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Magnetic fields of stars and fundamental particle physics

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Abstract. Low-mass particles such as neutrinos, axions, Nambu-Goldstone bosons and gravitons can be produced in the hot and dense cores of stars. Magnetic fields in and out interior of stars can amplify the processes of generation or absorption of these particles. Therefore, astrophysical data and arguments constrain really the properties of these particles and hence derive the prospects of development of modern Supersymmetric (SUSY) Particle Physics. It means that the stars with magnetic fields are the cosmic laboratories for testing new ideas of modern Particle Physics. My talk provides an update on the most important magnetic stellar evolution limits and give some information that is very important for cosmology.

1 Introduction

Magnetic field is one of the basic elements of the Universe. The study of stellar magnetic fields is the traditional and one of the oldest direction of research activity of astrophysical observations and, especially, of Special Astrophysical Observatory of the Russian Academy of Sciences. The measurements show that magnetism is a wide-spread phenomenon among the stars. As a rule, different types of bursts, explosions and other instabilities are connected with magnetic fields. For instance, winds of many stars show cyclic or even strictly periodic variability on a rotational timescale. It is magnetic fields that have been suggested to be the cause of this variability.

Magnetic fields play a completely central role in the star formation process. Ap and Bp stars are main-sequence A and B stars in the spectra of which the lines of some elements are abnormally strong (e.g. Si, Sr, and rare earths). To properly understand the physics of these stars it is very important to identify the origin of their magnetic fields that play the key role in production of these anomalies.

One of the most remarkable recent achievements of modern astrophysics has been the discovery of magnetic white dwarfs and neutron stars which have extremely huge magnetic fields $B = 10^6 - 10^9$ G and $10^{11} - 10^{14}$ G, respectively. The magnetic fields of neutron stars and white dwarfs are much higher than those achieved in a laboratory or those of ordinary stars. Such a large difference gives rise to new quantitative effects in the interaction of radiation with matter.

Now the role of magnetic fields in astronomy has highly increased. First of all, this fact is connected with close interaction between modern astrophysics and fundamental particle physics. One of the most exciting and fruitful areas of astrophysics in recent years has been a study of problems which lie at the boundary between particle physics and cosmology. A crucial test of a cosmological model is how well it produces the rich structures of clusters, walls and voids, that are seen in the large-scale distribution of galaxies. Another basic problem is the origin of such new fractions of matter in the Universe as cold dark matter and dark energy. The role of cosmic magnetic

Table 1: Observations of magnetic fields of stars

Traditional Methods
1. Zeeman spectropolarimetry
2. Hanle effect
3. Circular broadband polarimetry
4. Cyclotron spectroscopy: white dwarfs, neutron stars
5. Measurement of the Faraday rotation measure of position angle – Radio astronomy
6. Spectrum and polarization of synchrotron radiation
New Methods
1. Proton cyclotron spectroscopy: Neutron Stars – X-ray proton cyclotron lines
2. Magnetic fields due to Faraday rotation on the electron scattering free path length (Gnedin and Silant'ev)
3. Synchrotron radiation with synchrotron self-absorption.

field in solving these problems is extraordinary high.

Below we consider the physical phenomena with close intersection between astrophysics of magnetic stars and fundamental particle physics.

The history of stellar magnetism began with George Hale who was the first to observe the magnetic field of sunspots. But the real founder of research of stellar magnetism was, of course, P. Zeeman who discovered the famous effect of splitting atomic spectral lines in a magnetic field called after him.

Now the research areas and the study of stellar magnetic field has greatly grown. New methods of magnetic field measurements are intensively developed.

Table 1 presents the basic traditional and new methods of measurements of magnetic fields in astrophysics.

2 Cold Dark Matter and Cosmic Magnetic Fields

Observation of primordial deuterium produced in Big Bang nucleosynthesis as well as Cosmic Microwave Background (CMB) radiation observations show that the total number of baryons in the Universe contributes about $\Omega_b = 0.04$. Host of observations related to large-scale structure and rotation curves of galaxies suggest the Universe is populated by a non-luminous component of matter (dark matter — DM) made of weakly interacting particles. This component contributes about $\Omega_{DM} = 0.23$.

The luminosity distance–redshift relation obtained from the observations of the SN Ia has been interpreted as if our Universe is a homogeneous Friedmann-Lemaitre-Robertson-Walker (FLRW) substance with accelerating expansion. This acceleration is generally considered as the influence of a dark energy (DE) component, a cosmological constant or a negative pressure fluid with $\Omega_\Lambda = 0.73$. A cosmological constant is usually considered as the vacuum energy of which current particle physics cannot explain the low magnitude and a negative pressure fluid remains a mysterious phenomenon. This fact is known as the cosmological problem.

The problem of origin of dark matter and dark energy (DM and DE) has been open to question till now. The solution of this problem lies probably in the framework of new particle physics — supersymmetry theory (SUSY). The next consideration is motivation for a new physical theory. The standard theory is quite successful but not complete. SUSY is required because it is difficult to explain neutrino oscillations (it means that neutrinos are massive), and, so-called, hierarchy problem. The last one means existence of a giant break between strong interaction energy scale $\sim 10^3$ GeV and Planck mass $M_{Pl} = 10^{19}$ Gev. SUSY suggests boson - fermion unification. It means that every fermion has its boson superpartner, and vice versa. SUSY predicts also the existence of new light supersymmetric particles that obtain the name of neutralino. SUSY also considers the possible existence of extra spatial dimensions $(3+n)$.

SUSY muon anomalous moment is derived as $a_{mu} = 14 \times 10^{-10} (M_{SUSY}/100GeV)^{-2} \tan\theta$, where θ is the mixing angle. Recently the Brookhaven New Experiment (Bennet et al. 2002) has delivered a new and more precise measurement for the anomalous magnetic moment of the muon:

$$a_{mu} = 11659203(8) \times 10^{-10}, \tag{1}$$

where $a_{mu} = (g_{mu} - 2)/2$. g_{mu} is the Bohr magnetic moment magnitude. As a result, the discrepancy between the Standard Model theoretical prediction and the experimental value for the anomalous magnetic moment of the muon becomes significant (Bennet et al. 2002):

$$\Delta a_{mu} = (361 \pm 16) \times 10^{-11}, \tag{2}$$

which corresponds to a 3.3σ deviation.

Axions are the most popular candidates for dark matter (DM). Unlike many other exotic particles the axion is presented as a result of a minimal extension of the Standard QCD model and is a consequence of the Peccei-Quin (PQ) mechanism to solve one of the key difficulties of modern QCD - the strong CP problem.

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

Axions can be detected through their coupling to photons. They can decay into two photons (Fig.1).

The axion decay time is (Ressell, 1991):

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

The free axion lifetime (3) is sufficiently large to allow for observations of decay of axions with mass much less than 1 eV. However, axion interaction with magnetic fields can provide photon production with energy comparable to the total axion energy.

The probability of axion conversion into a photon and the inverse process of a photon conversion into an axion (Gnedin and Krasnikov, 1992):

$$P_{||}(\gamma \leftrightarrow a) = \frac{1}{1+x^2} \sin^2(1/2 B_\perp g_{a\gamma} L \sqrt{1+x^2})\,, \tag{4}$$

where

$$x = \frac{(\varepsilon - 1)\omega}{2B g_{a\gamma}}\,, \tag{5}$$

where ω is the radiation frequency, ε is the dielectric constant permittivity of the medium in which the radiation is propagating. Only one polarization state when the electric vector oscillates into the plane of directions of the magnetic field and the photon propagation is subject to conversion.

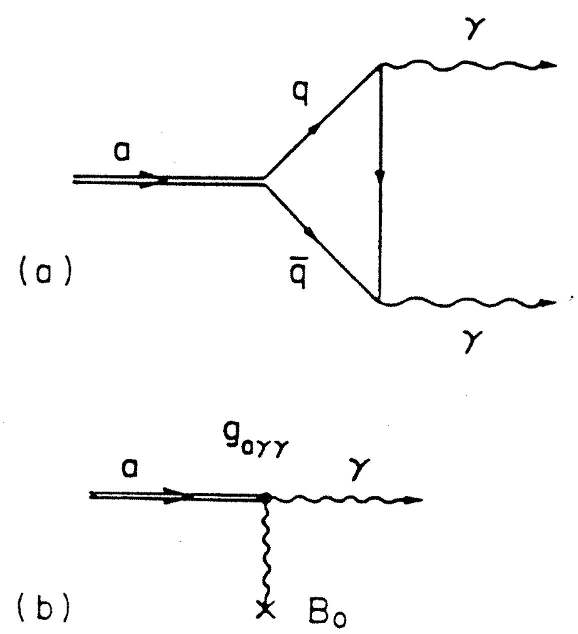

Figure 1: (a) Two-photon coupling of the axion through a triangle anomaly; (b) Axion-photon transition in a magnetic field.

$B_{\perp} = B\sin(\theta)$, where θ is the angle between the photon propagation and magnetic field directions. A commonly accepted system of units is used here for which $h = c = 1$. The probability has an oscillatory manner, the phase being depended on the product of magnetic field strength B and the size L.

The pure vacuum solution of Eq.(4) transform to

$$P_{||}(\gamma \leftrightarrow a) = \sin^2(1/2B_{\perp}g_{a\gamma}L) \approx 1/4B^2L^2g_{a\gamma}^2 \qquad (6)$$

(in the case of a weak effect of conversion).

The Sun and stars are powerful sources for weakly interacting particles such as neutrinos, gravitons and axions that can be produced by nuclear reactions or by thermal processes in the hot stellar interior (Fig.2). The comparison of this axion generation process with standard energy loss mechanisms via neutrino and photon emission gives bounds of axion-to-photon and axion-to-matter coupling constants. The potential effect of axion emission on stars is evident: i.e., the acceleration of their evolution and shortening their lifetimes.

The direct searching for axions by ground-based experiments can be made by using magnetic conversion process of solar axions. Axions can be produced in the Sun's interior through the scattering of thermal photons in the Coulomb field of nuclei (Primakoff effect). In a transverse magnetic field the Primakoff effect can work in reverse, coherently converting the solar axions back into X-ray photons of a few keV.

One method of detecting solar axions on the Earth is to make the Primakoff effect work in reverse, using a strong transverse magnetic field in a laboratory to coherently convert the solar axions into X-ray photons. Inside a magnetic field the axion couples to a virtual photon producing a real photon with the energy being equal to the total energy of the axion. The CERN Axion Solar Telescope (CAST) (Zioutas et al. 1998, 2005) is primarily designed to search for solar axion

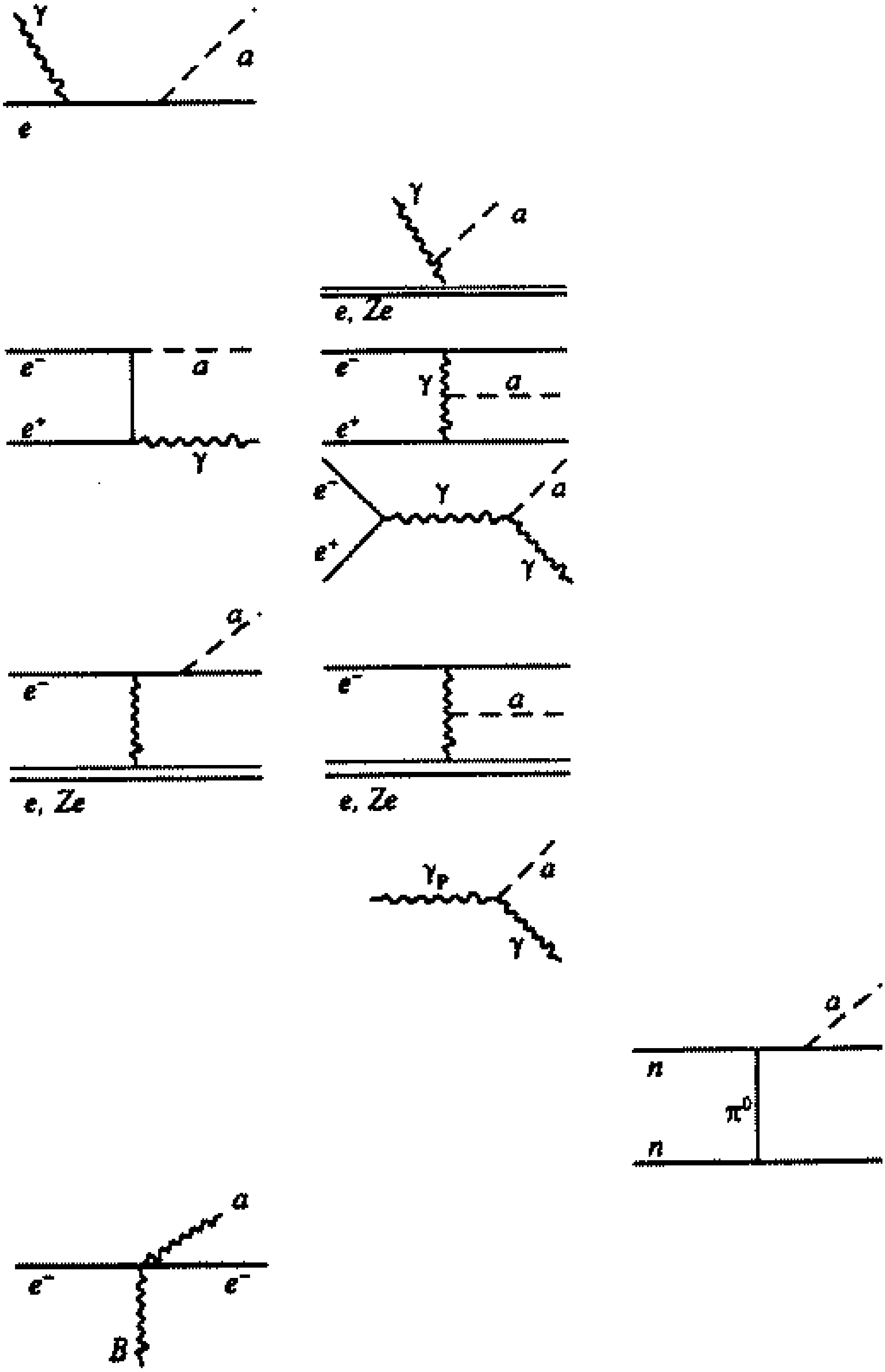

Figure 2: The most effective axion emission processes. From top to bottom: Compton process, Primakoff process, annihilation process, bremsstrahlung and scattering, plasma emission, bremsstrahlung in nucleon scattering, axion cyclotron emission.

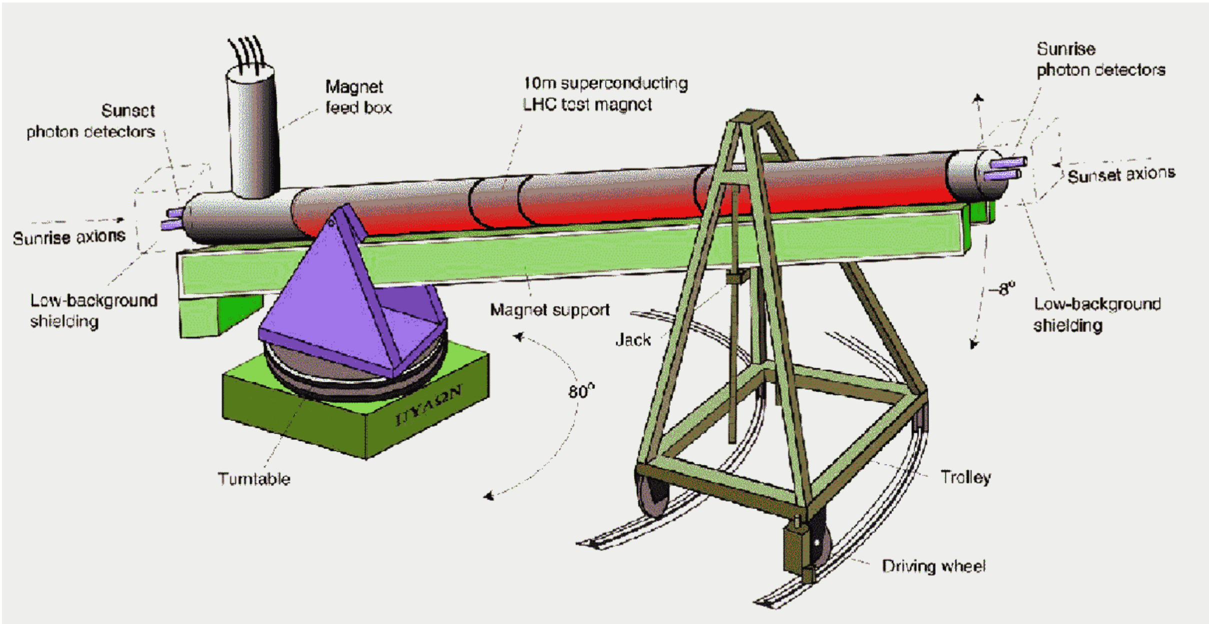

Figure 3: The CERN Axion Solar Telescope — CAST (from Zioutas et al., 1998, 2005).

generated via photoproduction by Coulomb interaction in a solar plasma (the Primakoff process) using above mentioned method. Fig. 3 presents the CAST device. The magnetic field (magnetic box in Fig.3) is provided by a decommissioned Large Hadron Collider (LHC) prototype dipole magnet, which produces a magnetic field 9.0 Tesla in the interior of two parallel, straight 9.26 m long pipes with a cross sectional area $S = 2 \times 14.5cm^2$. The magnet is mounted on a moving platform with $\pm 8^o$ vertical and $\pm 40^o$ horizontal movement, allowing the observation of the Sun for 1.5 h at both sunrise and sunset during the whole year. The analysis of the first CAST data has provided an upper limit to the axion-photon coupling of $g_\gamma < 1.16 \times 10^{-10} GeV^{-1}$ at 95% C.L. for axion mass $m_a < 0.02eV$ (Zioutas et al. 2005).

The most exciting result has been recently obtained by Ziotas et al. (2004). They have studied published data from Yohkoh solar X-ray mission, with the purpose of searching for signals from radiative decays of massive axion-like particles (Fig.4). They based on the prediction that emission of decay X-rays from the Sun direction beyond the limb with a characteristic radial distribution, and these X-rays should be observed more easily during periods of quiet Sun. They have shown that the recent observations made by RHESSI of a continuum emission from the non-flaring Sun of X-rays in the 3–15 keV range displayed quite well to the generic axion scenario.

3 Extreme Low Mass Axions and Cosmological Alignment of Quasar Optical Polarization Vectors

Recently Hutsemekers (1998) and Hutsemekers et al. (2005) have considered a sample of 170 optically polarized quasars with accurate linear polarization measurements and discovered that quasar polarization vectors are not randomly oriented over the sky as naturally expected. It appeared that in some regions of three dimensional Universe (i.e. in regions delimited in right ascension, declination and redshift) the quasar polarization position angles are concentrated around preferential directions, suggesting the existence of very large-scale coherent orientation or alignment of quasar polarization vectors. The existence of coherent orientations of quasar polarization vectors have been

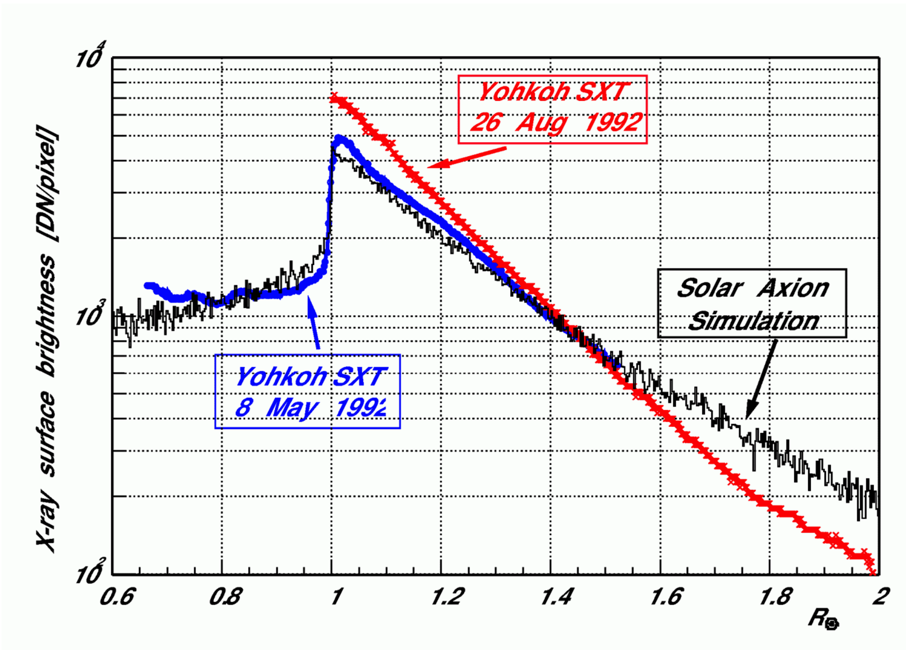

Figure 4: Theoretical solar axion simulation and experimental soft X-ray surface flux distributions from the quiet Sun (from Zioutas et al., 2004).

later on confirmed in series of works by Hutsemekers & Lamy (2001) and Jain et al. (2004) with use of a sample of 213 quasars. The final sample that was used for analysis includes 355 objects (see Hutsemekers et al. (2005)). Hutsemekers et al. (2005) used this sample of quasars with significant optical polarization and using complementary statistical methods they confirmed that quasar polarization vectors are not randomly oriented over the sky with a probability often in excess of 99.9%. The polarization vectors seem coherently oriented or aligned over huge ($\sim 1Gpc$) regions of the sky located in both low ($z \sim 0.5$) and high ($z \sim 1$) redshifts and looked characterized by different preferred directions of the quasar polarization (Fig. 5).

The linear dichroism of aligned interstellar dust grains in our Galaxy produces linear polarization along the line of sight. This polarization contaminates to some extent the quasar measured data and may change their position angles. Sluse et al. (2005) have shown that interstellar polarization has a little effect on the polarization angle distribution of significantly polarized ($p_l \geq 0.6\%$) quasars.

The interpretation of such large-scale alignment is difficult within the commonly accepted cosmological models. Ongoing theoretical works develop the idea that one might detect a specific property of dark matter or dark energy. Preliminary possible interpretations of the alignment effect have been discussed by Hutsemekers (1998), Hutsemekers & Lamy (2001) and more recently by Jain et al. (2002, 2004) and Hutsemekers et al. (2005). Since the alignments occur on extremely large scales one must seek for global mechanisms acting at cosmological scales.

From this point of view photon-pseudoscalar (ultra light axion or axion-like pseudoscalar particle) mixing with a magnetic field seems as a quite promising interpretation (see Harari & Sikivie (1992); Gnedin & Krasnikov (1992); Gnedin (1994); Das et al. (2004)) especially because many of the observed properties of the alignment effect were qualitatively predicted.

Recently the exciting event have taken place in the photon-pseudoscalar mixing science. PVLAS Collaboration (Zavattini et al. 2005a) reported the experimental observation of a laser light polarization rotation in vacuum in the presence of a transverse magnetic field. They claimed that the average measured rotation is $(3.9 \pm 0.5) \times 10^{-12}\, rad/pass$, at $5T$ with 44000 passes through a 1m

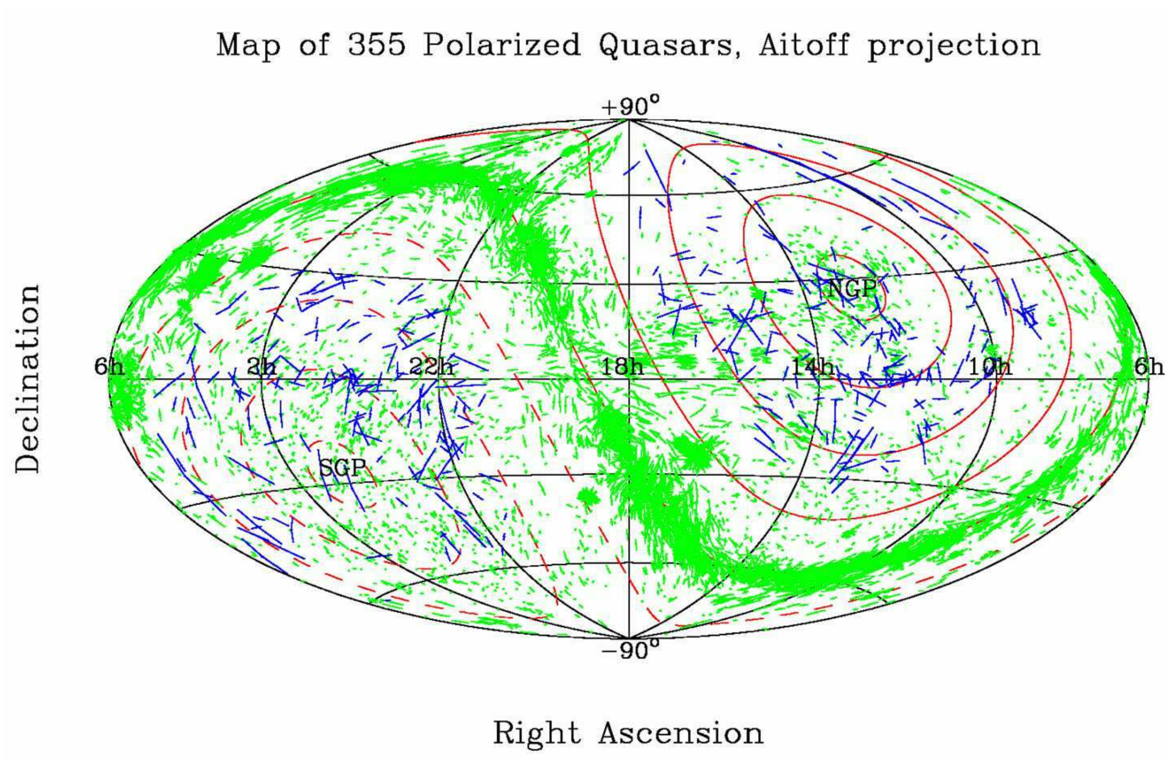

Figure 5: The sample of 355 polarized QSOs analysed by Hutsemekers et al. (1998, 2005).

long magnet. Using Eq.(8) one can estimate the value of the constant coupling of photon-axion mixing $g_{a\gamma}$. We estimate its value as

$$g_{a\gamma} \approx 3.8 \times 10^{-6} (GeV)^{-1}. \tag{7}$$

This value seems extremely higher than the corresponding value for Peccei-Quin axion.

First of all we may estimate the strength of the intergalactic (IG) magnetic field using this value of the coupling constant $g_{a\gamma}$, the characteristic size of alignment region $L \sim 1Gpc$ and the rotation rate of position angle $\Delta\theta \sim 30^0 (Gpc)^{-1}$ (Hutsemekers et al.(2005)). Eq.(7) gives the following value of the IG magnetic field:

$$B \approx 10^{-16} G. \tag{8}$$

This magnitude appears significantly less than the magnitude predicted by some current works ($\leq 10^{-9}$ see, for instance, Kronberg (1994); Furlanetto & Loeb (2001)).

Nevertheless Langer et al. (2005) presented a new model for generating magnetic fields of cosmological interest. They have shown that the photoionization process by photons from the first luminous sources provides the magnetic field amplitudes as high as $2 \times 10^{-16} G$. Takahashi et al. (2006) discussed generation of magnetic field from cosmological perturbations. They computed numerically the magnitudes of the various contributions in the generation process (three component plasma (electron, proton and photon) evolution, the collision term between electrons and photons) and showed that the amplitude of the produced magnetic field could be about $\sim 10^{-19} G$ at 10kpc co-moving scale at present.

Siegel & Fry (2005) examined the generation of seed magnetic fields due to the growth of cosmological perturbations. In the radiation era, different rates of scattering from photons induce local differences in the ion and electron density and velocity fields. The currents due to the relative method of these fluids generate magnetic fields on all cosmological scales. They estimated the peak of a magnitude of these fields of $\sim 10^{-30}G$ at the epoch of recombination. The major source of amplification of an initial seed field comes from dynamo effect. A main problem is connected with many mechanisms that produce quite weak seed fields at times insufficiently early for dynamo amplifications. As an example one should mention the Biermann mechanism that can produce seed fields of order $\sim 10^{-19}G$, but only at redshift of $z \sim 20$. It is remarkable that this magnitude is to be close to our estimation (10) of intergalactic magnetic field strength.

Rogachevskii et al. (2006) have discussed a new mechanism of generation of intergalactic large-scale fields in colliding protogalactic clouds and emerging protostellar clouds. Their mechanism is due to a "shear-current" effect ("vorticity-current" effect) caused by the large-scale shear motions of colliding clouds. Self-consistent plasma-neutral gas simulations by Birk et al. (2002) have shown that seed magnetic field strengths $\leq 10^{-14}G$ arise in self-gravitating protogalactic clouds of spatial scales of 100pc during 7×10^6 years.

Recently Dolag et al. (2002) have studied the evolution of magnetic fields in galaxy clusters with the use of cosmological magneto-hydrodynamic simulations. They have showed that the magnetic field strength profiles closely follow the cluster density profiles outside a core region. Their main result is evidence of strong decreasing of the mean magnetic field in the cluster cores with increasing redshift $B \sim 10^{-2.5z}\mu G$. It means that for large redshifts $z \sim 3 \div 4$ the magnetic field in a cores of galaxy clusters may reach so less magnitude as $B \leq 10^{-14}G$. Then one should expect the mean intergalactic magnetic field of more less magnitude.

It should be reminded that Nodland & Ralston (1997) have claimed evidence of a systematic rotation of plane of polarization of radio waves propagating over cosmological distances. Unfortunately their result seemed to be controversial (see discussions by Wardle et al. (1997) and Carrol & Field (1997)). Nevertheless the lower bound of this effect can be used for estimation of the photon-to-pseudoscalar coupling constant $g_{a\gamma}$ for intergalactic space with the use of Eqs.(5)–(8) of our paper. It appears that the lower bound of this effect does not strongly contradict to PVLAS experiment.

Thus, we can conclude that the intergalactic magnetic field magnitude is quite probably to be $\sim 10^{-16}G$, i.e. it is keeping the value of early cosmological origin. Below we analyze some additional observational consequences of positive PVLAS experiment for astronomy.

4 Vacuum polarization by a strong magnetic field and its astrophysical manifestations

The high magnitudes of magnetic fields of neutron stars and white dwarfs give rise to new effects in the traditional physical processes involving interaction of radiation with matter.

The high magnitudes of magnetic fields of neutron stars and white dwarfs give rise to new effects in the traditional physical processes involving interaction of radiation with matter. One of the most important effects is so-called polarization of electron-positron plasma by a strong magnetic field. Just as in an ordinary magnetoactive plasma the photon propagation in a magnetized vacuum is also described in terms of two normal modes (waves) with different polarization states and refractive indices $n_{1,2}$. The polarization of the vacuum itself is due to virtual e^+e^- pairs and becomes significant when the magnetic field strength

$$B \geq B_C = \frac{m_e^2 c^3}{e\hbar} = 4.414 \times 10^{13}G \tag{9}$$

where B_C is the magnetic field value at which the electron cyclotron energy $\hbar\omega_B = \frac{\hbar eB}{m_e c}$ is equal to electron rest mass energy $m_e c^2$. Nevertheless it appeared that the vacuum polarization must be taken into account in the analysis of many radiation processes even if the magnetic strength $B \ll B_C$.

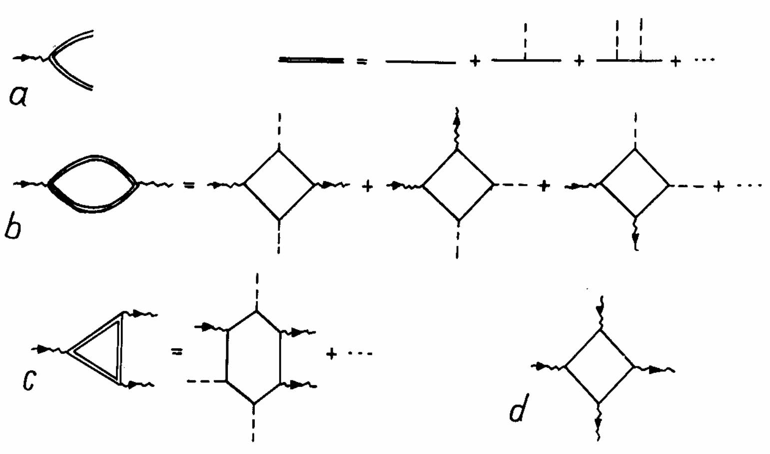

Figure 6: The interactions of photons with the electromagnetic field: (a) pair production by a photon in a magnetic field; (b) vacuum polarization by a magnetic field; (c) splitting of a photon into two photons; (d) one of the lower-order diagrams for photon-photon scattering (from Pavlov and Gnedin, 1984).

In his excellent review Adler (1971) presented the expressions for refractive indices of normal modes in the magnetized vacuum at $B < B_C$ and $\hbar\omega < m_e c^2$:

$$n_1 = 1 + \frac{7}{90\pi}\frac{e^2}{\hbar c}\left(\frac{B_\perp}{B_C}\right)^2 ;$$

$$n_2 = 1 + \frac{2}{45\pi}\frac{e^2}{\hbar c}\left(\frac{B_\perp}{B_C}\right)^2 , \qquad (10)$$

where $B_\perp = B\sin\theta$ and θ is the angle between the photon wave vector and the magnetic field directions.

The normal modes in this case are linearly polarized, the electric vector of mode 1 oscillating in the magnetic field and wave vector plane and that of mode 2 oscillating in the perpendicular plane. Vacuum polarization effect modifies the dielectric property of the medium and the polarization of photon modes propagated in a magnetoactive plasma, thereby altering the radiative scattering and absorption opacities.

The existence of quite strong magnetic fields of neutron stars and white dwarfs provides possibilities for searching the vacuum polarization effects in astrophysical observations of compact objects. Novick et al. (1977), were the first who have considered the possibility of measuring the phase shift between the vacuum polarization modes in radiation of neutron stars. Pavlov & Gnedin (1984), were the first who mentioned the importance of the vacuum polarization effect and for magnetic white dwarfs. The following step was to analyze the interaction of radiation with a "mixture" of vacuum and plasma in a strong magnetic field (Fig. 6). The modern detailed analysis of this situation was made in the series of papers by D. Lai & W.C.G. Ho (2002), W.C.G. Ho & D. Lai (2003), W.C.G. Ho & D. Lai (2004).

The first important step for estimation of the vacuum polarization effect is to calculate the magnitude of the phase shift φ between the two normal waves due to the difference in their phase velocities:

$$\varphi = \frac{\omega}{c}\int |n_1 - n_2| dl =$$

$$= \frac{l}{5\times10^{-7}cm}\frac{\hbar\omega}{m_e c^2}\left(\frac{B_\perp}{B_C}\right)^2 . \tag{11}$$

For neutron stars (NS) at $\hbar\omega = 1KeV$, $B_\perp = 4\times10^{12}G$ the magnitude $\varphi \sim 1$ after transversing a very small $l = 0.3mm \ll R_{NS}$ distance (R_{NS} is the radius of NS). It means that the radiation of NS will be partially depolarized via the so-called Cotton-Mouton effect, which is the analog to the familiar Faraday effect for a medium in which the normal modes are polarized linearly. In this case the polarization ellipse "oscillates" around the direction of polarizations of the normal waves, changing the ratio of the axes and the direction of rotation of the electric vector in an oscillatory manner. It may lead to a perfect depolarization of circularly polarized radiation from a NS and to partially depolarized the linearly polarized radiation (except the cases where the electric vector lies in the **KB** plane or at right angle to it).

For WDs:

$$\varphi = 1.2\left(\frac{\hbar\omega}{3eV}\right)\left(\frac{B_\perp}{4\times10^8G}\right)^2\left(\frac{R_{WD}}{10^9cm}\right) \tag{12}$$

in the optical spectral range. The situation for WDs looks better because there is no complete depolarization in this situation. In a result the possibility arises of searching the vacuum polarization effect in the optical spectral range via the polarimetric observations.

Especially interesting effects arise if one analyzes the interaction of radiation with a "mixture" of vacuum and plasma in a strong magnetic field due to the different types of the anisotropy in plasma and vacuum. These effects arise in the region where the contribution from the vacuum to polarization of normal waves is of the same order of magnitude as that from the plasma. Specifically there are two values of photon energy at which the contributions of the vacuum and plasma to the linear polarization of normal modes cancel out each other. This case is called by "vacuum resonance". One of these specified energies lies in the region of cyclotron energy $\hbar\omega_B$ and corresponds to the vacuum resonance number density

$$N_{V,1} = \frac{1}{60\pi^2}\left(\frac{m_e c}{\hbar}\right)^3\left(\frac{\hbar\omega_B}{m_e c^2}\right)^4 \cong$$

$$\cong 3\times10^8\left(\frac{B}{4\times10^8G}\right)^4 cm^{-3} . \tag{13}$$

Another "vacuum resonance" phenomenon can exist in the region outside the cyclotron energy if only the vacuum resonance number density is to be:

$$NS: \; N_{V,2} = 6\times10^{19}\frac{1}{Y_e}\left(\frac{E}{1KeV}\right)^2\left(\frac{B}{10^{12}}\right)^2 cm^{-3},$$

$$WD: N_{V,2} = 10^8\frac{1}{Y_e}\left(\frac{1\mu m}{\lambda}\right)^2\left(\frac{B}{3\times10^8}\right)^2 cm^{-3}, \tag{14}$$

where Y_e is an electron fraction. In the completely ionized plasma $Y_e = \frac{Z}{A}$.

The location of the vacuum resonance photon (wavelength) at a given number density is:

$$NS: \;\; E_V = 0.24\left(\frac{Y_e N_V}{6\times10^{19}}\right)^{1/2}\left(\frac{10^{12}}{B}\right) KeV ,$$

$$WD: \ \lambda_V = 0.283 \left(\frac{10^8}{Y_e N_V}\right)^{1/2} \left(\frac{B}{3\times 10^8}\right) \mu m\,. \tag{15}$$

Neutron stars and white dwarfs are characterized by different situation. For neutron stars the vacuum resonance lies in the deep layers of the atmosphere (photosphere) of a star. For magnetic WDs the number density value $\leq 10^8 cm^{-3}$ lies only in the uppermost layer of the atmosphere ($N_V \sim 10^8 cm^{-3}$ corresponds to the distance $l \sim 20H$, where H is the density scale height if only the electron fraction is not extremely low) or in the plasma environment (coronas or plasma envelopes produced by the pressure of cyclotron radiation, see Zheleznyakov (1996)). Namely Zheleznyakov and his colleagues showed that the pressure of cyclotron radiation in the magnetic WD photosphere can be compared and even can surpass the gravity force. Then hydrostatic equilibrium of plasma on magnetic white dwarfs can be disrupted by large radiation pressure and the radiation-driven ejection from the white dwarf photosphere can be possible. Zheleznyakov and his colleagues called this situation "radiation discon" object. They claimed that the structure of plasma envelopes of magnetic WDs with the effective temperature $T_e \geq 10^4 K$ is drastically different from the structure of thin hot corona. If the plasma density of such an envelope is large enough, it can strongly distort the photosphere spectrum and give rise to the broad and deep depressions bands in the observed radiation spectrum.

Also one needs to take into consideration that the influence of strong large-scale magnetic fields on the structure and temperature distribution in WD atmospheres. For example, Fendt and Dravins, 2000, displayed that magnetic fields may provide an additional component of pressure support, thus inflating the atmosphere compared to non-magnetic case. They found quantitatively that a mean surface poloidal field strength 100 MG and a toroidal field strength of 10 MG may increase the scale height at least by a factor of 10.

Let us now consider the basic effects arising if photons are propagating across the vacuum resonance. The first main effect is changing the orientation of the polarization ellipse. It can rotate by the definite angle $\leq 90^0$. The magnitude of the rotation angle is dependent on the peculiarities of the plasma region at the vacuum resonance because the orthogonality of normal modes in the resonance region may be violated. The rotation of the polarization ellipse is result of resonant conversion of photon modes across the vacuum resonance.

Lai and Ho (2002), investigated this process in detail and showed that the physics of this mode conversion is analogous to the Mikheyev-Smirnov-Wolfenstein mechanism for neutrino oscillations (Fig. 7). They have demonstrated that the conversion process is more effective if the adiabatic condition is fulfilled at resonance. The last one requires for MWD:

$$E_{con} \geq 1.5eV \left(\frac{10^9 cm}{R_{WD}}\right)\,. \tag{16}$$

In this case the adiabatic probability of conversion is $P_{con} = 1 - \exp\left(-\frac{\pi}{2}\frac{E}{E_{con}}\right)$. The jump probability can be calculated with the Landau-Zener formula: $P_j = \exp\left(-\frac{\pi}{2}\frac{E}{E_{con}}\right)$. This process is accompanied without the essential conversion of photon modes.

The second important for observations effect is the suppression of Rayleigh-Jeans region of the black body spectrum and, partially, the proton cyclotron lines for neutron stars and other spectral lines. For magnetic WDs (MWDs) the essential modification of the electron cyclotron lines is realized because in the "vacuum+plasma" mixture the ordinary wave acquires also cyclotron resonance and increases the cyclotron absorption. In the Zheleznyakov radiation-driven discon model of MWD the increase of cyclotron absorption may strongly distort the photospheric spectrum and give rise to the broad and deep depression bands in the observed radiation from such radiation-driven discon (Zheleznyakov (1996)).

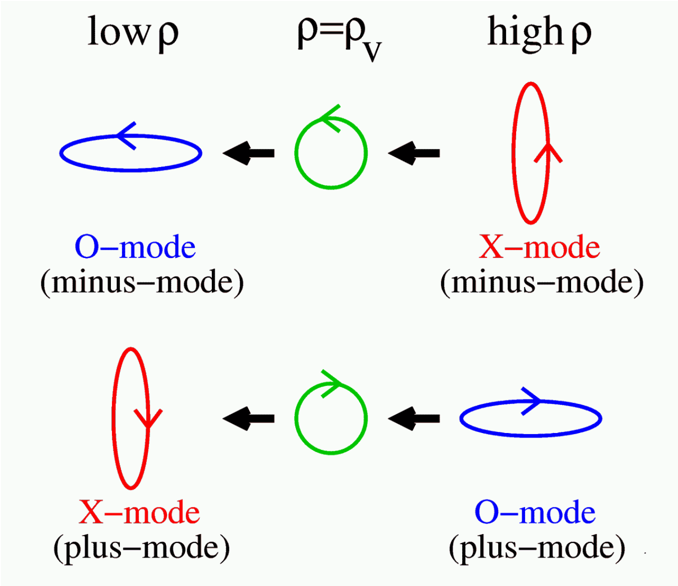

Figure 7: The diagram of the conversion of the normal modes each into other (from Lai and Ho, 2002).

In conclusion one can say that the vacuum polarization may produce the observable effects in the radiation from radiation-driven discon of a magnetic white dwarf.

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