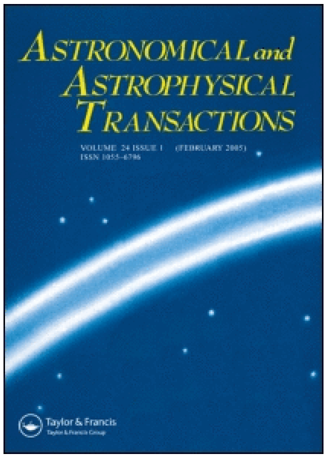

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Axion astronomy: Searching for dark matter particles

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AXION ASTRONOMY: SEARCHING FOR DARK MATTER PARTICLES

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I present a review of the astronomical methods of the search for light Goldstone bosons (axions and arions). The basic topics of this review are: (a) ground-based cavity experiments: searching for galactic axions; (b) searching for the hadronic axion decay line into galactic and extragalactic light: observations by the Russian 6-m telescope; (c) experimental search for solar and stellar axions; (d) polarimetric search for massless and very light axions: observations of magnetic stars and QSOs; (e) cosmological rotation of polarization plane; (f) UHE ($E_\gamma > 10^{19}$ eV) photons and axions; (g) limits on axion mass and coupling constant.

KEY WORDS Invisible dark matter, particles, axions, search

1 INTRODUCTION

At present the axion has consistently remained one of the leading candidates for dark matter (DM) in the Universe. Unlike many other exotic particles the axion depends only on a minimal extension of the Standard QCD model and is a consequence of the Peiccei–Quin (PQ) mechanism to solve one of the key difficulties of modern QCD – the strong CP problem. It results as a massless Goldstone boson from the spontaneous breaking of the PQ symmetry by the vacuum expectation of a definite scalar field with $\langle\varphi\rangle = f_{\rm PQ}$. But the chiral anomaly of QCD induces at low temperature

$$T \leq \Lambda_{\rm QCD} \approx 200 \text{ MeV} \tag{1}$$

an axion mass $m_a \approx \Lambda^2_{\rm QCD}/f_{\rm PQ}$. The numerical value of the axion mass is given by Turner (1990):

$$m_a = \frac{0.6 \times 10^7 \text{ GeV}}{f_{\rm PQ}} \text{ eV}. \tag{2}$$

The axion has properties similar to those of a light neutral pion, but much weaker couplings to photons and ordinary matter.

There are two generic types of axions. The hadronic or KSVZ axions only couple to heavy quarks, not to leptons or light quarks (Raffelt, 1991; Kim, 1979, 1998). The other DFS axions only couple to electrons and light quarks (Dine *et al.* 1981). In both cases the coupling is proportional to the mass and is very weak. Recently three new types of exotic bosons like axions have been suggested. Anselm (1988) has showed the possibility of the existence of a massless boson which is very similar to an axion and named it an arion; $m_a = 0$. Berezhiani *et al.* (1992) have developed a model with broken symmetry of quarks and lepton generation. The broken symmetry has produced the new Goldstone boson, which was called an 'archion'. It is quite similar to a hadronic axion with a strong depression of its coupling with leptons. Another type of invisible axion has recently been suggested by Chang and Kim (1994). They called it a heavy quark axion. The main idea of this prediction is to combine the two different scales, the axion decay constant and the right-handed neutrino mass in the see-saw model.

Axions can be detected through their coupling to photons. They can decay into two photons. This $a \to 2\gamma$ coupling arises due to two different decay mechanisms: through axion–pion mixing and via the electromagnetic (EM) anomaly of PQ symmetry. The axion decay lifetime is (Ressell, 1991):

$$\tau_a(a \to 2\gamma) \cong 6.8 \times 10^{24} \zeta^{-2} \left(\frac{m_a}{1\ \mathrm{eV}}\right)^{-5}\ \mathrm{s}, \tag{3}$$

where

$$\zeta_N = \frac{|E/N - 1.95|}{0.72}, \tag{4}$$

and E and N are the values of EM and colour anomalies of PQ Symmetry, respectively.

The free axion lifetime (3) is sufficiently long to allow for observations of axion decay with mass less than 1 eV. However, axion interactions with magnetic fields can lead to photon production with energy comparable to the total axion energy (the Primakoff effect).

There are three main features of the probability of axion conversion into a photon and of the inverse process of a photon into an axion (Anselm, 1988; Gnedin and Krasnikov, 1992)

$$P_{11}(\gamma \leftrightarrow a) = \frac{1}{1+x^2} \sin^2\left(\frac{1}{2} B_\perp g_{a\gamma} l \sqrt{1+x^2}\right) \approx \frac{1}{4} B_\perp^2 l^2 g_{a\gamma}^2, \tag{5}$$

where

$$x = \frac{\bar{\varepsilon}\omega}{B g_{a\gamma}}, \quad \bar{\varepsilon} = \frac{\varepsilon - 1}{2}, \tag{6}$$

ω is the radiation frequency and ε is the dielectric constant.

(a) The probability has an oscillatory character.

(b) The phase depends on the product of the magnetic field strength B, the size l of the region where the magnetic field is approximately homogeneous and the coupling constant of an axion with a photon $g_{a\gamma}$.

(c) The conversion process is very sensitive to the polarization state of the photon, since only a single polarization state, when the electric vector oscillates into the plane of the directions of the magnetic field and propagation of the photon, is subject to the conversion. Here $B_{\perp} = B \sin \Phi$ where Φ is the angle between the photon propagation and the magnetic field.

Excellent reviews of the problem of the ground-based and astrophysical search for an invisible axion are given by Turner (1990), Raffelt (1991, 1995, 1996), Morales (1998).

2 GROUND-BASED EXPERIMENTS: SECOND-GENERATION GALACTIC AXION EXPERIMENT, EXPECTED NEW LIMITS

The central idea of searching for axions by ground-based experiments is to use the process of axion magnetic conversion.

Axions are now considered as one of most popular non-baryonic candidates for the ubiquitous dark matter (DM). They may also exist as primordial cosmic relics copiously produced in the early Universe and thermalized similarly to the cosmic background radiation (CBR).

The search for relic and DM axions is based mainly on the Primakoff effect and is performed with superconducting resonant cavities (Wuenschch *et al.*, 1989; van Bibber *et al.*, 1989, 1994; Ogawa *et al.*, 1995b) or, also recently, with CERNs SMC polarized target (Semertzidis *et al.*, 1995).

Galactic axions are non-relativistic, and can be converted into monochromatic microwave photons: $h\nu = m_a c^2$ via the Primakoff effect in a static magnetic field B, A high-Q microwave cavity is usually used for resonant enhancement of this process. The expected signal, normalized to current experimental parameters, is (Sikivie, 1983; Krauss *et al.*, 1985):

$$P_{a\to\gamma} \approx 10^{-22} \left(\frac{B}{10T}\right) \left(\frac{V}{10^5\ \mathrm{cm}^3}\right) \left(\frac{C}{0.7}\right) \times \left[\frac{Q}{10^5}\right] \left(\frac{f}{1\ \mathrm{GHz}}\right) \left(\frac{\rho_a}{\rho_h}\right) W, \quad (7)$$

where V is the cavity volume, C is a mode-dependent factor, Q is the loaded quality factor, and ρ_a is the local axion density. The average halo axion density is $\rho = 300$ MeV cm^{-3}.

The power (7) is calculated for hadronic KSVZ axions and corresponds to a few thousand converted axions per second. For DSEZ axions the expected signal is approximately one order less than (7).

The principal signature of this experiment is a narrow peak with a fractional width of 10^{-6} due to the kinetic energy above the thermal background. Since the axion mass is not known the cavity should be slowly scanned in frequency.

Hagmann *et al.* (1996, 1998) intend to cover an interval of axion masses (1.3–13) μeV in the next three years. Their sensitivity is sufficient to probe the halo axions. The proposed mass region is shown in Figure 1 from Hagmann *et al.* (1996, 1998).

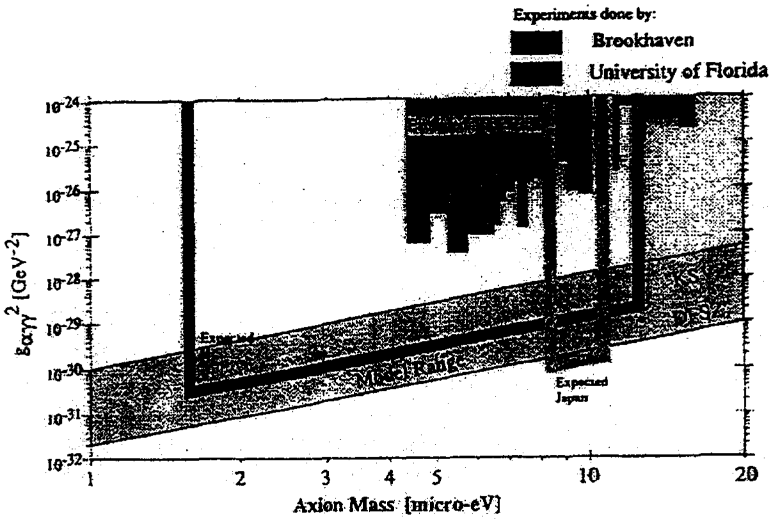


Figure 1

The heavy dark line on this figure indicates the already scanned level of sensitivity in the region 660–720 MHz which corresponds to the range of hadronic axion masses (2.7–3.0) μeV. The total data analysis is still in progress.

The next idea of direct searching for axions by ground-based experiments is to use the magnetic conversion process of solar axions. In the interior of the Sun photons can transform into axions in the fluctuating electric fields of the charged particles by the Primakoff process. A detailed treatment of solar axion calculation of their differential flux at the Earth and a proposed method of detecting them was given by van Bibber *et al.* (1989, 1994). The average solar axion energy is

$$E_a = 4.2 \text{ KeV (X-ray range).} \tag{8}$$

The rate at which DFSZ axions should carry away energy generated at the centre of the Sun is (van Bibber *et al.*, 1989, 1994)

$$\dot{E}_a \approx 1 \left(\frac{T}{10^7 \text{ K}}\right)^6 \left(\frac{m_a}{1 \text{ eV}}\right)^2 \text{ ergs g}^{-1} \text{ s}^{-1}. \tag{9}$$

Details of a theory for searching for axions with germanium detectors were recently given by Avignone III *et al.* (1997).

The next important step of the development of the solar axion experiment is connected with the use of coherency effects for the increase of sensitivity level of these experiments. Vorobjev and Kolokolov (1995) were the first to propose the use of a coherent axion–photon transformation in the system of polarized spins. In this case the efficiency of the conversion process is ensured by the resonance axion–spin wave coupling.

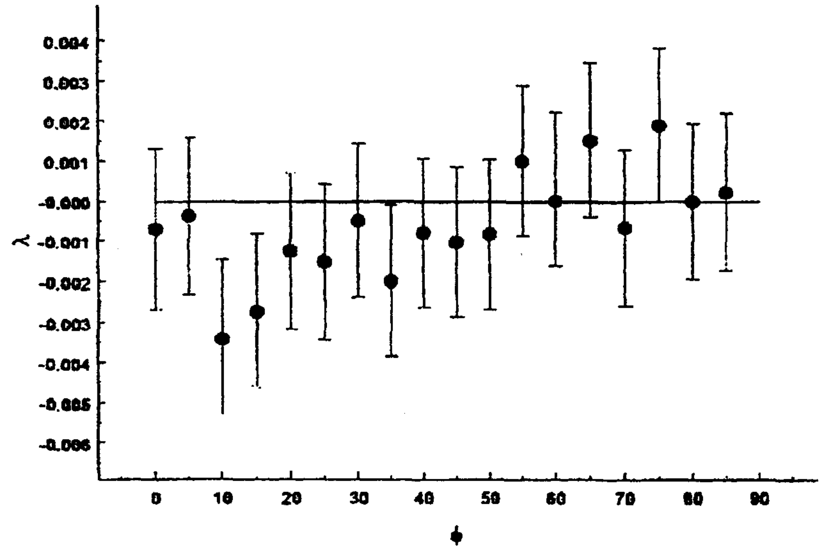


Figure 2

In Avignone III *et al.* (1997) the first results have been reported of an experimental search for the unique, rapidly varying temporal pattern of Solar axions coherently converting into photons via the Primakoff effect in a single-crystal germanium detector. This conversion process exists when axions are incident at a Bragg angle with a crystalline plane. Avignone III *et al* (1997) have analysed approximately 1.94 kg yr of data from the 1 kg DEMOS detector in Sierra Grande, Argentina, and have given a new laboratory bound on axion–photon coupling of

$$g_{a\gamma} < 2.7 \times 10^{-9}\ \mathrm{GeV}^{-1}\ (95\%\ \mathrm{c.l.}) \tag{10}$$

independent of axion mass up to ~ 1 KeV.

Their basic results are presented at Figures 2 and 3. Figure 2 shows the axion detection rate versus the azimuthal solar angle ϕ calculated from 707 days of data. Figure 3 shows exclusion plots on the $g_{a\gamma}$ versus axion-mass plane.

An international group (Zioutas *et al.*, 1998) have developed a new mode of this kind of experiment. It is going to use the 8.4 Tesla, 10 m long transverse magnetic field of the CERN twin aperture LHC bending magnet as a macroscopic coherent solar axion-to-photon converter. Zioutas *et al.* (1998) have shown by numerical simulation that the integrated time of alignment with the Sun would be 33 days per year with the magnet on a tracking table capable of $\pm 5°$ in the vertical direction and $\pm 40°$ in the horizontal direction. Zioutas *et al.* (1998) estimated the probability of detecting a photon in the $\sim$ 1–15 KeV region, per solar axion as

$$P_{a\to\gamma} \approx 1.8 \times 10^{-17} \times \left[\left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 \left(\frac{g_{a\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2 \right]. \tag{11}$$

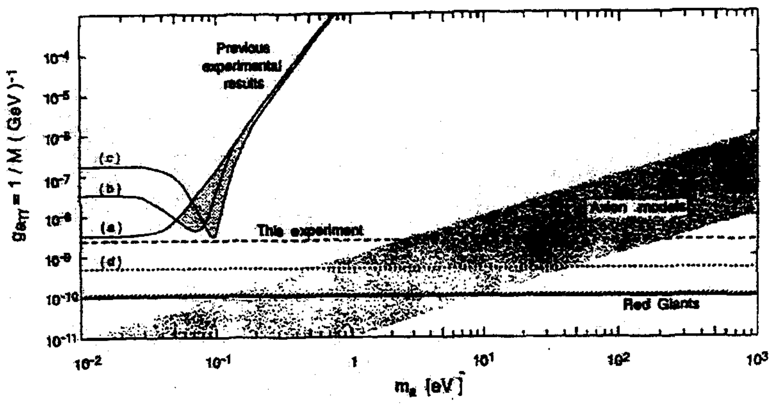


Figure 3

On the Earth, the total solar axion flux Φ_a is (van Bibber *et al.*, 1989, 1994)

$$\Phi_a \approx 3.5 \times 10^{11} \left(\frac{g_{a\gamma}}{10^{-10}}\right)^2 \text{ cm}^{-2} \text{ s}^{-1}. \tag{12}$$

For two years of measuring time, $\pm 40°$ horizontal and $\pm 5°$ vertical tracking and 33 days of integrated solar-alignment time per year, the estimated number R of X-rays due to converted axions gives:

$$R \approx 195 \left(\frac{g_{a\gamma}}{6.6 \times 10^{-11} \text{ Gev}^{-1}}\right)^4 \text{ events (66 days)}^{-1} \text{ in 2 years.} \tag{13}$$

This is an improvement by a factor of ~ 55 compare to Lazarus *et al.* (1992). Zioutas *et al.* (1998) hope by using a single 14 m bending magnet or two 10 m magnets in series to improve the expected limits for the coupling constant $g_{a\gamma}$ up to 5.2×10^{-11} GeV^{-1} and 4.6×10^{-11} GeV^{-1}, respectively.

Figure 4 shows the expected limits for the coupling constant $g_{a\gamma}$ of all known ground-based experiments.

3 POLARIMETRIC GROUND-BASED EXPERIMENTS: OPTICAL ACTIVITY IN VACUUM WITH A STRONG MAGNETIC FIELD

It is well known that a plasma in a magnetic field is characterized by two important magneto-optical effects: namely, dichroism, i.e. the dependence of the extinction cross-section on the polarization of propagating or generating radiation; and birefrigency, i.e. the difference of the refraction coefficients or phase velocities of polarized electromagnetic waves. In the strong magnetic fields of neutron stars and white dwarfs the electron–positron vacuum behaves as an anisotropic medium that has birefrigent properties.

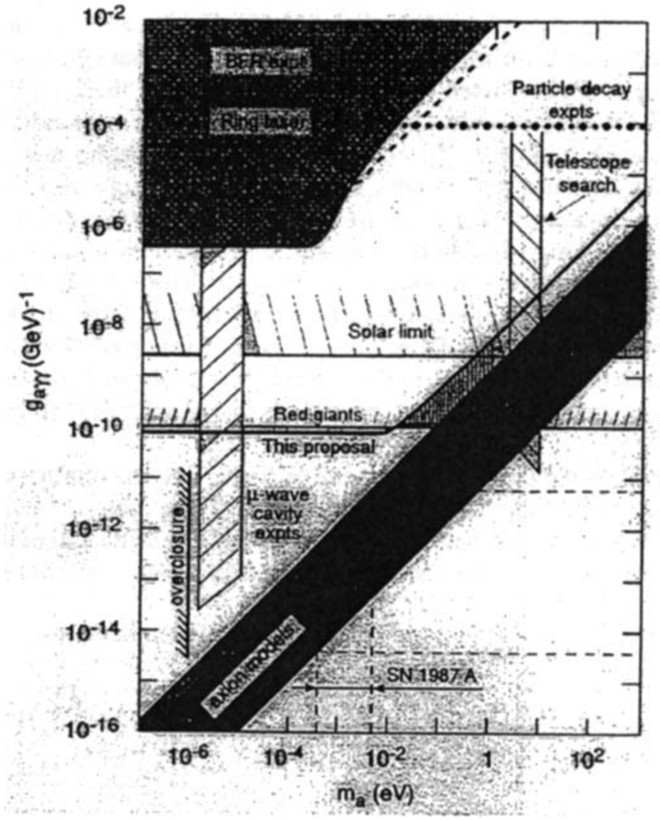


Figure 4

Photon–axion mixing also yields birefrigent effects in a magnetic field because the change of parallel polarization mode takes place via the conversion process of photons into axions. Therefore the plane of polarization will be rotated and ellipticity will be acquired by a beam propagated across magnetic field lines (Maiani *et al.*, 1986; Raffelt and Stodolsky, 1988)

$$\Theta(L) \approx \frac{1}{8} g_{a\gamma}^2 B_\perp^2 L^2,$$
$$P_\nu(L) \approx \frac{(B_I m_a)^2}{48\omega} g_{a\gamma}^2 L^3, \tag{14}$$

where L is the path length of photon propagation. Equation (14) means that ellipticity is acquired only for non-massless axions. Also there is the very important fact that the axion rotation angle (14) does not depend on the photon frequency and axion mass.

In a recent paper, Nodland and Ralston (1997) claim that they found a systematic rotation of the plane of polarization of electromagnetic waves propagating over cosmological distances. They have analysed radio and optical observations of polarized radiation from well-resolved high-redshift quasars and radio galaxies. The data used by them consisted of radio measurements of the integrated polarization of extragalactic radio sources. After correcting for Faraday rotation they claimed to find evidence for a redshift (i.e. cosmological) and a direction dependent rotation effect in existing data, and besides the rotation angle appeared to be independent of radiation frequency. Their claimed effect appears large, requiring the plane of polarization from high red shift objects to be rotated by as much as 3.0 radians – an extremely detectable signature. However Wardle *et al.* (1997) and Carroll and Field (1997) re-examine the same data and argue that there is no statistically significant signal present. Wardle *et al.* (1997) have reported new optical data taken with the Keck Telescope, and radio observations made with the Very Large Array (VLA) which show that any such rotation is less than 3° out to redshifts in excess of two.

This lower bound can be used for the estimation of the photon-to-axion coupling constant $g_{a\gamma}$ using Eq. (14) for intergalactic space. For the sake of justice one should mention that the polarization properties of electromagnetic waves as they propagate through cosmological background fields were first considered by Carroll *et al.* (1990), Carroll and Field (1991).

The estimation of Eq. (14) for cosmological distances gives:

$$\begin{aligned} g_{a\gamma} &\approx 2.6 \times 10^{-12}\ \mathrm{GeV}^{-1} \left(\frac{\Theta}{3^\circ}\right)^{1/2} \left(\frac{10^{-11}\ \mathrm{G}}{B}\right) h_{50}, \\ z &\approx 2. \end{aligned} \tag{15}$$

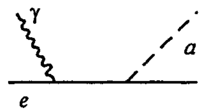
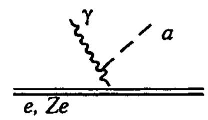
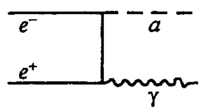
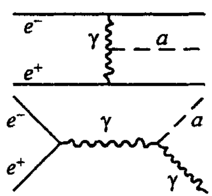
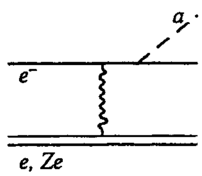
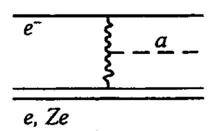
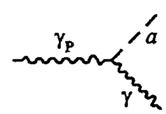
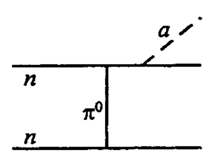
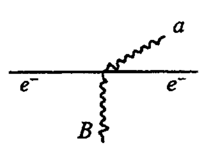
For estimation of intergalactic magnetic field we used the magnitude $B_{\mathrm{int}} = 10^{-11}$ G.

4 ASTRONOMICAL SEARCH FOR STELLAR AXIONS

Axions can be produced in stellar cores and easily escape the stars. Comparing this axion emission process with the standard energy loss mechanism through neutrino and photon emission gives a bound of axion-to-photon and axion-to-matter coupling constants. The potential effect of axion emission on stars is clear; the acceleration of their evolution and shortening of their lifetimes. Extensive reviews of axion phenomenology, and their effects on stellar evolution have been given by Raffelt (1991). He has tabulated the most effective axion emission processes (see Table 1).

In main sequence and red giant stars the primary axion emission processes are Compton-like processes and axion bremsstrahlung, both of which are proportional to $g_{ae}^2 \sim m_a^2$. Another very important process is the photoproduction of axions or the Primakoff process. In very-low-mass stars ($M < 0.2M_\odot$) emission through the axio-electric effect (the analogue of the photo-electric effect) is also very important (Dimopoulos, *et al.*, 1986). The approximate axion emissivities (erg per gram of material per second) are presented in Turner (1990) and Raffelt (1991).

Table 1. Possible stellar production processes.

	electron coupling	*2-photon coupling*	*nucleon coupling*
Compton process			
Primakoff process			
$e^- e^+$ interactions			
Bremsstrahlung e^--capture and scattering			
Plasma emission			
Bremsstrahlung in nucleon scattering			
Axion cyclotron radiation			

Axion bremsstrahlung in red giants and white dwarfs has been calculated by many authors (Raffelt, 1991; Isern *et al.*, 1992; Blinnikov and Dunina-Barkovskaya, 1984). Burrows *et al.* (1990) have calculated the axion emission that would have significantly affected the cooling of the neutron star associated with SN 1987a. They have computed the axion opacities due to inverse nucleon–nucleon, axion bremsstrahlung and then used these numerical models to calculate the integrated

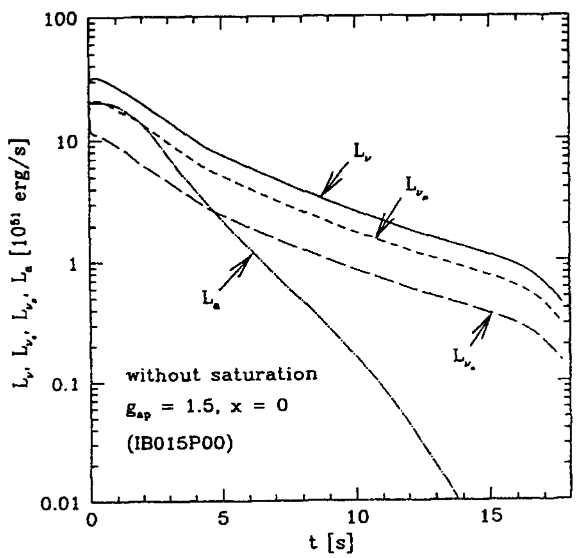


Figure 5

axion luminosity, the temperature of the axion sphere, and the effect of axion emission on the neutrino bursts detected by the Kamiokande II and Irvine–Michigan–Brookhaven water-Cherenkov detectors.

The typical axion and neutrino emission spectra produced during an SN explosion is presented in Figure 5. The last results in this field of research are connected with the calculation of pion processes that can produce axions due to many-body effects. As a result, axion–proton coupling and correspondingly the axion mass is decreasing:

$$m_a < 0.5 \times 10^{-3} \text{ eV}.$$

Recently the process of axion cyclotron emissivity of magnetized white dwarfs and neutron stars has been investigated (Borisov and Grishina, 1994; Gnedin *et al.*, 1999). The energy loss rate of a magnetized electron gas emitting axions due to the process $e^- + B \to e^- + B + a$ has been calculated for an arbitrary magnetic field strength B. The axion emissivity due to the cyclotron process as a function of $B/B_{\rm cr}$ ($B_{\rm cr} = m_e^2/e \approx 4.41 \times 10^{13}$ G) for $N_e = 10^{26}$ cm^{-3} and $T = 10^8$K, 10^7K, 10^6K is presented in Gnedin *et al.* (1999). Kachelriess *et al.* (1997) have applied the results of their calculations to magnetic white dwarfs. The internal temperature T of a white dwarf with mass M is related to its surface photon luminosity L_γ by Raffelt (1996):

$$\frac{L_\gamma}{M} = 3.3 \times 10^{-3} \frac{\text{erg}}{gs} \left(\frac{T}{10^7\text{K}}\right)^{7/2}. \tag{16}$$

The axion energy loss rate is given by Landstreet *et al.* (1989):

$$\varepsilon_a = 2.6 \frac{\text{erg}}{\text{cm}^3\ \text{s}} \left(\frac{B}{10^9\ \text{G}}\right)^4 \left(\frac{T}{10^7 \text{K}}\right). \tag{17}$$

If we now require that magnetized white dwarfs do not emit more energy in axions than that in photons, i.e. that $L_\gamma/M < \varepsilon_a/\rho$, where ρ is the density of the white dwarf core, we obtain

$$g_{ae} \leq 9 \times 10^{-13} \left(\frac{T}{10^7}\right)^{5/4} \left(\frac{B}{10^{10}\ \text{G}}\right)^{-2}. \tag{18}$$

Axion and massless pseudoscalars that are generated in cores of magnetic stars can be converted into photons in the stellar environment.

The transformation of massless bosons (arions) which are generated in the cores of stars into photons in the magnetic field of a star produces noticeable additional X-ray radiation. The luminosity of this X-ray radiation depends very strongly on the physical parameters of arions and the constant of its coupling to matter. Detection of this additional radiation of stars of various types provides a means to derive these physical parameters. Gnedin and Krasnikov (1992) have calculated the additional X-ray fluxes from stars of different types. The results of their calculation are presented here:

1. Red giants:

$$L_x \approx 1.9 \times 10^{-3} L_\otimes \left(\frac{g_{a\gamma}}{3 \times 10^{-11}}\right)^2 \left(\frac{g_{ae}}{3 \times 10^{-13}}\right)^2 \left(\frac{B_s}{100\ \text{G}}\right)^2 \left(\frac{R_s}{10^{13}}\right)^2 \times \left(\frac{M_c}{0.5 M_\otimes}\right) \left(\frac{T_c}{10^4 \text{K}}\right)^4. \tag{19}$$

2. Magnetic white dwarfs:

$$L_x \approx 10^{-3} L_\otimes \left(\frac{M_{wD}}{M_\otimes}\right) \left(\frac{T_c}{10^7}\right)^{7/2} \left(\frac{g_{a\gamma}}{3 \times 10^{-11}}\right)^2 \left(\frac{g_{ae}}{3 \times 10^{-13}}\right)^2 \times \left(\frac{B_s}{10^8}\right)^{2/5} \left(\frac{R_s}{10^9}\right)^2. \tag{20}$$

3. Magnetic Ap stars:

$$L_x \approx 10^{-5} L_s \left(\frac{M_s}{M_\otimes}\right) \left(\frac{g_{a\gamma}}{3 \times 10^{-11}}\right)^2 \left(\frac{B_s}{10^4}\right)^2 \left(\frac{R_s}{10^{11}}\right)^2 \approx 10^{30}\ \text{erg s}^{-1}, \tag{21}$$

where M_c is the mass of the helium core, T_c is its temperature, L_s is the total photon luminosity of the Ap star, and $M_\otimes = M_\odot$. The magnitudes of X-ray fluxes are to be found at the level of sensitivity of modern X-ray observations.

Leone (1994) has analysed the incidence of X-ray sources among magnetic chemically peculiar stars. Using EINSTEIN and ROSAT satellite data he has found that of the four magnetic CP stars showing X-ray emission, three are members of a binary system, so that emission from CP stars directly is now questionable. It would be worth mentioning that Carlson (1995), has considered the situation when pseudoscalars can be produced in interiors of hot stars and then reconverted into photons in the presence of the galactic magnetic field.

5 SEARCHING FOR THE AXION RADIATIVE DECAY LINE BY ASTRONOMICAL METHODS

An axion with a mass greater than 1 eV should be detected through its decay into two photons. There are astrophysical and cosmological limits which define the window of the allowed axion mass between 3 eV and 8 eV. An upper bound to the axion mass of $m < 8$ eV is derived by considering the effect of decaying axions upon the diffuse extragalactic background radiation and the brightness of the night sky due to axions in the halo of our Galaxy. But the intergalactic light of clusters of galaxies seems to be a very good place to search for an emission line arising from the radiative decay of axions. Decaying axions will produce an emission line at wavelength:

$$\lambda_a(z) = 24\,800\ \text{Å}\left(\frac{1\ \text{eV}}{m_a}\right)\cdot(1+z), \tag{22}$$

where z is the cluster redshift. This line will be Doppler broadened by the velocities which axions have in the cluster to a width $\Delta\lambda \sim 100$ Å. M. T. Ressel (1991) has estimated the line intensity of

$$I_a \approx 1.5\times10^{-17}\left(\frac{m_a}{3\ \text{eV}}\right)^7\zeta^2 \tag{23}$$

with units: erg cm^{-2} arcsec^{-2} Å^{-1} s^{-1}.

To detect this feature the signal must be compared with the brightness of the night sky. The night sky is characterized by a continuum intensity level of

$$I_{\text{NS}} \sim 10^{-17}\ \text{erg cm}^{-2}\ \text{arcsec}^{-2}\ \text{Å}^{-1}\ \text{s}^{-1} \tag{24}$$

and many strong atmospheric emission lines.

The result of observations of spectra of galaxy clusters A2256 and A2218 obtained at Kitt Peak Observatory have not shown the existence of axion lines.

Figure 6 shows the results of observations (principal observer S. N. Dodonov) of spectra of galaxy clusters A2256 made at the Russian 6-m telescope with the help of the Multi-Pupil Field Spectrograph (MPFS) which is intended for objects with moderate spectral resolution. At 1 hour exposure in the range 4000–6500 Å one can obtain spectra of the portions of extended objects that have surface brightness $V \sim 19-20$ mag arcsec^{-2} with a spectral resolution of about 4–5 Å at $S/N \sim 5$.

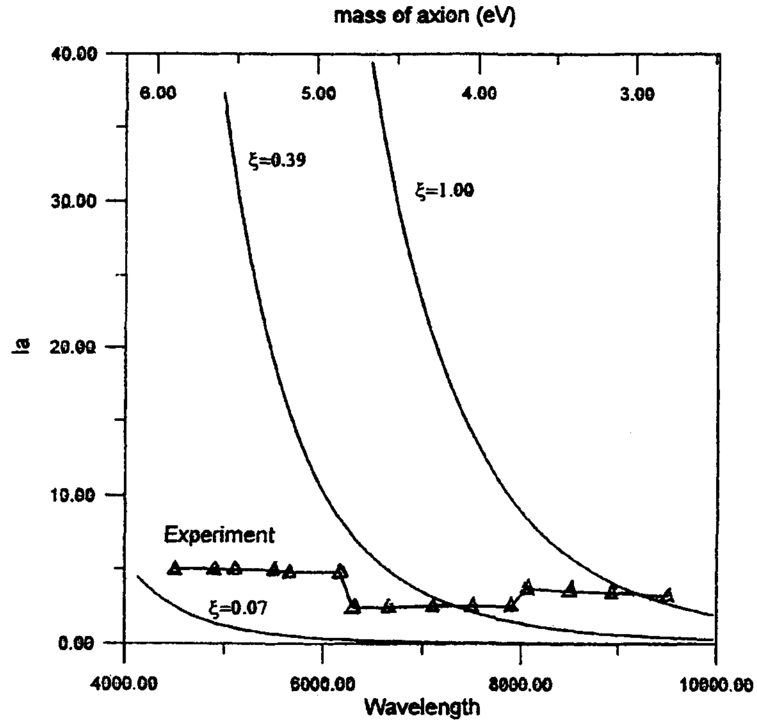


Figure 6

Our total exposure in the range λλ 6000–8000 Å is 200 hours: 100 spectra each with 2 hours of exposure. The solid lines of Figure 6 show the bounds of the parameter ξ of a non-standard axion. For a standard axion $\xi = 1$. The curves of Figure 6 show the intensity of radiation from the galaxy cluster A2256 versus the wavelength and the axion mass for standard and non-standard ($\xi = 0.39$ and 0.7) axion models. The observational data are also show in Figure 6. From the existing data, it is clear that standard and non-standard hadronic axion masses lying between 3 and 6 eV are definitely excluded.

Let us come back to the night sky brightness problem due to axions in the halo of our Galaxy. The density of the galactic halo in the case of a homogeneous distribution is derived as

$$\rho(r) = \rho_0(R_0^2 + r^2)(r^2 + a^2)^{-1}, \tag{25}$$

where

$$\rho_0 \simeq 5 \times 10^{-25} \text{ g cm}^{-3} \approx 0.01 M_\odot \text{ pc}^{-3} \simeq 300 \text{ MeV cm}^{-3} \tag{26}$$

is the local halo density. $R_0 = 8.5$ kpc is the distance from the Sun to the galactic centre, and a is the halo core radius which lies between 2 and 8 kpc. The typical halo velocity dispersion gives the width of axion decay line as ~ 20 Å$\sigma(1\ \mathrm{eV}/m_a)$, where $\sigma = \Delta V/100\ \mathrm{km\ s^{-1}}$.

The intensity of the halo line is estimated (Ressell, 1991) as:

$$I_a^{\mathrm{halo}} \approx 1.7 \times 10^{-23} \left(\frac{m_a}{1\ \mathrm{eV}}\right)^{10} \zeta^2\ \mathrm{erg\ cm^{-2}\ arcsec^{-2}\ Å^{-1}\ s^{-1}}. \tag{27}$$

This value is less than or comparable to the background level of the night sky:

$$I_{\mathrm{NS}}^{\mathrm{halo}} \approx 10^{-17}\ \mathrm{erg\ cm^{-2}\ arcsec^{-2}\ Å^{-1}\ s^{-1}}. \tag{28}$$

The results of observations of BNS by the 6-m telescope of SAO RAN (Leroy, 1990, 1995) do not give evidence of the existence of an axion decay line.

However these estimations are valid only for a homogeneous distribution of axion dark matter in the halo of the Galaxy. But there exist a number of scenarios of inhomogeneous axion field configuration, which provides an inhomogeneous distribution of the halo axion dark matter. For example, during the QCD epoch fluctuations in the misalignment angle (displacement of the initial value of the field away from the eventual minimum of the temperature-dependent potential) on scales comparable to the Hubble radius at that time are transformed into large-amplitude density fluctuations, which later lead to tiny gravitationally bound clouds ('mini clusters'). The density in miniclusters may exceed by ten orders of magnitude the local dark matter density in the solar neighbourhood.

6 POLARIMETRIC SEARCHES FOR PHOTON–AXION CONVERSION

The detection of axions is possible through their coupling to photons. Except for the direct decay of an axion into two photons, which has an extremely low cross-section, there exist so-called Primakoff processes of interaction with a magnetic field. This can lead to the production of a photon with energy comparable to the total energy of the axion. The reverse process, i.e. a photon–axion transition in a magnetic field, also exists. This conversion process is very sensitive to the polarization state of the photon, and it may lead to significant polarization of radiation. However, detailed consideration has shown that, for astrophysical conditions, the photon–axion conversion process is more probable only for the case of any massless or extremely light pseudoscalar bosons (see, for example, Gnedin and Krasnikov, 1992; Raffelt, 1991, 1995, 1996; Kim, 1979, 1998; Dine *et al.*, 1981; Anselm, 1988; Berezhiani *et al.*, 1992; Chang and Kim, 1994; Ressell, 1991).

The coupling between electromagnetic and pseudoscalar fields affects the polarization properties of the electromagnetic waves as they propagate through a magnetic field. Therefore polarimetric observations may yield strong constraints on the massless pseudoscalar boson–photon coupling constant. The best candidates for polarimetric observations are stars with a strong magnetic field, such as neutron stars, magnetic white dwarfs and magnetic Ap stars. For these objects, the process of photon–massless-axion conversion acts as an additional absorption process, strongly depending on the polarization state.

Broadband linear polarimetric observations may impose limits on the coupling constant $g_{a\gamma}$ between photon and massless axion fields. A systematic programme of broadband linear polarimetry, involving 66 Ap stars, has been developed during the last few years at the Pic du Midi Observatory.

The main goal of this programme was the search for magnetic time variability due to stellar rotation. A similar programme has also been developed at the SAO (6-m telescope) of Russia and the Crimea Astrophysical Observatory of Ukraine.

Leroy (1990, 1995) and Huovelin (1990) have developed a theory of broadband linear polarization (BLP) measurements in magnetic stars. They have showed that the effect of magnetic intensification was responsible for the appearance of broadband linear polarization. This polarization can be attributed directly to the presence of a magnetic field, the polarization being in this case due to the cumulative effect of all magnetically sensitive spectral lines in the observed passband. The polarization is a consequence of different amounts of saturation in orthogonal polarized π and σ components of spectral lines. The wavelength variation of this effect is an important feature allowing the magnetic intensification to be distinguished from other mechanisms.

The wavelength dependence varies with the spectral type and luminosity of the star. One can find sharp features in the spectral slopes in different spectral intervals (see, for example, Figure 1 from Huovelin, 1990). Huovelin (1990) has shown that for various spectral types BLP increases with decreasing the effective temperature T_e and with increasing gravity $\log g$. The typical values of BLP lie in the range 0.8×10^{-4}–5.6×10^{-4}.

The value of linear polarization due to magnetic conversion of photons into massless bosons for the case of an Ap magnetic star can estimated from Eq. (10):

$$P_e \simeq 0.0625 \left(\frac{B_s}{10^4\ \mathrm{G}}\right)^2 \left(\frac{R_s}{10^{11}\ \mathrm{cm}}\right)^2 \left(\frac{g_{a\gamma}}{3 \times 10^{-11}\ \mathrm{GeV}^{-1}}\right)^2 \%. \tag{29}$$

We consider the magnetic Babcock's star as a cosmic laboratory for studying the effects of particle physics. We used the process of magnetic conversion of photons into massless pseudoscalars as a new astrophysical process of generation of polarized radiation.

To use Eq. (10) one needs to measure the magnetic field and linear polarization of the star. The magnetic field of HD 215441 was measured through spectropolarimetry of this star. Landstreet *et al.* (1989) have shown that the Zeeman splitting of spectral lines is reasonably well reproduced by an axisymmetric superposition of dipoles quadrupoles and octupoles of polar strengths, 67, 55 and 30 kG, respectively. The series of observations that was made with the MINIPOL polarimeter at the 1-m telescope of SAO RAN were measurements of linear polarization of Babcock's star. Figure 7 presents the results of our observations.

There is some history of polarimetric observations of this star. Several previous linear polarization studies of Babcock's star are available. Two of them, Polosukhina (1964), and Kemp and Wolstencroft (1972), have led to the conclusion of the polarization being intrinsic to the star, presumably related to the large magnetic field variations.

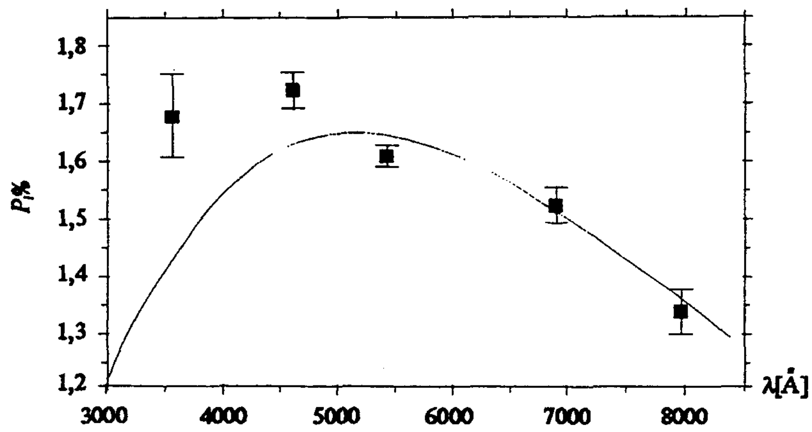


Figure 7

Our broadband (UBVR) polarimetric observations of HD 215441 were made at the 1-m telescope of SAO RAN with MINIPOL. The results of observations are presented in Figure 7 where the interstellar linear polarization curve is also presented. The extracted wavelength dependence gives evidence that Babcock's star seems to possess an intrinsic linear polarization. The BLP polarization calculated by Huovelin (1990), via the process of magnetic intensification is locked the same. Though the wavelength dependence of the measured polarization looks almost the same as for the calculated one its magnitude appears at least one order larger than the calculated value. It is now difficult to explain this difference. One of the probable explanations is to take into account the new physical process of magnetic conversion of photons emerging from the stellar surface into massless pseudoscalar bosons (for instance, arions). For the case of magnetic conversion of photons in a plasma the wavelength dependence of linear polarization takes the form $P(\lambda) \sim 1/\lambda^2$ (see Eq. (8)), i.e. the net polarization is increasing with decrease of wavelength.

We are not going to discuss the problem of the intrinsic polarization of HD 215441 in detail and shall use the observational data for estimation of the upper bound of the coupling constant between photons and massless Goldstone bosons. Substituting into (10) the magnitude of the measured magnetic field:

$$B^{\rm d}_{\rm eq} = 3.4 \times 10^4\,{\rm G}, \quad B^{\rm q}_{\rm eq} = 2.8 \times 10^4\,{\rm G}, \quad B^{0}_{\rm eq} = 1.5 \times 10^4\,{\rm G},$$

and $R_s = 2.00 \times 10^{11}$ cm, one gets at the level $P_e \approx 0.02\%$, that is one error of measurement,

$$g_{a\gamma} = 1.41 \times 10^{-12}\,{\rm GeV}^{-1}. \tag{30}$$

The result (15) we consider as the upper bound for the coupling constant $g_{a\gamma}$.

The additional polarization can be produced via the photon–massless-axion transition in the interstellar and intergalactic media. The low strength of the magnetic field in these media is compensated in accordance with (5) by a larger distance l for light propagation.

Recently Impey *et al.* (1995) and Koratkav *et al.* (1995), have presented results of spectropolarimetry of a number of QSOs with redshifts lying in the range 0.5–20. These results have been obtained with the Faint Object Spectrograph of HST. A sharp rise in polarization strongly below the Lyman edge has been discovered. The magnitude of the polarization rise has reached values as high as $\sim 20\%$. This value has never been seen before in non-blazar active galaxies. A power-law fit to the polarized flux has given for the polarized flux $\sim \lambda^{9.9}$ which is much steeper than that provided by any known polarization mechanism.

In many astrophysical conditions the probability of magnetic conversion is quite lower but nevertheless provides a noticeable amount of polarization.

But there is a single exclusive case when light propagates through the mixture of plasma and neutral gas. Then resonance can occur because the plasma and neutral gas polarizability are coming into the expression for the dielectric constant ε with opposite signs and therefore can cancel each other at the definite radiation frequency $\omega_{\rm res}$ or the wavelength $\lambda_{\rm res}$. Dr. Draine was the first to bring my attention to this situation.

One should have

$$\varepsilon = 1 + 4\pi N_{\rm H}\alpha_{\rm H} - \frac{\omega_{\rm P}^2}{\omega^2}, \tag{31}$$

where $\alpha_{\rm H}$ is the polarizability of a neutral gas atom, $N_{\rm H}$ is the neutral gas density. We have for a hydrogen plasma:

$$\begin{aligned} \frac{\omega_{\rm P}^2}{\omega^2} &= 9.0 \times 10^{-24} N_e \left(\frac{\lambda}{10^3\,\text{Å}}\right)^2, \\ 4\pi N_{\rm H^\alpha} &= 8.4 \times 10^{-24} N_{\rm H}, \end{aligned} \tag{32}$$

where $N_{\rm H}$ and N_e are numbers of species per cm^3.

The resonance wavelength is now

$$\lambda_{\rm res} \approx 1000 \left(\frac{N_{\rm H}}{N_e}\right)^{0.5} \text{Å}. \tag{33}$$

At $\lambda = \lambda_{\rm res}$ one has the case as if a pure vacuum and therefore Eq. (5) is acting. Equation (5) shows that one should not need to get a strong magnetic field for observing the magnetic conversion effect because the probability of conversion depends not on the magnetic field strength alone, but on the product of the magnetic field strength and path length of photons into the magnetic field.

Wolfe *et al.* (1992) have shown that the QSOs most likely to exhibit Faraday rotation are those located behind damped Ly-α systems. From their observations they have estimated only the product of the electron X_e and the parallel B-field component:

$$X_e B_{\|} \approx \mu G.$$

Further, considering $X_e < 0.1$ as a conservative upper limit on the electron fraction they have concluded that the real magnitude of $B_{\|}$ should form a value $\sim$ few microgauss. The redshifts of observed QSOs lies into the range $Z = 0.4$–2. I would like to note that if one uses the electron fraction value as $X_e < 0.1$ one can get for QSO 0957+561 A a magnetic field strength of 54 μG(!) (see Table 1 from Wolfe *et al.*, 1992).

For the estimation of the probability of resonance magnetic conversion let us calculate the value $B_\perp l g_{\alpha\gamma}$.

Supposing $B_\perp \sim B_\parallel \approx 10^{-6}$ G, $l \sim 10$ kpc (Wolfe *et al.*, 1992) $g_{\alpha\gamma} \approx 3 \times 10^{-12}$ (Krasnikov, 1996) one can get:

$$B_\parallel l g_{\alpha\gamma} \approx 0.3.$$

This provides the expected degree of polarization as $\sim 10\%$, that is, close to the observed value. But there is the electron fraction, which follows from Eq. (7):

$$X_e \equiv \frac{N_e}{N_{\rm H}} \geq 1.$$

Apparently it is not the same as a protogalactic disk absorber. It is possible that unsaturated Ly-α absorbers (Katz *et al.*, 1996) are namely responsible for the observed polarization phenomenon.

In conclusion I would like to stress that the resonance magnetic conversion effect takes place for light in visible *u* UV spectral ranges only when the energy of a photon is not considerably larger than the ionization energy of a neutral hydrogen atom (13.6 eV) that corresponds to the condition:

$$\lambda \geq 900\ \text{Å}.$$

For X-rays the situation is opposite. They interact as if free, and with bound electrons increasing, as a result, the effective plasma frequency $\omega_{\rm P}$.

If the idea of resonance magnetic conversion is valid one should expect the appearance of polarization features for QSOs with a noticeably Faraday rotation measure. On the other hand, the observable QSOs with a strong polarization feature are most likely to exhibit Faraday rotation due to their location behind magnetized damped Ly-α systems.

7 ORIGIN OF EXTREMELY HIGH ENERGY EHE PHOTONS DUE TO EHE AXION CONVERSION INTO GALACTIC MAGNETIC FIELD

Recently the strong problem of the origin of the highest cosmic radiation ($E \geq 10^{19}$ eV) has become one of the major questions in modern astrophysics. The cosmic radiation comprises all particles of high energy, including photons that are produced by astrophysical sources and reach the Earth. The energy spectrum of this cosmic radiation reaches from some MeV to several 10^{20} eV particle^{-1}, the highest energy of any kind of radiation. At such high energies the observations can be done only with detectors that are located deep underground and air shower arrays that cover the ultra-high-energy (UHE – (> 10^{14} eV)) and extremely high-energy (EHE – (> 10^{18} eV)) ranges.

At higher energies simple power laws in energy can describe the spectrum of cosmic radiation

$$\frac{\mathrm{d}F}{\mathrm{d}E} = F_0 E^{-\delta}, \tag{34}$$

where $\mathrm{d}F/\,\mathrm{d}E$ denotes the differential flux in particles $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ (TeV particle^{-1})$^{-1}$, F_0 is the absolute flux normalization at 1 TeV, E is the energy particle^{-1} measured in TeV, and δ is the spectral index. This spectral index appears slightly different for different particles (protons, nuclei, photons, etc; see, in detail, Wiebel-Sooth and Biermann, 1998). Beyond 10^{19} eV the detailed shape of the spectrum is of special interest. Greisen (1966) and independently Zatsepin and Kuzmin (1966) predicted a natural end of the cosmic ray spectrum. It is the so-called GZK cut-off. Above 3×10^{19} eV the cosmic ray protons and photons will interact with the thermal 2.7K photons (Biermann and Strittmatter, 1987):

$$\begin{aligned} p + \gamma_{2.7} &\rightarrow \left\{ \begin{array}{c} n + \pi^+ \\ p + \pi^0 \end{array} \right. , \\ \gamma + \gamma_{2.7} &\rightarrow e^- + e^+. \end{aligned} \tag{35}$$

The cross-section of photoproduction of electron–positron pairs takes the form:

$$\sigma(E_\gamma, E_{\gamma_{2.7}}) = \frac{\pi r_e^2}{2}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right], \tag{36}$$

where

$$\beta = \sqrt{1 - \frac{(m_e c^2)^2}{E_\gamma E_{\gamma_{2.7}}}}, \quad r_e = \frac{e^2}{m_e c^2}, \tag{37}$$

E_γ is the photon energy and r_e is the classical radius of an electron. Equation (36) is valid for high-energy photons:

$$E_\gamma > m_e c^2 \frac{m_e c^2}{E_{\gamma_{2.7}}} \approx 10^{15}\,\mathrm{eV}. \tag{38}$$

At $E_\gamma \geq 10^{19}$ eV the optical thickness with respect to the photoproduction of an electron–positron pair becomes very large: $\tau(\gamma + \gamma_{2.7}) \gg 1$.

Astrophysical mechanisms to accelerate protons to energies of up 10^{21}–10^{22} eV that can produce EHE photons in collisions, have been identified (Greisen, 1966). But they require exceptional distant sites. Indeed none are found within the expected scattering cone of the highest energy event at less than the GZK distance (Elbert and Sommers, 1995).

Proposals to resolve the puzzle range from positing relic-topological defects or elementary particles whose decay produces nucleons and photons within the GZK distance (Kuzmin and Rubakov, 1997; Hill *et al.*, 1986).

I propose to explain the GKZ excess by the conversion process of an EHE axion into an EHE photons in the magnetic field of the Galaxy or Earth's magnetosphere. It is easy to make the following estimation.

The expression for the probability of axion conversion into a photon was given by Raffelt (1991):

$$P_{a\to\gamma} = \frac{B^2\omega^2 g_{\alpha\gamma}^2}{m_a^4}, \tag{39}$$

where ω is the photon energy and m_a is the axion mass. Using Eq. (2) and the relation between the coupling constant $g_{\alpha\gamma}$ and the value of the spontaneous breaking scale of the PQ symmetry

$$g_{\alpha\gamma} = \frac{\alpha}{2\pi f_{\rm PQ}}, \tag{40}$$

we obtain the following expression for the probability of EHE axion conversion into the Galactic magnetic field:

$$P_{a\to\gamma} \approx 0.36\left(\frac{B}{3\times10^{-6}\,{\rm G}}\right)^2\left(\frac{\omega}{10^{20}\,{\rm eV}}\right)^2\left(\frac{f_{\rm PQ}}{10^{12}\,{\rm GeV}}\right)^2. \tag{41}$$

Equation (41) corresponds to the value of the axion mass

$$m_a \approx 0.6\times10^{-5}\,{\rm eV}.$$

8 CONCLUSIONS

The astronomical methods of searching for light Goldstone bosons and axion have been discussed here. The basic idea of this search is to use processes of coupling between bosons (axions) and photons: (*a*) the decay of an axion into two photons and (*b*) the transformation processes of an axion into photons and photons into bosons. Axions and massless bosons (arions) can be generated in the cores of stars and produce their noticeable cooling. The decaying axions affect the diffuse extragalactic background radiation, the brightness of the night sky and especially the intergalactic light of clusters of galaxies due to the generation of the axion radiative decay emission line. Spectroscopic observations of clusters of galaxies and the brightness of the night sky at the Special Astrophysical Observatory BTA-6m telescope in Russia have been used to estimate the hadronic axion mass. The main result of these observations is to exclude mass values of hadronic axions lying in the interval of the optical spectral range not only for the standard axion model, but also for most non-standard models.

Figure 8 gives an upper bound on the axion mass, which is given by all ground-based and pure astronomical methods.

The results of broadband linear polarimetric observations of magnetic Ap stars have been made to obtain the best upper bound of the photon–massless-pseudoscalar coupling constant.

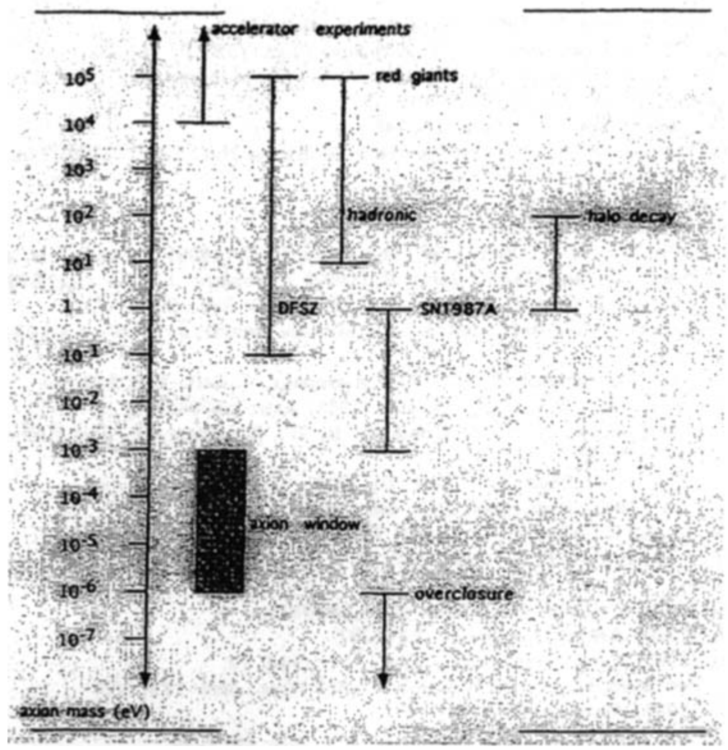


Figure 8

Acknowledgments

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