Producing Chameleons in the Sun

Philippe Brax,

Institut de Physique Théorique, CEA, IPhT, CNRS, URA 2306,
F-91191Gif/Yvette Cedex, France.

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We present a mechanism whereby chameleons can be produced in the strong magnetic field of the solar tachocline. A small fraction of the resulting chameleons can be back-converted into photons which would naturally have a spectrum in the soft X-ray region. The remaining chameleons are energetic enough to penetrate into helioscopes and could trigger a photonic X-ray signal.

1 Introduction

Chameleon fields [1] can be responsible for the late time acceleration of the expansion of the universe while preserving gravity locally. Chameleons can disturb the growth of structures on large scales and even lead to testable predictions for Casimir experiments and optical cavity experiments. In the latter case, the physics of chameleons is extremely similar to axion physics. It is well known that axions may modify the burning rate of stars. In a similar fashion, chameleons may lead to an enhanced dissipation of energy in the sun. On the other hand, chameleons have a density dependent mass which hampers their creation by the Primakoff effect in very dense environments, hence cutting the spectrum of created chameleons below their mass threshold. In most circumstances, this prevents their appearance apart from a depleted number of very energetic ones. Fortunately, chameleons feel the presence of the surrounding plasma and this interaction may be resonant when the mass of the chameleons (almost) coincides with the plasma frequency. In this case, the plasma becomes almost transparent to chameleons which can therefore be produced in an enhanced manner. Now it happens that the chameleon mass varies inside the sun as the density changes from the inner sun to the solar surface. When the mass of the chameleon varies (almost) like the matter density, the whole solar interior becomes transparent to chameleons. If produced deep inside the sun in the tachocline, a region of intense magnetic field, these chameleons escape the sun producing a soft X-ray chameleon flux which can eventually reach the earth. Of course, along their path from the inner sun to the outer sun, chameleons can be back-converted into photons. This process is a second order effect which is therefore suppressed compared to the chameleon creation inside the sun. If the back-converted photons are produced deep inside the sun, the smallness of the photonic mean free path implies that these photons contribute as a small perturbation to the radiative transfer with negligible effects. On the other hand, back-converted photons at the surface of the sun have a long enough mean free path to escape the sun. Moreover their spectrum is a mirror image of the photon spectrum in the tachocline (modulo a transfer function corresponding to the creation and then disappearance of the intermediate chameleons). This spectrum is predominantly in the soft X-ray band. It happens that we can impose that the back-converted photons saturate the Sphinx bound on the luminosity of the quiet sun. Of course, this is a strong prior and the back-converted photons could be contributing to a much smaller fraction of the soft X-ray flux. Once chameleons have been emitted by the sun, they reach the earth and again some of the chameleons do not penetrate inside the atmosphere which acts as a first barrier to the incoming chameleon flux. Due to the low density of the earth atmosphere, most chameleons go through and could even penetrate inside helioscopes when their energy is greater than the chameleon mass in dense materials such a lead. In this case, the remaining chameleons could be converted into X-ray photons. These photons would then be detectable by helioscope detectors provided their number exceeds the detector sensitivity. In the following, we will give a numerical example where all these conditions are met. The study of the parameter space, for which the back-converted photons in the outer sun do not exceed the Sphinx bound and the number of soft X-ray photons produced in the helioscope pipes is large enough to overcome the detector noise, is in progress.

2 Chameleon Production

Chameleons are particles which couple to matter in such a way that their effective potential becomes matter density dependent

$$V_{\rm eff}(\phi) = V(\phi) + e^{\beta\phi/M_{Pl}}\rho \tag{1}$$

This potential has a density dependent minimum $\phi_{\rm min}$. This is the vacuum of the theory in a given environment. The density-dependent minimum is such that the mass of the scalar field becomes also density dependent. We will mainly focus on inverse power law models defined by

$$V(\phi) = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n} + \dots \tag{2}$$

where we have neglected higher inverse powers of the chameleon field. We will choose $\Lambda = 2.4\ 10^{-12}$GeV to lead to the acceleration of the universe on large scales. The potential has a minimum located at $\phi_{\rm min} = (\frac{nM_{\rm Pl}\Lambda^{4+n}}{\beta\rho})^{1/(n+1)}$ where ρ is the total non-relativistic matter density. The chameleon rest mass at the minimum is $m^2 \approx \beta\frac{e^{\beta\phi_{\rm min}/M_{\rm Pl}}\rho}{M_{\rm Pl}}\frac{n+1}{\phi_{\rm min}}$. Chameleons also couple to photons in a way akin to the axion coupling

$$S_{EM} = -\int d^4x\sqrt{-g}\frac{e^{\phi/M_\gamma}}{4}F^2 \tag{3}$$

implying that the effective matter density in the effective potential is

$$\rho = \rho_m + \frac{m_{\rm Pl}}{\beta M_\gamma}\frac{B^2}{2} \tag{4}$$

The chameleon mixes with photons when a constant magnetic field is present. We find that the chameleons couple to the polarisation orthogonal to the constant magnetic field. The chameleon mixes with the orthogonal polarisation of the photon, resulting in an effective momentum

$$k^2(\omega) = \omega^2 - (m^2 - \frac{B^2}{M_\gamma^2} - \omega_{\rm pl}^2)(\frac{\cos\theta + 1}{2\cos 2\theta}) \tag{5}$$

where ω is the initial frequency of the incoming photons. This depends on the mixing angle which is given by

$$\tan 2\theta = \frac{2\omega B}{M_\gamma (m^2 - \frac{B^2}{M_\gamma^2} - \omega_{\rm pl}^2)} \tag{6}$$

and the plasma frequency is $\omega_{\rm pl}^2 = \frac{4\pi\alpha_{EM} n_e}{m_e}$. Electro-neutrality implies that in the sun $n_e = \frac{\rho_m}{m_p}$, where m_p is the proton mass. The chameleons propagate when $k^2 > 0$ and are forbidden to propagate when $k^2 < 0$. The thermal photons inside the fully ionised inner sun evolve as free particles for a length equal to their mean free path λ. The chameleon production rate is obtained from the transition probability

$$P_{\rm chameleon}(\omega) \approx \frac{1}{2}\theta^2. \tag{7}$$

This is the conversion probability of one photon into a chameleon over the length of one mean free path. During one second, the photons experience N interactions inside the rather static solar magnetic field, where $N = \frac{1}{\lambda}$ in reduced units with $c = \hbar = 1$. The probability of creating one chameleon per second out of one thermal photon is then $P_{\rm total}(\omega) = NP_{\rm chameleon}(\omega)$ as $P_{\rm chameleon} \ll 1$. For the thermal photons, we assume a Planckian distribution $p_\gamma(\omega) = \frac{\omega^2}{\pi^2 \bar{n}} \frac{1}{e^{\frac{\omega}{T}} - 1}$ where the average number of photons at temperature T is $\bar{n} = \frac{2\zeta(3)}{\pi^2} T^3$, implying that the chameleon spectrum is

$$\Phi_{\rm cham}(\omega) = p_\gamma(\omega) P_{\rm total}(\omega) n_\gamma \tag{8}$$

where n_γ is the photon flux corresponding to the number of photons going through a sphere of radius R from the centre of the sun. We take it to be a constant in the magnetic region near the tachocline we are considering.

The photons which can be suddenly created in the photosphere from the chameleon flux are such that they will not thermalise and escape relatively quickly after their creation with a spectrum reflecting directly the nature of the chameleon production spectrum inside the sun. The flux of back-converted photons in the photosphere from chameleons created in the tachocline region ($R \sim 0.7 R_{\rm sun}$) is then

$$\Phi_{\rm photon}(\omega) \approx \frac{1}{2}\theta_{\rm outer}^2 \Phi_{\rm cham}(\omega) \tag{9}$$

where $\theta_{\rm outer}$ is the mixing angle in the photosphere.

3 Phenomenology

A first constraint on the chameleon production is the Sphinx direct observation of the quiet sun X-ray brightness which specifies that the photon energy flux in the range of energies larger than ~ 1 keV is about 10^{-3}erg/s $\cdot$ cm^2. A second constraint is the non-observation of photons by the CAST experiment which also restricts the parameter space (β, M_γ, n) of the model.

For instance, these constraints can be satisfied when $M_\gamma = 10^{5.8}$ GeV. A strong enough resonance in the outer sun can be obtained with $\beta = 10^{7.09218}$ and $n = 8.7$. For these values, we have presented the spectrum of the chameleon flux out of the sun in Fig. 1. These chameleons go through the earth atmosphere. Similarly they would enter the CAST magnet. There, in the pipes, the chameleons can be back-converted into photons via the inverse Primakoff effect. Now,

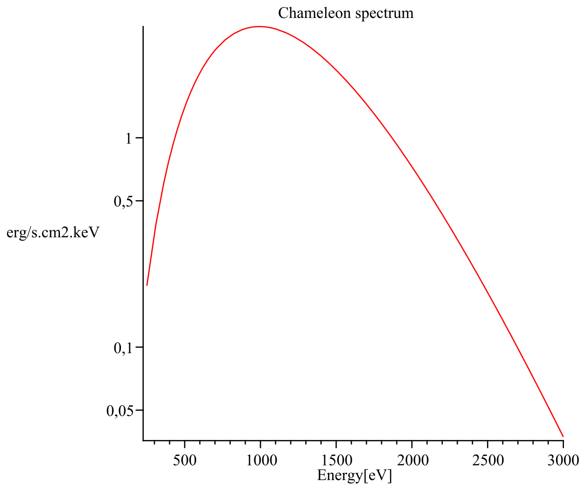

Figure 1: The energy spectrum of the emitted chameleons. Energies are expressed in eV and the spectrum in erg/s·cm^2·keV. The coupling is chosen to be $M_\gamma = 10^{5.8}$ GeV and the magnetic field in the lower convection region is B=30 T which is the solar chameleon source. The integrated flux at the solar surface is 4 $\text{erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$.

the spectrum of the regenerated X-ray photons can be evaluated using $B_{\text{cast}} = 9$ T, taking the length of the magnetic region to be $L_{\text{cast}} = 9.26$ m, the diameter of the pipes $d = 43$ mm and the pressure in the vacuum pipes less than 10^{-6} mbar ($T \approx 1.8\ K$). We can calculate the rate of excess photon production and we find $N_\gamma \approx 0.04$ photon per hour. The CAST experiment has taken data with vacuum in the magnetic pipes for ~ 200 hours and the noise level is 0.13 photon per hour in the 1-7 keV band. The number of converted photons represents a 1.5 σ effect and therefore it could not have been seen. A better performing CAST experiment has the potential to observe such an X-ray excess. The situation would improve drastically with a new CAST configuration, where we assume the following specifications: $B = 6$ T, $L = 15$ m and aperture surface 0.15 m^2. In this case, the number of photons per hour becomes $N_\gamma = 12$ in the keV region. With a noise level of 4 photons per hour, a 5 σ detection would only take 3 hours of solar tracking.

In conclusion, the fact that chameleon models for some values of the parameters can be within the CAST ball-park is encouraging. A thorough study of the parameter space would certainly be valuable and help putting new bounds on chameleon couplings.

References

[1] See P. Brax and K. Zioutas, Phys. Rev. D **82** (2010) 043007 [arXiv:1004.1846 [astro-ph.SR]] and references therein.