Detecting solar chameleons through radiation pressure

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Abstract

Light scalar fields can drive accelerated expansion of the universe. Hence, scalars are obvious dark energy candidates. To make these models compatible with test of General Relativity in the solar system and fifth force searches on earth, one needs to screen them. One possibility is the chameleon mechanism, which renders an effective mass depending on the local energy density. If chameleons exist, they can be produced in the sun and detected on earth through their radiation pressure. We calculate the solar chameleon spectrum and the sensitivity of an experiment to be carried out at CAST, CERN, utilizing a radiation pressure sensor currently under development at INFN, Trieste. We show, that such an experiment will be sensitive to a wide range of model parameters and signifies a pioneering effort searching for chameleons in unprobed parameter space.

Introduction: The standard model of cosmology, the ΛCDM model, describes the history of our universe based on Einstein’s theory of general relativity (GR), cold dark matter (CDM), and a cosmological constant (Λ). Whilst being in good agreement with astronomical and astrophysical observations, it provides no explanation for the value of its parameters. Although accounting for the accelerated expansion of the universe by a cosmological constant is the most simple model, its value must be fine-tuned. Such problems of the ΛCDM model motivate modified gravity models (MOG). One such model is scalar-tensor gravity, where GR is modified by introducing a gravitationally coupled scalar field $\phi$ with potential $V(\phi)$. The equation of motion for $\phi$ is

$$\partial^2 \phi = V,_{\phi}(\phi) + A,_{\phi}\rho,$$

where $\rho$ is the matter density, related to the Einstein frame density $\rho^E$ and Jordan frame density $\rho^J$ by $\rho = A^{-1}\rho^E = A^{-3}\rho^J$. The dynamics of $\phi$ are governed by the matter density dependent effective potential $V_{\text{eff}}(\phi) \equiv V(\phi) + A(\phi)\rho$. For suitable $V(\phi)$ and $A(\phi)$, the field will have a local minimum at some value $\phi_{\text{min}} = \phi_{\text{min}}(\rho)$. The effective mass is calculated from the curvature of the effective potential at $\phi_{\text{min}}$:

$$m_{\phi,\text{eff}}^2 = V_{\text{eff}}(\phi_{\text{min}}) = V,_{\phi}\phi_{\text{min}} + A,_{\phi}\phi_{\text{min}}\rho,$$

which itself is explicitly dependent on the local mass density $\rho$.

It has however been shown that chameleons can not explain the observed accelerated expansion of the universes as true MOG effect [3], but only as a form of dark energy. In the following, we work with an inverse power law potential

$$V(\phi) = \Lambda n \phi^{-n},$$

where $\Lambda$ is a mass scale. For $n \neq -4$, the $\lambda$-parameter can be absorbed into $\Lambda$. If one adds a constant term, the chameleon fields acts like a cosmological constant on large scales. Such a potential can also be understood as the first (non-trivial) order approximation of an exponential potential:

$$V(\phi) = \Lambda^4 e^{\lambda n}/\phi^n \approx \Lambda^4 \left(1 + \Lambda^n/\phi^n\right).$$
Since the constant term has no effect on the dynamics of the field, we neglect it in the following and absorb $\lambda$ into $A$ for $n \neq -4$. The chameleon-matter coupling is parametrized by $A (\phi) = e^{\frac{\beta_\gamma}{\rho_m} \phi}$. Our effective potential now reads:

$$V_{\text{eff}} (\phi) = \frac{\Lambda_{+n}}{\rho^{n+2}} + e^{\frac{\beta_m}{\rho_m} \phi} \rho_m + e^{\frac{\beta_\gamma}{\rho_m} \phi} \rho_\gamma,$$

(6)

where $\rho_m$ is the local matter density. We assume universal chameleon-matter coupling $\beta_{m,i} \equiv \beta_m$ for simplicity. $\rho_\gamma$ is the local energy density of the electromagnetic field. There is an ongoing debate, whether the chameleon-photon coupling arises from loop corrections or must be added by hand through a term $e^{\frac{\beta_\gamma}{\rho_m} \phi} F_{\mu \nu} F^{\mu \nu}$ in the action. In the following, we consider the chameleon-photon coupling $\beta_\gamma$ to be independent of $\beta_m$. From this effective potential we find

$$\phi_{\text{min}} = \left( n \Lambda_{+n} / \beta_m \rho_m \right)^{\frac{1}{n+2}},$$

(7)

where we assume $\rho_m / M_{Pl}, \rho_\gamma / M_{Pl} \ll \phi$ and $\rho_\gamma \ll \rho_m$. The effective chameleon mass reads:

$$V_{\text{eff,}\phi} (\phi) = n (n + 1) \frac{\Lambda_{+n}}{\rho^{n+2}} + \left( \frac{\beta_m}{M_{Pl}} \right)^2 e^{\frac{\beta_m}{\rho_m} \phi} \rho_m + \left( \frac{\beta_\gamma}{M_{Pl}} \right)^2 e^{\frac{\beta_\gamma}{\rho_m} \phi} \rho_\gamma \approx n (n + 1) \frac{\Lambda_{+n}}{\rho^{n+2}},$$

(8)

with approximations as above and neglecting terms $O \left( \frac{\beta^2}{M_{Pl}} \right)$. Hence, for small excitations around the minimum the effective mass reads:

$$m_{\text{eff}}^2 = (n + 1) \frac{\beta_m \rho_m}{M_{Pl}} \frac{1}{\phi_{\text{min}}}.$$

(9)

Chameleons would be produced in regions of high photon density and strong magnetic field, e.g. inside the sun. One can search for solar chameleons on Earth by detecting their radiation pressure. In the following, we calculate the sensitivity of such an experiment in three parts:

- chameleon production in the sun
- the chameleons’ journey to the detector
- detecting chameleons on Earth.

**Chameleon production in the sun:** Armed with our chameleon model, we can study chameleon production in the sun. We build our calculations on the previous works of Brax et al. [4,5]. Photons mix with chameleons in regions of strong magnetic field, cf. the case for Axions. The conversion probability for photons of energy $\omega$ in a magnetic field $B$ traveling by a length $L$ is given by [6]:

$$P_{\text{chameleon}} (\omega) = \sin^2 (2 \theta) \sin^2 \left( \frac{\Delta}{\cos 2 \theta} \right),$$

(10)

where $\Delta = (m_{\text{eff}}^2 - \omega_{pl}^2) L / 4 \omega$ and $\tan (2 \theta) = \frac{2 B_\gamma \beta_\gamma}{(m_{\text{eff}}^2 - \omega_{pl}^2) M_{Pl}}$ is the mixing angle. $\omega_{pl}^2 = 4 \pi m_e / m_e$ is the plasma frequency with $n_e$ the electron number density, $m_e$ the electron mass, and $\alpha$ the fine structure constant. If chameleons are predominantly produced in the sun’s tachocline, this simplifies greatly. Assuming $\rho_{\text{tacho}} \approx 10^3 \text{g/cm}^3$, $B_{\text{tacho}} \approx 30 \text{ T}$, and $T_{\text{tacho}} = 2 \times 10^6 \text{ K}$, we find $\tan (2 \theta) \approx 10^{-20} \text{ eV}^2 \times \frac{m_e}{m_{\text{eff}}^2 - \omega_{pl}^2}$. Since chameleons can only travel in the sun for an effective momentum

$$k^2 = \omega^2 - (m_{\text{eff}}^2 - \omega_{pl}^2) \geq 0,$$

(11)

we find $\tan (2 \theta) = \sin (2 \theta) = 2 \theta$ and $\cos (2 \theta) = 1$ for a reasonable choice of parameters $\beta_\gamma < 10^{11}$, where the upper bound on $\beta_\gamma$ originates from solar evolution constraints and afterglow experiments. Furthermore we find $\Delta (L) \gtrsim 10^3 \times \left( \frac{L}{\text{cm}} \right)$ where we need to compare $L$ with the photon mean free path in the tachocline $\lambda \approx 0.25 \text{ cm}$ [7]. Since $\Delta (\lambda) \gg 2 \pi$, we average $\langle \sin^2 \Delta (\lambda) \rangle = 1 / 2$. Hence, the conversion probability reads

$$P_{\text{chameleon}} (\omega) = 2 B \beta_\gamma = 2 \left( \frac{\omega B \beta_\gamma}{M_{Pl} (m_{\text{eff}}^2 - \omega_{pl}^2)} \right)^2.$$

(12)

We are now prepared to calculate the spectral density of chameleons produced in the tachocline:

$$\rho_{\text{chameleon}} (\omega) \propto \rho_{\gamma,\text{tacho}} (\omega) \times P_{\text{chameleon}} (\omega) \times \Theta (k^2),$$

(13)
where $\Theta (k^2)$ is the Heaviside step function and the photon spectrum in the tachocline is given by

$$\rho_{\gamma,\text{tacho}} (\omega) = \frac{1}{4\pi^4} \frac{1}{4\omega/\omega_{\text{tacho}} - 1}. \quad (14)$$

Once produced in the tachocline, the chameleons leave the sun unscathed: The interaction rate with fermions can be estimated as $\Gamma_f = n_f \beta_m^4 \frac{m_f^2}{\rho_{\text{max}}} [5]$. Hence, interactions with protons dominate in the sun. With $n_f = \rho_{\text{sol}}/m_p$, we can estimate the mean free path of chameleons in the sun to

$$\lambda_{\text{chameleon}} = \frac{1}{\Gamma_p} = \beta_m^{-4} \frac{M^4_p}{m_p \rho_{\text{sol}}} \sim 10^{24} \times \left( \frac{10^{10}}{\beta_m} \right)^4 \times \left( \frac{100 \text{ g cm}^{-3}}{\rho_{\text{sol}}} \right) \times R_{\text{sol}}, \quad (15)$$

where $R_{\text{sol}}$ is the solar radius.

A detailed calculation of not only the shape but also the normalization of the solar chameleon spectrum may be obtained from integrating our spectrum over the thermalized photons performing a random walk in the tachocline. However, since the results are highly dependent on not only the chameleon model but also the solar model, such a detailed analysis is left for the future. For this work, we normalize our spectra to $\Phi_{\text{chameleon}} = \lambda \Phi_{\text{sol}}$, where $\Phi_{\text{chameleon}} (\Phi_{\text{sol}})$ is the total chameleon (visible) flux from the sun. Stellar evolution constrains the total exotica flux from the sun to $\lambda < 10\%$.

**The chameleons’ journey to the detector:** Chameleons leaving the sun will travel to the detector unscathed, provided their energy is greater than their effective mass in whichever medium they transverse. Since the effective mass scales like $m_{\text{eff}} \propto \rho_{\text{max}}^{n + 2}$, the chameleons’ spectrum at the detector is cut off for $\omega_{\text{chameleon}} < m_{\text{eff}} (\rho_{\text{max}})$ if $n \geq -1$, where $\rho_{\text{max}}$ is the medium of highest density the chameleons travel through. In our case, the most dense medium is the window the chameleons have to penetrate when entering the experiment’s vacuum chamber with $\rho_{\text{window}} \approx 1 \text{ g cm}^{-3}$. Hence, we introduce a cutoff of the chameleon spectrum $\rho_{\text{chameleon}} (\text{detector}) \propto \rho_{\text{chameleon}} (\text{sun}) \times \Theta (\omega - m_{\text{eff}} (\rho_{\text{max}}))$.

**Detecting chameleons on Earth:** A radiation pressure sensor for chameleon detection dubbed Kinetic WISP detection (KWISP) is currently under development at INFN Trieste. The sensor employs a 100 nm-thick Si$_3$N$_4$ micromembrane ($\rho = 3.2 \text{ g cm}^{-3}$) mounted in a high finesse Fabry-Perot cavity. The 5 mm $\times$ 5 mm membrane may optionally be coated with a gold layer up to 20 nm thick. At room temperature, the sensor is sensitive to a force induced by radiation pressure $F/\sqrt{t_{\text{meas}}} = 5 \times 10^{-11} \text{ N}/\sqrt{\text{s}}$, where $t_{\text{meas}}$ is the measurement’s duration. If we assume the chameleon flux $\Phi_{\text{chameleon}}$ to be $\Phi_{\text{chameleon}} = \lambda \Phi_{\text{sol}}$ and $\Phi_{\text{sol}} = 1.36 \text{ kW/m}^2$, we need

$$\Phi_{\text{chameleon}} \geq 2 \times 10^{-3} \times \left( \frac{10 \%}{\lambda} \right) \times \sqrt{\frac{1 \text{ s}}{t_{\text{meas}}}} \quad (16)$$

of the total chameleon flux to be reflected by the sensor in order to detect chameleons.

The sensor’s membrane will reflect all chameleons with energies smaller than the chameleons effective mass in the membrane’s material. Hence, the fraction of the chameleon flux reflected by the sensor is given by

$$\frac{\Phi_{\text{reflected}}}{\Phi_{\text{chameleon}}} = \frac{m_{\text{eff}}}{\int_0^\infty \rho_{\text{chameleon}} (\omega) \times \Theta (\omega - m_{\text{eff}} (\rho_{\text{max}})) \, d\omega} \times \int_0^\infty \rho_{\text{chameleon}} (\omega) \, d\omega. \quad (17)$$

The sensitivity of the experiment can be optimized by introducing an incident angle of the chameleons on the membrane $\theta > 0$. Then all chameleons with $k_{\perp} = \cos \theta \times \omega \leq m_{\text{eff}}$ are effective. On the other hand, this implies that the force on the sensor is reduced by $\cos \theta$ and the effective area of the sensor reduced by a factor $\sqrt{\cos \theta}$. Thus, after introducing an incident angle the fraction of the flux reflected by the sensor reads:

$$\frac{\Phi_{\text{reflected}}}{\Phi_{\text{chameleon}}} = (\cos \theta)^{3/2} \frac{m_{\text{eff}}/\cos \theta}{\int_0^\infty \rho_{\text{chameleon}} (\omega) \times \Theta (\omega - m_{\text{eff}} (\rho_{\text{max}})) \, d\omega \times \int_0^\infty \rho_{\text{chameleon}} (\omega) \, d\omega}. \quad (18)$$

Further improvement of the experiment’s sensitivity can be achieved by employing an X-Ray telescope (XRT) like the ABRIXAS telescope employed by CAST. Since the telescope’s mirrors’ are coated with gold and the grazing angle of the telescope is smaller than $1^\circ$, all chameleons reflected by the membrane will be focused by the telescope for an incident angle of the membrane $\theta < 89^\circ$. For our calculations, a gain factor of 500 is assumed for the XRT. One can furthermore cool down the membrane below 0.3 K, which gives another gain factor 100. Modulating the chameleon flux with a chopper would result in another sensitivity gain $> 10$. 

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Figure 1: Fraction of the total chameleon flux reflected by the sensor’s membrane for a grazing angle of \(1^\circ\) (left panels) and \(10^\circ\) (right panels) and the chameleon potential’s mass scale fixed to the dark energy scale \(\Lambda = 2.4 \times 10^{-3} \text{eV}\). The 1st and 3rd panel show the fractions for the membrane coated with gold, the 2nd and 4th panel for the bare membrane respectively. The horizontal black dash-dotted lines show the minimum fraction needed to detect chameleons, assuming the total chameleon flux is 10\% of the total solar luminosity and a measurement duration of 1000 s without CAST’s XRT, 100 s with XRT. An optimal case with the membrane cooled to 0.3 K, \(t_{\text{meas}} = 100 s\), a chopper system and using CAST’s XRT also shown.

Figure 2: Fraction of the total chameleon flux reflected by the sensor’s membrane for a grazing angle of \(5^\circ\). The chameleon potential’s mass scale is fixed to 0.1 eV (left), \(2.4 \times 10^{-3} \text{eV}\), the dark energy scale, (middle) and \(10^{-5} \text{eV}\) (right) respectively. For further explanations, see the description of Fig. 1.

Figure 3: Effective mass in gold (membrane) × thickness of gold coating (membrane) vs. matter coupling for a chameleon model mass scale of 0.1 eV (left), \(2.4 \times 10^{-3} \text{eV}\), the dark energy scale, (middle) and \(10^{-5} \text{eV}\) (right). Only chameleons with \(m_{\text{eff}} d \gtrsim 1\) will be reflected.
Projected sensitivity: The sensitivity of KWISP to solar chameleons depends strongly on the chameleon model. Since the sensor’s sensitivity relies on rapid scaling of the effective mass with the local energy density, the experiment will be most sensitive to strongly coupled chameleons, i.e. large matter couplings $\beta_m$, large $n$, and small mass scales $\Lambda$ (cf. figures 1, 2). If the coupling becomes too strong though, chameleons will not be able to penetrate the experiment’s window or eventually even exit the sun. Due to the shape of the solar chameleon spectrum, it is of great advantage to install the membrane at small grazing angle with respect to the direction of the incoming chameleons to extend the sensitivity to less strongly coupled models (cf. Figure 1). In order for the chameleon field to "see" the membrane, its Compton wavelength in the membrane $m_{\text{eff}}^{-1}$ must be of the order of the thickness of the membrane/gold coating, respectively, or smaller (cf. Figure 3). If we assume the chameleon mass scale to be the dark energy scale, $\Lambda = 2.4 \times 10^{-3}$ eV, and a first set-up using CAST’s XRT and measuring for $100\text{ s}$, which is the time the XRT can focus solar chameleons without being moved, the experiment would already explore an uncharted area of parameter space of $\beta_m \sim 10^3 \ldots 10^9$, depending on the potential’s power $n$. In an optimal case, one would cool the membrane below $1\text{ K}$ and employ a better XRT as well as a shutter to modulate the chameleon flux. This extends the sensitivity to smaller matter couplings $\beta_m \gtrsim 10^{2.5}$.

If we instead assume a much bigger mass scale $\Lambda = 0.1$ eV, the experiment would only be sensitive to very strongly coupled chameleons, whilst in the case of a much smaller mass scale $\Lambda = 10^{-5}$ eV, the experiment would be sensitive to weaker coupled chameleons, with the sensitivity to strongly coupled models diminished, since they could not be produced in the sun anymore.

Our calculations also show that coating the membrane with gold is highly advantageous. Furthermore, we showed by comparing the chameleon’s Compton wavelength with the thickness of the gold coating or membrane, respectively, that for chameleon-models within the sensitivity a 20 nm thick gold coating or 100 nm thick uncoated membrane suffices.

Conclusion: We calculated the solar chameleon spectrum for a range of model parameters. We showed that detecting the pressure caused by reflection of solar chameleons on a micromembrane gives access to a wide range of chameleon models and that the sensitivity of the KWISP sensor currently under development at INFN Trieste is sufficient to explore previously uncharted areas of the chameleon model parameter space.

Carrying out this experiment will provide a chameleon search complementary to previous experiments, such as fifth force experiments (Eötvös, Casimir force, gravitationally trapped ultracold neutrons), afterglow experiments (GammeV-CHASE) or previous searches at CAST looking for X-Ray photons from Chameleon-photon conversion inside CAST’s magnet.

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