IL NUOVO CIMENTO **38 C** (2015) 37
DOI 10.1393/ncc/i2015-15037-x

COLLOQUIA: IFAE 2014

# Astrophysical hints of axion-like particles

M. RONCADELLI(1)(*), G. GALANTI(2), F. TAVECCHIO(3) and G. BONNOLI(3)

(1) *INFN, Sezione di Pavia - Pavia, Italy*
(2) *Universittà dell'Insubria - Como, Italy*
(3) *Osservatorio di Brera-INAF - Milano, Italy*

received 7 January 2015

**Summary.** — After reviewing three astrophysical hints of the existence of axion-like particles (ALPs), we describe in more detail a new similar hint involving flat spectrum radio quasars (FSRQs). Detection of FSRQs above about 20 GeV pose a challenge to very-high-energy (VHE) astrophysics, because at those energies the ultraviolet emission from their broad line region should prevent photons produced by the central engine to leave the source. Although a few astrophysical explanations have been put forward, they are totally *ad hoc*. We show that a natural explanation instead arises within the conventional models of FSRQs provided that photon-ALP oscillations occur inside the source. Our analysis takes the FSRQ PKR 1222+206 as an example, and it looks tantalizing that basically the same choice of the free model parameters adopted in this case is consistent with those that provide the other three hints of the existence of ALPs.

PACS 14.80.Va – Axions and other Nambu-Goldstone bosons (Majorons, familons, etc.).
PACS 95.85.Pw – $\gamma$-ray.
PACS 95.85.Ry – Neutrino, muon, pion, and other elementary particles; cosmic rays.

## 1. – Introduction

Many extensions of the Standard Model (SM) of strong, weak and electromagnetic interactions and especially superstring theories generically predict the existence of axion-like particles (ALPs) (for a review, see [1]). ALPs are very light neutral pseudo-scalar bosons quite similar to the axion, namely the pseudo-Goldstone boson arising from the breakdown of the global Peccei-Quinn symmetry $U(1)_{\rm PQ}$ proposed to solve the well known strong *CP* problem. But in contrast with the axion, for ALPs —to be denoted

(*) Speaker

 

by $a$— the mass $m$ and the $a\gamma\gamma$ coupling constant $1/M$ are *unrelated* parameters. In addition, mainly to make the analysis as much as model-independent as possible *only* the ALP interaction with two-photons is considered, and so ALPs are described by the Lagrangian

$$\mathcal{L}^0_{\mathrm{ALP}} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2 + \frac{1}{M}\,\mathbf{E}\cdot\mathbf{B}\,a, \tag{1}$$

where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic components of the field strength $F^{\mu\nu}$. Only the CAST experiment at CERN gives a robust bound on $M$ which reads $M > 1.14 \cdot 10^{10}\,\mathrm{GeV}$ for $m < 0.02\,\mathrm{eV}$ [2]. As it is evident from the last term in eq. (1) —which represents the $a\gamma\gamma$ coupling— only the component of $\mathbf{B}$ parallel to the photon polarization couples to $a$. Moreover, in the presence of an *external* magnetic field the $a\gamma\gamma$ coupling produces a mismatch between the interaction eigenstates and the propagation eigenstates of the $\gamma a$ system, thereby giving rise to the phenomenon of photon-ALP oscillations. The present situation is similar to that of oscillations of massive neutrinos of different flavours, apart from the difference that here an external $\mathbf{B}$ field is necessary in order to compensate for the spin mismatch between photons and ALPs. Finally, from the interaction term in $\mathcal{L}^0_{\mathrm{ALP}}$ and the CAST bound it is straightforward to get the following order-of-magnitude estimate for the cross-sections $\sigma(a\,\gamma \to f^+ f^-) \sim \sigma(a\,f^\pm \to \gamma\,f^\pm) < 10^{-52}\,\mathrm{cm}^2$ (here $f$ denotes any charged fermion), which shows that effectively ALPs do not interact with anything.

While ALPs are unobservable in present-day accelerator experiments, their existence can likely show up in *blazar* observations (more about this, later) in the very-high-energy (VHE) band ($100\,\mathrm{GeV} < E < 100\,\mathrm{TeV}$) with the presently operating Imaging Atmospheric Cherenkov Telescopes (IACTs) H.E.S.S., MAGIC and VERITAS, even though a much better chance in this respect is offered by the planned new generation of VHE gamma-ray detectors.

Actually, some VHE astrophysical hints of the ALP existence have already been reported. First, they provide a solution of the so-called *pair-production anomaly* [3]. Second, they can explain the observed low value of the extra-galactic magnetic field [4]. Third, they offer a natural solution to the *cosmic opacity problem* [5]. All these effects are basically brought about by a simple fact. As we said, in the presence of an external magnetic field photon-ALP oscillations can take place, thereby giving the photons a split personality: during their propagation from a source to us, they sometimes behave as true photons and sometimes as ALPs. In the former case they scatter off the extragalactic background light (EBL) —namely the infrared/optical/ultraviolet background radiation emitted by galaxies during the whole cosmic evolution— through the process $\gamma\gamma \to e^+e^-$ thereby disappearing from the game, whereas in the latter case they propagate freely. As a consequence, the effective photon mean free path $\lambda_{\mathrm{eff}}$ gets larger than that predicted by conventional physics. Now, discarding for simplicity cosmological effects and denoting by $d$ the source distance, the crux of the argument is that the photon survival probability is given by $P_{\gamma\to\gamma}(d) = e^{-d/\lambda_{\mathrm{eff}}}$ and so even a *small* increase of $\lambda_{\mathrm{eff}}$ brings about a *large* increase of $P_{\gamma\to\gamma}(d)$ as compared to the conventional expectation, thereby also considerably extending the $\gamma$-ray horizon [6].

Our aim is to present a new hint supporting the existence of ALPs, namely the VHE emission by flat spectrum radio quasars (FSRQs) at energies well above $20\,\mathrm{GeV}$, which is detected by IACTs but absolutely forbidden by conventional physics (more about this, later) [7].

Before leaving this section, an important remark is in order. We shall work throughout in the presence of an external magnetic field so that photon-ALP oscillations can occur. In such a situation the Lagrangian $\mathcal{L}^0_{\rm ALP}$ is appropriate as long as one-loop QED vacuum polarization effects are negligible. However, in the case discussed below this is not true, and so they have to be taken into account. They are described by the Heisenberg-Euler-Weisskopf (HEW) effective Lagrangian [8]

$$\mathcal{L}_{\rm HEW} = \frac{2\alpha^2}{45 m_e^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right], \tag{2}$$

where $\alpha$ is the fine-structure constant and $m_e$ is the electron mass. Therefore, we shall be dealing throughout with the full Lagrangian $\mathcal{L}_{\rm ALP} = \mathcal{L}^0_{\rm ALP} + \mathcal{L}_{\rm HEW}$.

## 2. – Flat spectrum radio quasars (FSRQs)

With the advent of IACTs the VHE astrophysics has undergone a stunning development. Among the many discoveries, a remarkable one is that a class of active galactic nuclei (AGN) emits photons up to energies of a few TeV. Now, AGN are basically supermassive black holes (SMBHs) located at the centre of bright galaxies and accreting matter from the surrounding, which —before disappearing into the SMBH— heats up tremendously and consequently radiates an enormous amount of *thermal* energy. Roughly 10% of the AGN possess two opposite relativistic and highly collimated jets orthogonal to an accretion disk. Whenever one of the jets happens to be directed towards the observer, the AGN is called *blazar*. Electrons accelerated in the jet are a source of *non-thermal* radiation, which spans the entire electromagnetic spectrum. The corresponding spectral energy distribution (SED) is characterized by two humps. The first one peaks somewhere between the infrared and the x-ray band and is due to the synchrotron emission of relativistic electrons in the jet. The second peak lies in the $\gamma$-ray band, but its origin is debated. Two mechanisms have been proposed for its origin: one leptonic and the other hadronic. In the leptonic case the peak is due to the inverse Compton scattering off the same electrons responsible for the synchrotron peak (with a possible contribution from external photons), while in the hadronic mechanism the considered peak is due to reactions involving relativistic hadrons with neutral and charged pions decaying into $\gamma$-rays and neutrinos, respectively.

Blazars are further divided into two broad classes: BL Lac objects (BL Lacs) and flat spectrum radio quasars (FSRQs). BL Lacs show very weak or even no emission lines in their spectra, hence they are believed to be poor of soft photons. On the contrary, FSRQs show intense broad emission lines arising from the existence of photo-ionized clouds rich of ultraviolet photons and rapidly rotating around the central SMBH, giving rise to the so-called *broad line region* (BLR) at about $10^{18}$ cm from the centre. Because of the very high density of ultraviolet photons in the BLR, photons with $E > 20\,\text{GeV}$ —which are produced *before* the BLR along the jet by about two orders of magnitudes— are absorbed due to the process $\gamma\gamma \to e^+e^-$ when the jet crosses the BLR. As a result, FSRQs have an optical depth for VHE photons which is huge so that photons with energy $E > 20\,\text{GeV}$ should be totally unobservable.

However, as already pointed out observations tell us that this is expectation is just wrong. For, at least 3 FSRQs have been detected by the IACTs in the energy range 100 GeV–1 TeV: PKS 1222+216, 3C 279 and PKS 1510-089. And their fluxes are similar to those of the BL Lacs. So, what is going on?

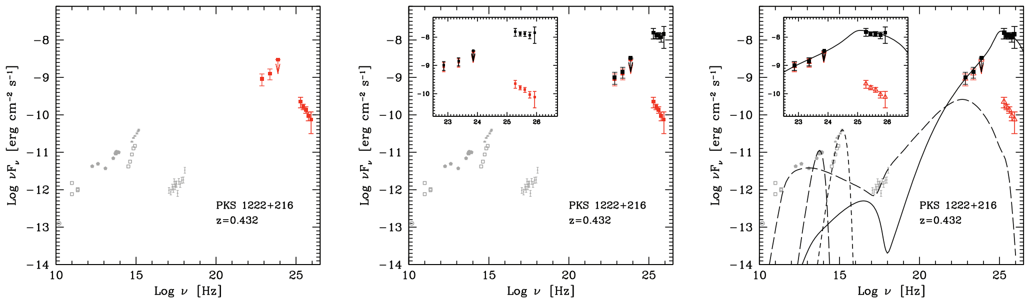


Fig. 1. – Left panel: red triangles at high and VHE are the spectrum of PKS 1222+216 recorded by *Fermi*/LAT and the one detected by MAGIC but EBL-deabsorbed according to conventional physics. Central panel: red triangles are the same as before, while black squares represent the same data once further corrected for the photon-ALP oscillation effect. Right panel: red triangles and black squares are the same as before, whereas the solid black line is the SED of our model (the other points and broken lines should be presently ignored).

Actually, the most striking case is that of PKS 1222+216 which has been observed simultaneously by *Fermi*/LAT in the band 0.3–3 GeV [9] and by MAGIC in the band 70–400 GeV [10]. In addition, MAGIC has detected a flux doubling in about 10 minutes, which implies that the VHE emitting region has a size of about $10^{14}$ cm, but the observed flux is similar to that of a BL Lac. Thus, we have to face *two* problems at once.

Various astrophysical solutions have been proposed, but all of them are totally *ad hoc* —in the sense that they have been devised *only* to explain the observation in question— even because one has to suppose that a blob with size $10^{14}$ cm at a distance of more than $10^{18}$ cm from the centre exists with the luminosity of a whole BL Lac.

## 3. – A natural ALP-based explanation

Our idea is remarkably simple. We assume that photons are produced by a standard FSRQ emission model at the jet base, but that ALPs exist. Then photons can become mostly ALPs *before* reaching the BLR in the jet magnetic field $B_{\rm jet}$. As a result, ALPs can go unimpeded through the BLR and *outside* it they can reconvert into photons in the outer magnetic field. Because of lack of space, we cannot report the calculations which can anyway be found in our original work [7], but by trial and error we have found that the best choice to reduce the photon absorption by the BLR is $B_{\rm jet} = 0.2\,{\rm G}$, $M = 7 \cdot 10^{10}\,{\rm GeV}$ and $m < 10^{-9}\,{\rm eV}$.

Yet, this is not enough. For, we have supposed that photons are produced by a standard emission mechanism and we have stressed that PKS 1222+216 has been simultaneously observed by *Fermi*/LAT and MAGIC. So, we should pretend that the detected photons have a *standard* SED, namely that both data sets lie on the same inverse Compton peak. This requirement is *a priori* not guaranteed, since in the presence of absorption and one-loop QED effects the photon-ALP conversion probability is *energy-dependent*. Nevertheless, it turns out that a standard two-blob emission model with realistic values for the parameters yields the SED shown in the right panel of fig. 1. Hence, we see that the *Fermi*/LAT and MAGIC data indeed lie on the same inverse Compton peak.

## 4. – Conclusions

Including photon-ALP oscillation into standard FSRQ emission models we have been able to solve the conundrum posed by the MAGIC observations of PKS 1222+216. Because this source has been simultaneously detected also by *Fermi*/LAT, our scenario is logically consistent only if in addition our SED fits both data sets. And we have shown that this is the case for a realistic two-blob model. Needless to say, our scenario naturally applies also to the other FSRQs detected at VHE. It looks tantalizing that basically the same choice of the free parameters $M$ and $m$ adopted here are *consistent* with those that provide the other hints of the existence of ALPs mentioned in the Introduction. Moreover, this kind of ALP is a good cold dark matter candidate [11]. Finally, we stress once again that ALPs with same properties considered here can be discovered by the presently operating IACTs like H.E.S.S., MAGIC and VERITAS, but more likely with the planned observatories CTA, HAWC and HiSCORE. A very remarkable fact is that the same goal can be independently achieved by the laboratory experiments ALPS II at DESY and IAXO, as well as with those based on the techniques discussed in [12].

* * *

MR acknowledges the INFN grant TASP.

REFERENCES


[1] Masso E., *Lect. Notes Phys.*, **741** (83) 2008; Jaeckel J. and Ringwald A., *Annu. Rev. Nucl. Part. Sci.*, **60** (2010) 405; Ringwald A., *Phys. Dark Univ.*, **1** (2012) 116.
[2] Arik E. *et al.* (CAST Collaboration), *JCAP*, **02** (2009) 008.
[3] Horns D. and Meyer M., *JCAP*, **2** (2012) 33; Meyer M., Horns D. and Raue M., *Phys. Rev. D*, **87** (2013) 035027; Horns D. and Meyer M., arXiv:1309.3846.
[4] Finke J., Reyes L. and Georganopoulos M., arXiv:1303.5093.
[5] De Angelis A., Galanti G. and Roncadelli M., *Phys. Rev. D*, **84** (2011) 105030; **87** 109903(E) (2013).
[6] De Angelis A., Roncadelli M. and Mansutti O., *Phys. Rev. D*, **76** (2007) 121301.
[7] Tavecchio F., Roncadelli M., Galanti G. and Bonnoli G., *Phys. Rev. D*, **86** (2012) 085036.
[8] Heisenberg W. and Euler H., *Z. Phys.*, **98** (1936) 714; Weisskopf V. S., *K. Dan. Vidensk. Selsk. Mat. Fys. Medd.*, **14** (1936) 6; Schwinger J., *Phys. Rev.*, **82** (1951) 664.
[9] Tanaka Y. T. *et al.*, *Astrophys. J.*, **733** (2011) 19.
[10] Aleksić J. *et al.*, *Astrophys. J.*, **730** (2011) L8.
[11] Arias P. *et al.*, *JCAP*, **06** (2012) 013.
[12] Avignone III F. T., *Phys. Rev. D*, **79** (2009) 035015; Avignone III F. T., Crewick R. J. and Nussinov S., *Phys. Lett. B*, **681** (2009) 122; Avignone III F. T., Crewick R. J. and Nussinov S., *Astropart. Phys.*, **34** (2011) 640.