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Extrasolar planets as a probe of modified gravity

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ABSTRACT

We propose a new method to test modified gravity theories, taking advantage of the available data on extrasolar planets. We computed the deviations from the Kepler third law and use that to constrain gravity theories beyond General Relativity. We investigate gravity models which incorporate three screening mechanisms: the Chameleon, the Symmetron and the Vainshtein. We find that data from exoplanets orbits are very sensitive to the screening mechanisms putting strong constraints in the parameter space for the Chameleon models and the Symmetron, complementary and competitive to other methods, like interferometers and solar system. With the constraints on Vainshtein we are able to work beyond the hypothesis that the crossover scale is of the same order of magnitude than the Hubble radius $r_c \sim H_0^{-1}$, which makes the screening work automatically, testing how strong this hypothesis is and the viability of other scales.

1. Introduction

Gravity theories beyond General Relativity (GR) are a possible theoretical framework to explain several cosmological problems [1]. In particular, the intriguing present day's cosmic accelerated expansion [2,3]. Theoretical models which predict an extension to General Relativity must, however, comply with strong requirements: first of all the model must have similar predictions to those of the benchmark model ΛCDM at cosmological scales: observational data from both the background evolution and the linear large scale structure formation regime is fully consistent with ΛCDM [4]. Another condition is that the modifications to General Relativity must be suppressed, by physical mechanisms, in the regimes which are well tested, e.g. solar system scales. This requirement is assured via the so called screening mechanisms [5].

Modified gravity models with screening mechanism have been extensively studied in the literature: either focusing on the background cosmology [6,7], large and linear cosmological scales [8–11] or on astrophysical scales in the nonlinear regime [12], and finally at the small solar system scales using local gravity tests [13,14].

Any weakness in the screening mechanisms should result in appreciable deviations in what we predict from the General Relativity or, in weak field regime, from the Newtonian gravity. This kind of deviations have been used to test modified gravity inside the solar system with, for instance, spectral deviation data from the Cassini space mission, which ensures that the gravitational potential at the Sun surface must deviates less than 10^{-5} from the value predicted by the Newtonian gravity [13]. Another interesting work investigates how much the gravity may deviates from the Newtonian gravity using the well measured solar system bodies orbits [14].

An important feature in the screening mechanisms is the dependence on the physical properties of the environment as the density field, for instance. Thus we expect that the information from different planetary systems should give more statistical significance once the screening works in different ways for each one. On the other side any significantly deviation should already be measured in Solar System, therefore this deviation must be small even in other planetary system.

In this work we investigate the possibility of using exoplanet data to test and constrain modified gravity models. This is not the first attempt to constrain modified gravity with exoplanets [15], but in there the authors just compared the theoretical prediction with only one measurement, the transiting exoplanet HD209458b "Osiris". This lacks statistical rigor, and in this work, we use more

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than one hundred data points and propose a statistical method to make a thorough treatment and study of these systems. The data are obtained from exoplanets.org portal [16].

2. The method

For any gravitational theory the planetary motion is described by the dynamics of a particle under the influence of a central force, i.e. the spatial dependence of the force is only on the distance of the planet to the force center, inside the host star. The relation between the revolution period, T, of a planet in a circular orbit, of radius r, and the absolute value of the gravitational force, $F(r)$, is given by [17]

$$T^2 = \frac{4\pi^2 r}{F(r)}\left(\frac{1}{M_\star}+\frac{1}{M_\mathrm{p}}\right)^{-1}, \tag{1}$$

where M_p and $M_\star$ are the masses of the planet and the star respectively. For a modified gravity the total force is the sum between the Newtonian force and a fifth force, $F(r) = F_N(r) + F_{5th}(r)$. If the fifth force is null this relation reduces to the third Kepler law

$$T_K^2 = \frac{4\pi^2 r^3}{G(M_\mathrm{p}+M_\star)}, \tag{2}$$

where $G = 6.67384 \times 10^{-8}$ cm^3 g^{-1} s^{-2} is the Newton gravitational constant. So the deviation of the square period from the third Kepler law is

$$\left(\frac{T_K}{T}\right)^2 - 1 = \frac{F_{5th}}{F_N} = \varepsilon. \tag{3}$$

Therefore, we can use the measured values of ε to constrain modified gravity using a χ^2 given by the sum between the weighted residuals of all the N measurements

$$\chi^2(\boldsymbol{\theta}) = \sum_{i=1}^{N}\left(\frac{\varepsilon_{th}(\phi(\mathbf{x}_i,\boldsymbol{\theta})) - \varepsilon_{obs,i}}{\sigma_i}\right)^2, \tag{4}$$

where ε_{th} is the theoretical prediction for ε (the ratio between the fifth and Newtonian forces predicted by theory), ε_{obs} is the observed value of ε (the deviation of the square period from the third Kepler law computed from the data), and σ_i is the standard deviation (computed from the data by error propagation, the theoretical error can be neglected because it is proportional to ε^2). $\boldsymbol{\theta}$ is a vector of model parameters and $\mathbf{x}$ is a vector of the physical properties of the star-planet system, which are: r – the planet orbit radius, $R_\star$ – the star radius, $\rho_\star$ – the star density, Φ_S – the surface Newtonian potential. The field is also a function of the galaxy density, $\rho_g = 10^{-24}$ g/cm^3.

To compute the credible regions with 95% of confidence level (C.L.), we find the values of χ^2 which delimit the bounds (χ_b^2), i.e. the value which gives

$$P(\boldsymbol{\theta}) = \frac{1}{(2\pi)^{N/2}\prod_i^N \sigma^i}\int_{\Delta\chi^2<\Delta\chi_b^2} \mathrm{e}^{-\Delta\chi^2(\boldsymbol{\theta})/2}\mathrm{d}\boldsymbol{\theta}, \tag{5}$$

equals to 0.95. Where $\Delta\chi^2 = \chi^2 - \chi^2_{\mathrm{min}}$, and χ^2_{min} is the minimum value of χ^2. Fig. 1 (top) shows a comparison between the residuals distribution with a normal distribution of the same mean and standard deviation, which suggests that this is a good approximation for the data distribution. Therefore assuming this distribution to solve (5) we find $\Delta\chi_b^2 \simeq 5.99$ and $\Delta\chi_b^2 \simeq 8.08$ for models with 2 and 3 free parameters, respectively [18].

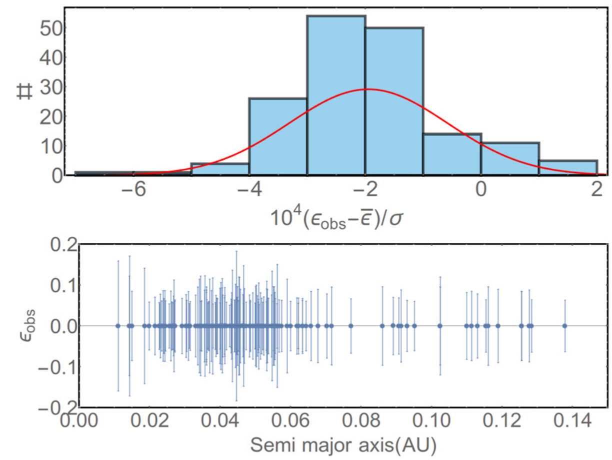

Fig. 1. Top: The residual distribution of ε_{obs} compared with a normal distribution with the same mean and standard deviation. Bottom: ε_{obs} with error bars in function of the semi major axis. However the values are very close to 0 ($\sim 10^{-5}$) the errors are much larger ($\sim 10^{-1}$), which permits a the existence of a fifth force.

The values of χ^2_{min} can me found minimizing the function (4), but this is not a single point for the tested models, there is a degeneracy between the parameters. To avoid this problem we assume χ^2_{min} equal to the value of χ^2 for which the fifth force is null, i.e. $\varepsilon_{th} \equiv 0$, this assumption does not change the results. For a constant deviation, for example, we find $\varepsilon = (0.0^{+6.0}_{-6.0}) \times 10^{-3}$ with this assumption and $\varepsilon = (-0.1^{+6.1}_{-5.9}) \times 10^{-3}$ without it. A shift less than 1% of the confidence interval, and it is reduced in the cases with screening.

3. The data

Our observational data comes from the website exoplanets.org [16], which has a compilation of all observed exoplanetary systems: there are 2926 planets with well defined orbits. From those we pick for our analysis 177 planets with circular orbits and with measurements of all properties listed above. These systems are typically composed by a star, similar to the Sun, with a mass that varies from $0.5M_\odot$ to $1.5M_\odot$, and planets like the jovian planets, with masses between $3.2M_\oplus$ and $600M_\oplus$ and typically close to the host star, with orbit radius smaller than 0.5 AU. This corresponds to short periods, less than a few months.

All the properties are measured by gravity-independent methods, except the orbit radius which use the third Kepler law [19]. However this looks like a circularity it does not affect considerably our analysis, any appreciable deviation in orbit radius such would already have been measured in the Solar System. The Cassini mission [13] measured, by light time delay, the possible deviation from Newtonian gravitational constant in Solar System and the obtained value is very short

$$\frac{\Delta G}{G} = \frac{\gamma - 1}{2} \lesssim 10^{-5}, \quad (0.68\%\ \mathrm{C.L.}). \tag{6}$$

However the photons may be coupled differently to the field, we expect a correction of the same order in the orbit radius, which is much smaller than σ_i. Fig. 1 (bottom) shows that the deviations from the third Kepler law ($\varepsilon_{obs} \sim 10^{-5}$) are very smaller than the errors ($\sigma \sim 10^{-1}$), suppressing any possible bias. In summary the possibility to measure deviations from Newtonian gravity is not in the measurements *per se* but with their errors. The relativistic corrections, which are less than 10^{-8}, are not appreciable, in solar system, for example, the most affected body is Mercury, which the orbit radius is well determined by the Newtonian gravity, the effect