

Solar Chameleons: Production and Detection

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Chameleon fields evade gravitational tests in the solar system and the laboratory while playing the role of quintessence on cosmological scales. They could be produced in magnetised regions of the inner sun, e.g. around the tachocline. Once produced, they can be backconverted into X-ray photons in the sun's atmosphere or reach helioscope detectors on earth where the spectrum of photons is typically peaked in the sub-keV region. Dedicated laboratory shining-through-a-wall experiments using powerful X-ray lasers could be used to test the existence of chameleons.

1 Introduction

Quintessence models used to analyse the acceleration of the expansion of the Universe suffer from the presence of an ultra-light scalar field of mass of order $H_0 \sim 10^{-43}$ GeV which would lead to the existence of a fifth force and strong violations of the equivalence principle. Unless the quintessence field is almost decoupled from ordinary matter, this fact would rule out most dark energy models. Fortunately, it turns out that on small scales compared to the size of the Universe, typically in the solar system or the laboratory, screening mechanisms can be at play. We will focus on the chameleon mechanism whereby a scalar field develops an environmentally dependent mass which can become large enough in dense regions to induce a Yukawa suppression of the fifth force between massive bodies.

Chameleons[1] can also couple to photons and could therefore be produced in magnetised regions by the Primakoff effect. This could well occur in the sun where strong magnetic fields are understood to be present around the tachocline at $0.7 R_\odot$ with a strength $B = 20 - 50$ T.

Chameleon production could be either resonant or non-resonant. The resonant case is restricted to very small regions where the spatially varying mass of the chameleon is equal to the plasma frequency in the sun, and is therefore depleted compared to the non-resonant production which takes place in large magnetised zones. Such solar chameleons mostly escape the sun unscathed reaching the earth where they are energetic enough to penetrate into helioscope pipes where they could regenerate X-ray photons. A small fraction of the solar chameleons can also regenerate photons in the weak magnetic field of the quiet sun's atmosphere, hence contributing to the solar X-ray spectrum. If X-ray photons were observed with helioscopes, an experimental signature of the existence of chameleon particles could be attained using powerful X-ray lasers shining into two magnetised pipes separated by a X-ray thick barrier.

Indeed chameleons would be created in the vacuum pipe, cross the barrier and regenerate X-rays in the second pipe downstream. This would not be the case anymore when the pipe is

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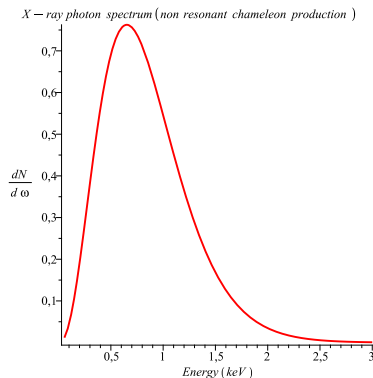


Figure 1: The spectrum of back-converted photons from solar chameleons giving the number of counts per hour and per keV predicted to be seen in a magnetic helioscope like CAST in vacuum as a function of the reconverted photon energy.

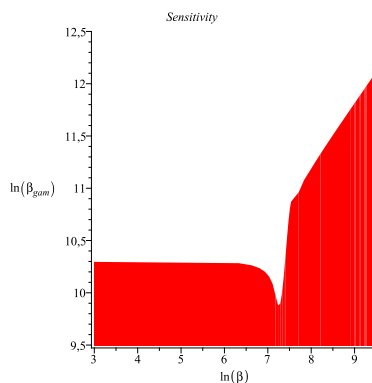


Figure 2: The sensitivity region at the 2σ level above the red region for a magnetic helioscope like CAST in vacuum at a temperature of 1.8K and for the photon coupling $\log \beta_\gamma$ as a function of the matter coupling $\log \beta$.

filled with a gas at moderate pressure, a clear demonstration of the density dependence of the chameleon mass.

2 Solar Chameleons

Chameleons are dark energy candidates. Chameleon models depend on the shape of the dark energy potential $V(\phi)$ and the coupling to matter β . Chameleons have an effective potential which becomes matter density dependent $V_{\text{eff}}(\phi) = V(\phi) + e^{\beta\phi/m_{\text{Pl}}}\rho$ where ϕ is the chameleon field and ρ the non-relativistic matter density. The effective potential has always a matter dependent minimum and fluctuations around the vacuum expectation values at the minimum can be seen as chameleon particles which couple to matter. The density-dependent minimum

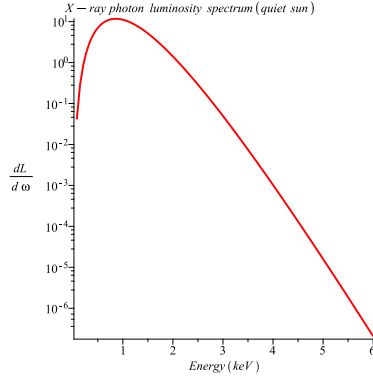


Figure 3: The X-ray luminosity spectrum from back-converted chameleons leaving the quiet sun as a function of the photon energy in keV in $\text{erg} \cdot \text{keV}^{-1} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$. The photons are backconverted at altitudes larger than 5000 km with a magnetic field of 1 Gauss and a density of order $10^{-16} \text{g} \cdot \text{cm}^{-3}$. We have used $B_{\text{out}} L_{\text{out}} \approx 10^4 \text{ T} \cdot \text{m}$ to determine the length of the magnetic region.

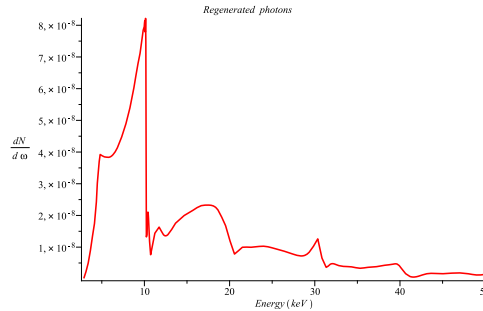


Figure 4: An example of photon flux in $\text{s}^{-1} \cdot \text{keV}^{-1}$ as a function of the photon energy in keV for the regenerated photons as predicted to be seen by a chameleon through wall experiment using two magnetic pipes on both sides of a thick barrier. The coupling to matter is $\beta = 10^6$ while the coupling to photons $\beta_\gamma = 10^{10.32}$ implies a corresponding 2σ result obtained in 300 days with a detection sensitivity of $10^{-6} \text{s}^{-1} \cdot \text{cm}^{-2}$. For magnetic pipes of 3 times the CAST pipe length, a 5σ result would only take 6 days.

is such that the mass of the scalar field becomes also density dependent. We will focus on inverse power law models defined by $V(\phi) = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n} + \dots$ where we have neglected higher inverse powers of the chameleon field. We will choose $\Lambda = 2.4 \cdot 10^{-12} \text{GeV}$ to accommodate the acceleration of expansion rate of the universe on large scales. The potential has a minimum located at $\phi_{\text{min}} = \left(\frac{n m_{\text{Pl}} \Lambda^{4+n}}{\beta \rho}\right)^{1/(n+1)}$ where ρ is the total non-relativistic matter density. The chameleon rest mass at the minimum is $m^2 \approx \beta \frac{\rho}{m_{\text{Pl}} \phi_{\text{min}}^{n+1}}$. Chameleons also couple to photons in a way akin to the axion coupling $S_{EM} = - \int d^4x \sqrt{-g} \frac{e^{\phi/M_\gamma}}{4} F^2$ where g is the determinant of the metric $g_{\mu\nu}$ and $F^2 = F_{\mu\nu} F^{\mu\nu}$ where $F_{\mu\nu}$ is the photon field strength. The chameleon

parameter space depends on the discrete index n and two continuous parameters $\beta = \frac{m_{\text{Pl}}}{M_m}$, the coupling to matter, and M_γ the suppression scale of the coupling to photons. It is also convenient to introduce the photon coupling parameter $\beta_\gamma = \frac{m_{\text{Pl}}}{M_\gamma}$.

Chameleons can be produced during the propagation of photons inside the macroscopic magnetic fields of the sun. The mixing of photons and chameleons depends on $k^2(\omega) = \omega^2 - m_{\text{eff}}^2 \left(\frac{\cos \theta + 1}{2 \cos 2\theta} \right)$ where the effective mass is $m_{\text{eff}}^2 = m^2 - \frac{B^2}{M_\gamma^2} - \omega_{\text{pl}}^2$ and ω is the initial frequency of the incoming photons. This depends on the mixing angle which is given by $\tan 2\theta = \frac{2\omega B}{M_\gamma m_{\text{eff}}^2}$ and the plasma frequency which is $\omega_{\text{pl}}^2 = \frac{4\pi\alpha n_e}{m_e}$ where α is the fine structure constant. Electro-neutrality implies that, in the sun, $n_e = \frac{\rho m}{m_p}$, where m_p is the proton mass. When $\theta \ll 1$: as is the case in most helioscope pipes and also inside the sun, we have $\theta = \frac{\omega B}{M_\gamma m_{\text{eff}}^2}$. Chameleon production in a magnetised region of size L is obtained from the transition probability $P_{\text{chameleon}}(\omega) = \sin^2(2\theta) \sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$ where $\Delta = m_{\text{eff}}^2 L / 4\omega$. It is important to notice that chameleon production is only possible when $\omega^2 \geq m_{\text{eff}}^2$ for small values of θ . We focus on a conservative assumption, where a constant magnetic field is present in a small shell of size $0.01 R_\odot$ around the tachocline about $0.7 R_\odot$ with $B = 30\text{T}$. Chameleons are non-resonantly produced in this magnetised region and would lead to the X-ray spectrum in a CAST-like experiment shown in Fig. 1. The couplings $\beta = 10^6$ and $\beta_\gamma = 10^{10.29}$ are chosen according to the sensitivity diagram shown in Fig. 2 at the 2σ level for a detection rate of one count per hour. The photon coupling is (almost) saturating the solar excess luminosity bound for exotic particle production $\beta_\gamma \leq 10^{10.32}$ and is below the CHASE bound $\beta_\gamma \leq 10^{11}$. Some of the escaping chameleons can regenerate photons in the quiet sun's atmosphere. The corresponding spectrum is shown in Fig.3, contributing to the solar X-ray spectrum and maybe providing a possible mechanism to tackle the corona problem. Finally, powerful X-ray lasers could be used to test the existence of (sub-) keV chameleons. Indeed, chameleons could be produced in a magnetised vacuum pipe and cross a X-ray thick barrier while regenerating X-rays downstream. This would not be the case anymore when a gas at moderate pressure is injected into the pipes. Indeed, the mass of chameleons would increase and reduce the photon to chameleon conversion probability. For a spectrum with a flux of 10^{19} X-rays photons per second, we have given the regenerated X-ray spectrum in Fig. 4. For long pipes (multiple CAST pipes), a few days of observations could be enough to detect keV chameleons.

References

- [1] see P. Brax, A. Lindner, K. Zioutas, [arXiv:1110.2583 [hep-ph]], and references therein.