bodies and by the strong field regime at the Galactic Center. This peculiar situation constitutes a formidable opportunity to test theories of gravity. However, it is important to stress that numerical results reported here by comparing models with astronomical observations, represent only upper bounds for the precession angle on the deviation from GR. More accurate studies will be necessary in future work to better constrain dynamics around the Galactic Center.

The present paper is organized as follows: in Section 2 we sketch the theory of hybrid gravity. In Section 3 we describe our simulations of stellar orbits in the gravitational potential derived in the weak field limit of hybrid gravity and we describe the fitting procedure to simulate orbits with respect to astrometric observations of S2 star. Results are presented in Section 4. Conclusions are drawn in Section 5.

2. Hybrid metric-Palatini gravity

In this Section, we present the basic formalism for the hybrid metric-Palatini gravitational theory within the equivalent scalar–tensor representation (we refer the reader to [50,51,62,63] for more details). The $f(R)$ theories are the special limits of the one-parameter class of theories where the scalar field depends solely on the stress energy trace T (Palatini version) or solely on the Ricci curvature R (metric version). Here, we consider a one-parameter class of scalar–tensor theories where the scalar field is given as an algebraic function of the trace of the matter fields and the scalar curvature [62]:

$$S = \int d^D x \sqrt{-g} \left[\frac{1}{2} \phi R - \frac{D-1}{2(D-2)(\Omega_A - \phi)} (\partial \phi)^2 - V(\phi) \right]. \qquad (1)$$

The theories can be parameterized by the constant Ω_A. The limiting values $\Omega_A = 0$ and $\Omega_A \to \infty$ correspond to scalar–tensor theories with the Brans–Dicke parameter $\omega = -(D-1)/(D-2)$ and $\omega = 0$. These limits reduce to $f(R)$ gravity in the Palatini and the metric formalism, respectively. For any finite value of Ω_A, its value depends both on matter and curvature. In the limit $\Omega_A \to \infty$ the propagating mode is given solely by the curvature, $\phi(R, T) \to \phi(R)$, and in the limit $\Omega_A \to 0$ solely the matter fields $\phi(R, T) \to \phi(T)$. In