ANNOTAION

of the dissertation for the degree of Doctor of Philosophy (PhD)
of the educational program of “8D05306 – Physics”

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THE EFFECTS OF NONLINEAR VACUUM ELECTRODYNAMICS AND GENERAL RELATIVITY FOR THE PASSAGE OF THE FRONT OF ELECTROMAGNETIC WAVES THROUGH THE MAGNETIC FIELD OF THE MAGNETAR

This work is devoted to the study of the effects of nonlinear vacuum electrodynamics and general relativity on the passage of the front of electromagnetic waves through the magnetic field of the magnetar.

Relevance of the topic

It is obvious that according to modern theoretical models vacuum electrodynamics is a nonlinear theory. This theory is studied in two sections: nonlinear optics, which studies nonlinear electrodynamic processes occurring in material media, and nonlinear vacuum electrodynamics (NLED), which studies similar processes occurring in a vacuum in the presence of strong electromagnetic fields.

Experiments on inelastic scattering of laser photons on gamma quanta, conducted at the Stanford linear accelerator, confirmed that vacuum electrodynamics has nonlinear properties. Many laboratory experiments were performed on Earth to observe the nonlinear effects of quantum electrodynamics [1-2]. In laboratory conditions, observation of the effects of NLED of vacuum is possible only in experiments in which the relative measurement accuracy must be at the level of 10^{-19} – 10^{-20}. Only precision ring lasers can provide such accuracy. Ring lasers and their application in precision optical measurements [3]. Although the accuracy of the instruments measuring NLED effects at present does not allow to study the effects in the vacuum of NLED. Therefore, the NLED of vacuum is much less known. At the same time, under conditions of extremely high magnetic fields, unattainable in terrestrial laboratories, charged and magnetized astronomical objects are likely to provide a more detailed understanding of the nonlinear effects of electrodynamics [4,5]. Therefore, there is an increasing interest in astrophysical compact objects with high levels of electromagnetic field, in particular, in charged black holes and magnetars. The propagation of a weak electromagnetic wave in an external electromagnetic field is accompanied by several nonlinear electrodynamic effects,

such as nonlinear electrodynamic bending of rays. The study of the delay of these curved rays using a detector makes a huge contribution to the understanding and study of the effects of NED vacuum. Naturally, the study of the effects of vacuum NED on the passage of EM rays through compact objects such as magnetars will be relevant.

The goals of the research: The aim of the study is a numerical investigation of combined gravitational and nonlinear magnetic lensing of electromagnetic radiation on the dipole magnetic field of a magnetar.

To accomplish this aim, it is essential to address the **following objectives**:

1. Study the processes of beam deflection in the plane of the dipole axis and the plane perpendicular to it under the influence of gravitational and magnetic fields. Determine the dependences of the deflection angle on the impact distance and magnetic field intensity for different distances (15-100 km) and magnetic fields in the conditions of a strong magnetar ($B = 10^{13}$ G).
2. Study the deformation of the radiation front passing through the dipole magnetic field of the magnetar to identify patterns of change in its shape. Estimate the degree of deviation from the ideal circular shape and approach to an ellipse, and determine the key parameters influencing this deformation.
3. Conduct a study of changes in the distribution of the energy flux of the radiation front as it passes through the magnetic field of the magnetar. Determine the ratio of energy at the input and output of the front and identify the factors influencing the minimum and maximum of the energy flows.

The object of the research: dipole magnetic field of a magnetar, gamma-ray burst, magnetar.

The subject of the research: combined gravitational and magnetic lensing when an EM radiation front passes through a magnetar.

Research methods: The analytical portion of the research relies on the principles of general relativity and techniques from differential geometry, in addition to employing perturbation theory methods for obtaining approximate solutions. The numerical analysis mainly utilizes the Runge-Kutta and Adams methods, as well as spectral methods tailored to the characteristics of the equations being studied.

Scientific provisions for the defense:

1. The deflection of the EM rays caused by the combined gravitational and dipole magnetic fields of the magnetar is 86 degrees and 3.36 degrees, respectively, for an impact distance between 15 and 100 km, with a magnetic field strength of $B = 10^{13}$ G.
2. The deformation of the wavefront $\Delta = \frac{r_{max} - r_{min}}{r_{max}}$ (dimensionless quantity) of electromagnetic radiation caused by the gravitational and dipole magnetic fields of the magnetar is 0.07.
3. Due to the combined effects of gravitational and dipole magnetic lensing, the flux density of the electromagnetic beam from GRB091006360, measured 30 km away from the magnetar (Swift J1822.3-1606), increases by 1.83 times compared to its initial value.

Scientific novelty: The uniqueness and innovation of the dissertation are demonstrated by the fact that;

– electromagnetic radiation passing through the combined gravitational and dipole magnetic field of the magnetar is deflected by a large angle in areas adjacent to the magnetar and by a small angle at a greater distance from it. When the dipole magnetic field strength on the surface of the magnetar approaches a critical value, the influence of nonlinear electrodynamics becomes significant;

– the combined gravitational and dipole magnetic field causes the electromagnetic radiation front to deform into an ellipse as it passes through the magnetar's magnetosphere. This phenomenon is not observed in an isolated gravitational field;

– as a result of the significant influence of the combined gravitational and dipole magnetic field on the flux density of gamma quanta passing through the magnetar's magnetosphere, a redistribution of this flux occurs.

Reliability and validity of the results: The obtained results are confirmed by publications in leading scientific journals with an impact factor and journals recommended by the Committee of Education and Science of the Republic of Kazakhstan. Additionally, the presence of publications in the collection of materials from domestic and foreign international scientific conferences further supports the validity of the results. The sources for the research are the original scientific works listed in the bibliography.

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The author's personal contribution:

Throughout the research process, including literature reviews, conducting relevant investigations to address research tasks, and obtaining satisfactory results, the author worked independently. However, the author consulted with supervisors to define tasks that align with the research topic and to analyze the results obtained.

Publications:

According to materials presented in the dissertation 10 publications have been published in total: one article in journal indexed in: Web of Knowledge (Thomson Reuters, USA), Scopus (Elsevier, Netherlands); 4 articles in journals recommended by the Ministry of Science and Higher Education of the Republic of Kazakhstan; 3 publications in the collection of international scientific conferences.

Articles with a high impact factor in the Thomson Reuters database or publications included in the international scientific database Scopus:

1. Beissen, N., Abishev, M., Toktarbay, S., **Yernazarov, T.**, Aimuratov, Y., Khassanov, M. (2023). Nonlinear electrodynamical lensing of electromagnetic waves on the dipole magnetic field of the magnetar. International Journal of Modern Physics D, 32(16), 2350106-142. (IF: 3.8, SCOPUS 80)

Articles in publications recommended by Committee for Quality Assurance in the Field of Science and Higher Education of Republic of Kazakhstan:

1. Beissen, N., Abishev, M., Toktarbay, S., **Yernazarov, T.**, Utepova, D., & Zhakipova, M. (2023). The Exploring nonlinear vacuum electrodynamics beyond Maxwell's Equations. International Journal of Mathematics and Physics, 14(1), 61-70.

2. Beissen, N. A., Utepova, D. S., Kossov, V. N., Toktarbay, S., Khassanov, M. K., **Yernazarov, T.**, Seydalieva, M. (2024). The influence of deformation in compact objects on redshift and radar echo delay. Recent Contributions to Physics, 88(1).

3. Beissen, N., Abishev, M., Toktarbay, S., **Yernazarov, T.**, Khassanov, M., Utepova, D., Abduali, A. (2024). An overview of light ray deflection calculation by magnetars in nonlinear electrodynamics. Bulletin of the Karaganda University" Physics Series", 11429(2), 65-71.

4. Beissen, N. A., Utepova, D. S., Kossov, V. N., Toktarbay, S., Khassanov, M. K., **Yernazarov, T.**, Imanbayeva, A. K. (2024). Comparing the efficiency of GPU and CPU in gravitational lensing simulation. International Journal of Mathematics and Physics, 15(1), 49-56.

Publications in materials of international and foreign scientific conferences, as well as domestic conferences:

1. Yernazarov, T., Abishev, M., Aimuratov, Y. Correspondence of gamma radiation coming from GRBs and magnetars based on the effects of nonlinear vacuum electrodynamics. In the Sixteenth Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Astrophysics and Relativistic Field Theories: Proceedings of the MG16 Meeting on General Relativity Online; 5–10 July 2021 (pp. 4401-4409).

The results of the work were presented and discussed at the following local and foreign international conferences:

- at the scientific seminars of the Theoretical and Nuclear Physics Department at Al-Farabi KazNU;
- at the International Scientific Online Conference «Sixteenth Marcel Grossmann Meeting» Rome, Italy, 2021;
- at the International Scientific Conference of Students and Young Scientists "Farabi alemi", Almaty, April 6-8, 2023;
- at the International Conference Abdildin readings (actual problems of modern physics) Al Farabi Kazakh National University, Faculty of Physics and Technology, Almaty, Kazakhstan, April 12 - 15, 2023;
- at the International Conference on Theoretical Physics and Astrophysics (ICTPA-2024), Institute of Fundamental and Applied Research, Tashkent, Uzbekistan, 13 - 18 May 2024.

Connection of the dissertation topic with the plans of scientific works:

The dissertation work was completed by the plans of fundamental research work (R&D) of the Scientific Committee of the Ministry of Education and Science of

the Republic of Kazakhstan “Grant financing of scientific research” on the topics: “Effects of nonlinear electrodynamics of vacuum and general relativity on magnetars” (2022-2024, code AP14869524 No. Agreement No. 253/30-22-24 dated October 18, 2022).

Volume and structure thesis:

The dissertation consists of an introduction, 2 chapters, and a list of references comprising 116 titles. It spans 111 pages of main text, including 27 figures.