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An overview of light ray deflection calculation by magnetars in nonlinear electrodynamics

Due to the lack of experimental confirmation of the effects of nonlinear electrodynamics (NED) of vacuum on the electromagnetic wave, it remains the most pressing issue. One of the most optimal media for studying these effects, occurring in astrophysics, are magnetars. Various methods of studying the bending of a wave passing through the magnetospheres of magnetars play a key role in a deeper understanding of vacuum NED. This article reviews modern methods for determining the angle of bending of the electromagnetic wave under the effect of NED of vacuum and gravity, with special attention paid to NED of vacuum in intense electromagnetic fields, which is a characteristic feature of magnetars. The article discusses various methods and techniques used to measure these angles, as well as their potential astrophysical applications.

Keywords: nonlinear electrodynamics of vacuum, magnetic dipole field, magnetars, gravitational and magnetic lensing.

Introduction

NLED are divided into two different fields: nonlinear optics, which deals with nonlinear electrodynamic phenomena on the surface of materials, and vacuum nonlinear electrodynamics, which examines similar phenomena in vacuums influenced by strong electromagnetic fields. Presently, nonlinear optics and its resultant effects are extensively employed in a multitude of theoretical and empirical investigations across diverse branches of physics. Instruments that leverage these effects have been integrated into practical applications. On the contrary, the nonlinear electrodynamics of the vacuum have been comparatively less explored and understood. Maxwell's electrodynamics within a vacuum, as is widely acknowledged, functions as a linear theory. The predictions of this theory, which span a wide array of topics, are continually validated with increasing precision. Indeed, the exploration of Maxwellian electrodynamics laid the groundwork for the formulation of the special theory of relativity, which revolutionized existing notions of space and time that prevailed in Newtonian mechanics. Yet, a series of foundational physical considerations indicate that Maxwell's electrodynamics merely constitutes an initial approximation of a more expansive, nonlinear electrodynamics of the vacuum. This approximation is true in scenarios of weak electromagnetic fields, specifically when the intensities of electromagnetic fields $\vec{B}$ and $\vec{E}$ are considerably lower than the characteristic quantum electrodynamical threshold $B_q = m_0^2 c^3 / e\hbar = 4.41 \cdot 10^{13}$G. Here, m_0 denotes the mass of the electron, e its charge magnitude, and $\hbar$ represents Planck's constant. Werner Heisenberg and Hans Heinrich Euler pioneered the concept of NLED in a vacuum, an advance based on the fundamental electromagnetic principles originally established by Gustav Mie. As high-power laser technology has advanced, numerous experiments have been designed to investigate these effects and have shown that the electrodynamics of the vacuum is definitely a nonlinear theory [1]. Despite such numerous ground laboratory experiments aimed at observing non-linearity in the presence of a strong magnetic field, conclusive evidence remains elusive.

An alternative method to explore is to study the effects on a cosmic scale, where celestial occurrences could shed more light on this phenomenon. Consequently, it is not surprising that the past decade has seen a wealth of proposals for NLED. Models such as rational, arcsin, arctangent, Mod-Max, and others [2], have unique features and implications that are worth further investigation. The main properties of non-linear vacuum electrodynamics and its recently proposed theories, as well as studies of light coupling, which is one of its phenomena, are reviewed [3]. Observationally, currently identified galactic pulsars and the characteristics of their magnetic fields are also obtained [4]. Identification of magnetars, possessing magnetic fields between 10^{10} and 10^{11} Tesla, was a result of the 1979 discovery of a massive flare from SGR 0526-66. This finding was instrumental in introducing the term "magnetar", credited to Duncan and Thompson, and is further elaborated in various studies [5]. There are also studies of the formation of virtual particles in the magnetosphere of growth symmetric pulsars using the global kinetic model [6]. The study of nonlinear electrodynamics in vacuum, particularly within the strong magnetic fields of magnetars, is often conducted in conjunction with an examination of gravitational effects due to their similar scales [7]. In compact astronomical bodies such as magnetars and black holes, non-linear electrodynamics provides fresh perspectives on astrophysical events. These studies delve into the interplay between electromagnetic and gravitational forces, contributing to black hole theories similar to the Reissner-Nordstrom model and addressing singularities in electric fields at their cores [1].

Research in the field of nonlinear electrodynamics of vacuum encompasses various aspects, including photon self-interaction and quantum electrodynamics considering loop corrections, leading to nonlinear electrodynamics. Special attention is paid to the phenomenon of vacuum birefringence in an external magnetic field, which finds experimental confirmation in various models of NLED. Research on vacuum birefringence sheds light on the relationship between the refractive indices and the phase velocity of electromagnetic waves, which influences our interpretation of black hole imagery, shadows, and rotational dynamics [8], thus enhancing our comprehension of these extreme cosmic conditions. An important aspect is also the study of pair-creation effects and polarization of the vacuum of particles of arbitrary spin with electric dipole and magnetic moments in a constant electromagnetic field, leading to nonlinear corrections in the Maxwell Lagrangian [9]. The work dedicated to Born-Infeld-type electrodynamics presents a new NLED model, which also considers the phenomenon of vacuum birefringence in an external magnetic field. Another study discusses various aspects of nonlinear electrodynamics, including its influence on phenomena in vacuum, underscoring the importance and diversity of emerging effects [2]. The spectral and polarization properties of magnetar radiation are also examined, considering models of condensed surface and magnetized atmosphere. The primary focus is on the influence of vacuum birefringence on polarization characteristics observable at infinity. There is considerable interest in exploring how nonlinear electrodynamics in vacuum behaves around strong-field astrophysical objects like pulsars and magnetars [10]. One of the significant discoveries in the study of nonlinear electrodynamics of the vacuum, particularly in the context of strong magnetic fields characteristic of neutron stars and magnetic white dwarfs, is the confirmation of vacuum birefringence. Investigation of the neutron star RX J1856.5-3754 using the Very Large Telescope (VLT) provided convincing evidence of this phenomenon, which is an important testament to quantum electrodynamics (QED) in strong fields and improves our understanding of the processes that occur under extreme astrophysical conditions. In addition to birefringence, considerable attention is paid to the effects of vacuum polarization. In strong magnetic fields, the vacuum behaves like an anisotropic medium, influencing the propagation of electromagnetic radiation and altering its spectrum. Particularly interesting is the change in the shape of cyclotron lines and the emergence of "vacuum lines" in X-ray spectra [10]. These studies broaden our understanding of physical processes in strong magnetic fields and provide important experimental data for the development of theoretical models in the field of QED.

Moving on to another significant aspect of nonlinear electrodynamics in vacuum, it is important to consider the phenomenon of electromagnetic beam deflection in the magnetosphere of magnetars. This effect, associated with the influence of the strong magnetic fields of magnetars on the propagation of electromagnetic waves, represents a crucial manifestation of the non-linear electrodynamical properties of the vacuum and is key to understanding electromagnetic phenomena under extreme astrophysical conditions. In-depth studies and observations on the birefringence and polarization of light in compact celestial bodies [10] focus on examining the deflection angles and the time delays of polarized light during gravitational lensing [10]. This research includes both detailed analytical and comprehensive numerical calculations of the deflection angles in the weak electric and magnetic field regimes, mainly focusing on the equatorial plane of the magnetosphere by using both the geometrical optics and one-loop effective action methods. Utilizing the principles of geometrical optics, the research has determined the deflection angles of rays passing through magnetic and electric fields and compared these findings with similar measurements in gravitational fields [11]. Furthermore, by applying the effective geodesic equation for individual photons, the study has analytically determined the impact parameter values for different ratios of this parameter to the radius of a magnetar, comparing them in the context of both gravitational and magnetic fields [12]. Also, there is the work [13-14] of studying the effective potential and deflection angles on the equatorial plane by using the polynomial Maxwell Lagrangian of some models. Additionally, analytical calculations of deflection angles of light have been carried out using the optical medium methods used in the Gauss-Bonnet theorem [10]. In these studies, the deflection of a beam passing through the strong magnetic fields of compact objects is calculated within the framework of the generalized Born-Infeld theory in the equatorial plane. Nevertheless, there are works where the deflection angles of the electromagnetic wave fronts coming to the magnetar are numerically calculated for different impact parameter values using the Newman–Penrose (NP) formalism [15] for the Euler-Heisenberg theory, without birefringence. These studies have defined the spatial distribution of the deflection of deflection angles for various values of the dipole magnetic field of magnetars.

However, analytical and numerical calculations of the angle of light deflection in cases where regions outside the equatorial plane of compact objects in a vacuum under the influence of strong electromagnetic and gravitational fields and light birefringence are considered remain a difficult task. However, the study of these problems plays a significant role in predicting and understanding the effects NLEDof vacuum. Thus, in this article we are going to review the latest methods for obtaining the deflection angles of an electromagnetic beam passing through compact objects, taking into account the NLED of vacuum and gravity.

Methods

Numerous techniques are available to determine both the approximate and precise angles of light deflection. These include methods like the null geodesics approach, which employs either perturbation techniques or directly integrates the null geodesic equations. In a study by Jusufi et al. [16], a different computational approach was presented.

This method incorporates the notion of refractive index in optical materials alongside the Gauss-Bonnet theorem applied to isotropic optical metrics. This combination yields a precise determination of the deflection angle in both Kerr and Teo wormhole geometries. This approach has proven effective across various studies, even in scenarios involving diverse spacetime characteristics. When a gradient in refractive index is present, geometric optics techniques can be utilized to ascertain the extent of deflection angle. This approach allows for highly accurate descriptions of how the light’s direction changes in various spacetimes [13, 17]. As a result, we can effectively assign a refractive index to the surrounding field.

Effective geodesic motion

As described in contemporary theoretical astrophysics, magnetars possess a magnetic dipole field, characterized by properties related to quantum electrodynamics induction $B_q = 4.41 \cdot 10^{13}$ G. In strong magnetic fields, vacuum non-linear electrodynamics becomes significant, influenced by various physical phenomena [10], described by the corresponding Lagrangians. By using polynomial Maxwell Lagrangians of the arbitrary model, it can be shown that the photon follows the null geodesic of its effective geometry:

$$g^{\mu\nu}_{eff} = \mathcal{L}_{\mathcal{F}} g^{\mu\nu} - 4\mathcal{L}_{\mathcal{F}\mathcal{F}} F^{\mu}_{\alpha} g F^{\alpha\nu}. \tag{1}$$

For weak electromagnetic wave fronts in strong external fields F_{ik}, the eikonal equation is used, as previously defined in literature [18]. It is demonstrated that these waves in nonlinear electrodynamics follow the geodesics of an effective pseudo-Riemannian space-time, influenced by the metric tensor g_{nk} and external electromagnetic field. The effective spacetime metric tensor G_{nk} is dependent on g_{nk} and the electromagnetic field tensor $F_{ni}g^{im}F_{mk}$. With different η_1 and η_2, non-linear electrodynamics induces two types of polarization. Effective metric tensors for each normal wave polarization are defined as [19]:

$$G^{(1)}_{nk} = g_{nk} - 4\eta_1 \xi F_{ni} g^{im} F_{mk}, \tag{2}$$

$$G^{(2)}_{nk} = g_{nk} - 4\eta_2 \xi F_{ni} g^{im} F_{mk}. \tag{3}$$

According to the Lagrange-Charpy theorem, to determine the paths of weak electromagnetic wave momentum in external fields and their motion, the isotropic geodesic equations in the effective spacetime with metric tensor $G^{(1,2)}_{nk}$ must be solved:

$$\begin{gathered} \frac{dK^i}{d\Sigma} + \Gamma^i_{mn} K^m K^p = 0, \\ G^{(1,2)}_{nm} K^n K^m = 0. \end{gathered} \tag{4}$$

Here, Γ^{i}_{mn} are the connection coefficients of space-time with effective metrics $G^{(1)}_{nk}$ or $G^{(2)}_{nk}$, depending on the polarization modes, Σ is an affine parameter and $K^{i} = dx^{i}/d\Sigma$ is a four-vector tangent.

Initially, the components of the effective pseudo-Riemannian space-time metric tensors $G^{(1,2)}_{nk}$ for the problem are determined as follows:

$$\begin{gathered} G^{(1,2)}_{00} = 1, \\ G^{(1,2)}_{\alpha\beta} = -\delta_{\alpha\beta}\left[1 - 4\eta_{\alpha\beta}\xi B^{2}(r)\right] + 4\eta_{1,2}\xi B_{\alpha}(r) B_{\beta}(r). \end{gathered} \tag{5}$$

The magnetic dipole field vector B in these equations is approximated by Maxwellian precision Figure. These effective geodesic equations are solvable by selecting the coordinate z as an independent variable instead of the affine parameter. Under this approach, the geodesic equations can be expressed as follows:

$$\begin{aligned} \frac{d^2ct}{dz^2} &= -\{\Gamma^{0}_{mp} - \frac{dct}{dz}\Gamma^{3}_{mp}\}\frac{dx^p}{dz}\frac{dx^m}{dz}, \\ \frac{d^2x}{dz^2} &= -\{\Gamma^{1}_{mp} - \frac{dx}{dz}\Gamma^{3}_{mp}\}\frac{dx^p}{dz}\frac{dx^m}{dz}, \\ \frac{d^2y}{dz^2} &= -\{\Gamma^{2}_{mp} - \frac{dy}{dz}\Gamma^{3}_{mp}\}\frac{dx^p}{dz}\frac{dx^m}{dz}. \end{aligned} \tag{6}$$

The system's first integral is represented as [16]:

$$G^{(1,2)}_{np}\frac{dx^n}{dz}\frac{dx^p}{dz} = 0. \tag{7}$$

Geodesic equation (6) is independently solved, and the deflection angles of the light front are determined using an expression that is defined as the ratio of velocities:

$$\phi = \frac{180\cdot\arcsin\left(\sqrt{\frac{v_x^2+v_y^2}{c}}\right)}{\pi} = \frac{180\cdot\arcsin(\sqrt{\frac{\left(\frac{dx}{dz}\cdot\frac{dz}{dt}\right)^2+\left(\frac{dy}{dz}\cdot\frac{dz}{dt}\right)^2}{c}}}{\pi}, \tag{8}$$

where c is the speed of light. By applying this equation, the distribution of the deflection angles of the electromagnetic ray front was obtained throughout the region by solving effective geodesic equations numerically [19], as well as specifically for the equatorial plane, was obtained. Additionally, the results were compared with previous works [17].

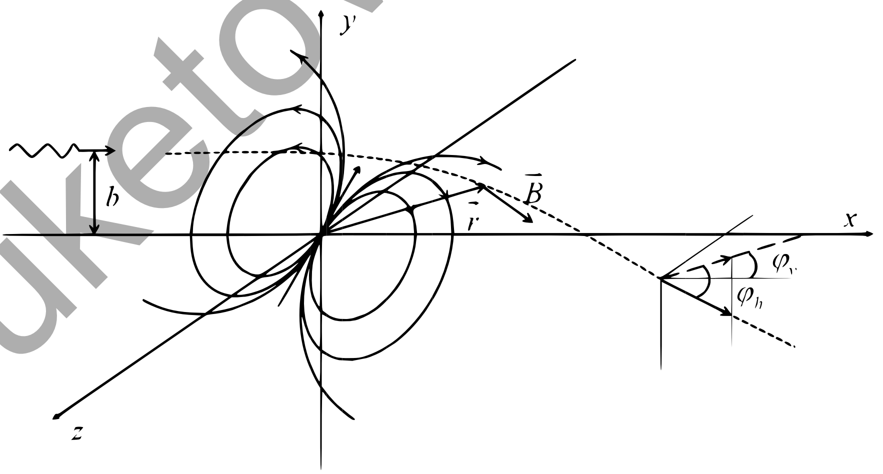

Figure. Diagram depicting the deflection of light by a magnetic dipole

The magnetic dipole is situated at the coordinate center. The photon's path is shown as a dotted line, while the projection of the outgoing photon's trajectory onto the xz-plane is illustrated with a dashed line. The angles of deflection in the horizontal (ϕ_h) and vertical (ϕ_v) directions are also indicated [22, 24-25].

Optical medium approach

Another method to compute the deflection angle of light is the optical medium. The process of deriving the equation for the light deflection angle in an arbitrary space-time through the refractive index encompasses multiple stages. This refractive index, denoted as (n(r)), can be interconnected with the corresponding arbitrary metric parameters, notably, for example, the black hole mass (M) and its angular momentum parameter (a) as for Kerr spacetime. Using this refractive index, the Gaussian optical curvature K is then determined [20]:

$$\mathcal{K} = -\frac{1}{f(r^\star)}\frac{\mathrm{d}^2 f(r^\star)}{\mathrm{d}r^{\star 2}} = -\frac{1}{f(r^\star)}\left[\frac{\mathrm{d}\rho}{\mathrm{d}r^\star}\frac{\mathrm{d}}{\mathrm{d}\rho}\left(\frac{\mathrm{d}\rho}{\mathrm{d}r^\star}\right)\frac{\mathrm{d}f}{\mathrm{d}\rho} + \left(\frac{\mathrm{d}\rho}{\mathrm{d}r^\star}\right)^2\frac{\mathrm{d}^2 f}{\mathrm{d}\rho^2}\right]. \tag{9}$$

Moreover, the concluding equation can be articulated using the refractive index it yields:

$$\mathcal{K} = -\frac{n(\rho)n''(\rho)\rho - \left(n'(\rho)\right)^2\rho + n(\rho)n'(\rho)}{n^4(\rho)\rho}. \tag{10}$$

One can derive for the Kerr spacetime metric the following Gaussian optical curvature as [3]:

$$\mathcal{K} \simeq -\frac{2M}{r^2} + \frac{18aMb}{r^5} + \mathcal{O}(M^2, a^2). \tag{11}$$

In addition, for the Born-Infeld Generelized NLED mode, the Gaussian curvature can be derived as [14]:

$$\mathcal{K} = \frac{18\mu^2}{\beta^2 r^8}. \tag{12}$$

The deflection angle of the ray, in addition to being found using equation (10), can also be applied for calculation and comparison using the effective metric method derived from the Newman-Penrose formalism [15]. Therefore, the equation for the bending angle in generalized Born-Infeld electrodynamics is defined as [14, 21–25]:

$$\Delta\theta = -\frac{15\pi}{16}\frac{\mu^2}{\beta^2 b^6}, \tag{13}$$

here, b represents the impact parameter, and the negative sign signifies that the bending is directed towards the magnetic dipole.

Discussion and summary

This review focuses on investigating the behavior of vacuum NLED, specifically in relation to the deflection of light around compact celestial objects like magnetars. The importance of studying NLED of vacuum in an astrophysical context is emphasized, highlighting its relevance in understanding such environments. The paper presents a comparative analysis of different theoretical frameworks of nonlinear electrodynamics, including the optical medium and the Newman-Penrose formalism. This analysis demonstrates the wide range and complexity of theoretical approaches needed to comprehend light deflection in strong electromagnetic fields. At the same time, scientific works presents that both calculations are reduced to the same value of deflection angles. Although this depends on the limitation of calculations. The conclusions drawn from these models enhance our understanding of electromagnetic phenomena in extreme settings and make significant contributions to the field of quantum electrodynamics. Understanding these interactions is crucial for understanding the behavior and characteristics of such entities. Additionally, the article highlights the importance of observational astrophysics in validating theoretical predictions and establishing a foundation for future astronomical observations and experiments. By connecting theoretical principles with their potential real-world applications, this review bridges theoretical physics with observational astronomy. It represents a significant advancement in unraveling complex phenomena in the universe and stimulates further research and discovery. The exploration of nonlinear electrodynamics in a vacuum and its implications for our understanding of the universe offers a fresh perspective in the field of astrophysics. As a result, this review contributes substantially to astrophysics by presenting innovative approaches to studying nonlinear electrodynamics in a vacuum and its implications for the cosmos. The authors advocate for further research and validation of the complex dynamics of astrophysical environments, particularly around magnetars, using both theoretical and empirical methods. This review serves as evidence of the ongoing evolution of our understanding of the cosmos, driven by the interplay between theory and empirical data.

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References

1 Mailliet, A.M., et al. (2024). Performance of a sagnac interferometer to observe vacuum optical nonlinearity. arXiv preprint arXiv:2401.13720

2 Kruglov, S.I. (2017). Born-Infeld-type electrodynamics and magnetic black holes. *Annals of Physics, 383,* 550–559.

3 Beissen, N., et al. (2023). The exploring nonlinear vacuum electrodynamics beyond maxwell's equations. *International Journal of Mathematics and Physics, 14*(1), 61–70.

4 Beloborodov, A.M. (2022). Scattering of ultrastrong electromagnetic waves by magnetized particles. *Physical Review Letters, 128*(25), 255003.

5 Kaspi, V.M., et al. (2003). Major Soft Gamma Repeater-like Outburst and Rotation Glitch in the No-longer-so- anomalous X-Ray Pulsar 1E 2259+586. *The Astrophysical Journal, 588*(2), L93–L96.

6 Rui, Hu & Beloborodov, A.M. (2022). Axisymmetric pulsar magnetosphere revisited. *The Astrophysical Journal, 939*(1), P. 42.

7 Vasili'ev, M.I., et al. (2017). The Effects of Vacuum Nonlinear Electrodynamics in an Electric Dipole Field. *Moscow University Physics Bulletin, 72*(6), 513–517.

8 Muratkhan, A., et al. (2023). Ashadows from the static black hole mimickers. *International Journal of Mathematics and Physics, 13*(2), 44–49.

9 Kruglov, S.I. (2001). Pair production and vacuum polarization of arbitrary spin particles with EDM and AMM. *Annals of Physics, 293*(2), 228–239.

10 Gnedin, Yu.N. (1990). Effect of vacuum polarization in a strong magnetic field and spectral features of x-ray source emission. *In International Astronomical Union Colloquium, 115,* 78–84.

11 Abishev, M., et al. (2016). Some astrophysical effects of nonlinear vacuum electro- dynamics in the magnetosphere of a pulsar. *Astroparticle Physics, 73,* 8–13.

12 Abishev, M.E., et al. (2018). Effects of non-linear electrodynamics of vacuum in the magnetic quadrupole field of a pulsar. *Monthly Notices of the Royal Astronomical Society, 481*(1), 36–43.

13 Beissen, N., et al. (2023). Gravitational Refraction of Compact Objects with Quadrupoles. *Symmetry, 15*(3), P. 614.

14 Beissen, N., et al. (2024). Bending of light by magnetars within generalized born–infeld electrodynamics: Insights from the gauss–bonnet theorem. *Symmetry, 16*(1), P. 132.

15 Newman, E., & Penrose, R. (1962). An approach to gravitational radiation by a method of spin coefficients. *Journal of Mathematical Physics, 3,* 566–578.

16 Beissen, N., et al. (2023). Nonlinear electrodynamical lensing of electromagnetic waves on the dipole magnetic field of the magnetar. *International Journal of Modern Physics D, 32*(6), 2350106.

17 Jusufi, K. (2018). Gravitational deflection of relativistic massive particles by Kerr black holes and Teo wormholes viewed as a topological effect. *Physical Review D, 98*(6), 064017.

18 Toktarbay, S., et al. (2022). Gravitational field of slightly deformed naked singularities. *European Physical Journal C, 82*(4), P. 382.

19 Denisov, V.I., Denisova, I.P., & Svertilov, S.I. (2001). Nonlinear Electrodynamic Effect of Ray Bending in the Magnetic-Dipole Field. *Physics — Doklady, 46*(10), 705–707.

20 Okyay, M. & Ovgun, A. (2022). Nonlinear electrodynamics effects on the black hole shadow, deflection angle, quasinormal modes and greybody factors. *Journal of Cosmology and Astroparticle Physics, 2022*(01), P. 009.

21 Jin, Young Kim. (2021). Deflection of light by a Coulomb charge in Born-Infeld electrodynamics. *European Physical Journal C, 81*(6), P. 508.

22 Jin, Young Kim. (2012). Bending of electromagnetic wave in an ultra-strong magnetic field. *Journal of Cosmology and Astroparticle Physics, 10,* P. 056.

23 Jin, Young Kim. (2022). Deflection of light by magnetars in the generalized Born-Infeld electrody- namics. *European Physical Journal C, 82*(5), P. 485.

24 Denisov, V.I., Denisova, I.P., & Sokolov, V.A. (2017). Nonperturbative QED vacuum birefringence. *Journal of High Energy Physics,* (5), P. 105.

25 Denisov, V.I., et al. (2016). Pulsar radiation in post — Maxwellian vacuum nonlinear electrodynamics. *Physical Review D, 94*(4), 045021.

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Сызықтыемес электрдинамикалық магнетарлардағы жарық сәулелерінің бұрылу бұрыштарын есептеуге шолу

Вакуумның сызықтыемес электрдинамикасының (СЕЭД) электрмагниттік сәулеге әсерінің эксперименталды расталмауына байланысты ол ең өзекті мәселе болып саналады. Астрофизикадағы осы әсерлерді зерттеудің ең оңтайлы ортасының бірі — магнетарлар. Магнетарлардың магнитсфералары арқылы өтетін сәуленің қисаюын зерттеудің әртүрлі әдістері вакуумдық СЕЭД-ны тереңірек түсінуде шешуші рөл атқарады. Мақалада магнетарларға тән қасиет болып табылатын қарқынды электрмагниттік өрістерде вакуумдық СЕЭД-ға ерекше назар аудара отырып, вакуумдық СЕЭД және ауырлық күшінің әсерінен электрмагниттік сәуленің қисық бұрышын анықтаудың заманауи әдістеріне шолу жасалған. Авторлар осы бұрыштарды өлшеу үшін қолданылатын әртүрлі әдістер мен тәсілдерді қарастырған және олардың потенциалды астрофизикалық қолданбаларын талқылаған.

Кілт сөздер: вакуумның сызықтыемес электрдинамикасы, магниттік диполь өрісі, магнетарлар, гравитациялық және магниттік бұрмалану.

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Обзор расчета отклонения лучей света магнетарами в нелинейной электродинамике

Из-за отсутствия экспериментального подтверждения эффектов нелинейной электродинамики (НЭД) вакуума на электромагнитный луч он является самым актуальным вопросом. Одной из самых оптимальных сред для изучения этих эффектов, происходящих в астрофизике, являются магнетары. Различные методы изучения искривления луча, проходящего через магнетосферы магнетаров, играют ключевую роль в более глубоком понимании вакуумной НЭД. Настоящая статья представляет собой обзор современных методов определения угла искривления электромагнитного луча под эффектом НЭД вакуума и гравитации, особое внимание уделяя НЭД вакуума в интенсивных электромагнитных полях, что является характерной чертой магнетаров. Авторами рассмотрены различные методы и техники, используемые для измерения этих углов, а также обсуждены их потенциальные астрофизические применения.

Ключевые слова: нелинейная электродинамика вакуума, магнитное дипольное поле, магнетары, гравитационное и магнитное линзирование.

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