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Specific features of the reflection effect in binary systems with compact source rotating about its axis

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HIGHLIGHTS

- Rotation of source about its axis influences on the reflection effect in binaries.
- Properties of reflected pulses are connected with geometric parameters of binary.
- Time of passage of the source beam pattern along companion surface must be considered.
- Obtained results can be applied to some binaries which involve pulsar.

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ABSTRACT

Reprocessing of X-ray pulsar radiation by the atmosphere of a companion in a binary system may result in reflected pulse radiation under suitable conditions. In this paper the influence of the rotation of the source of the radiation about its axis on the parameters of thus reflected pulses is investigated. The binary system is modeled by the spherical reflective screen and the compact source uniformly rotating about its axis; the beam pattern (BP) of the source periodically runs along the surface of the screen. Irradiation of the screen by the pulses which have infinitely narrow time spread and by the rectangular pulses is considered. The model does not concern the details of the reprocessing and reemission of the photons. In this model parameters of the pulses reflected in some directions are calculated. The main conclusion provided by the consideration of this model is that the properties of reflected pulses — their profile and observed time of arrival — substantially depend on the correlation between the light speed and the speed of the BP passing along the companion's surface. The possibility of applying of the obtained results to the known X-ray accretion-powered pulsars and rotation-powered pulsars in binary systems is examined.

1. Introduction

An important way of obtaining information about stars in binary systems is observation of the reflection effect which involves reprocessing and reemission of the radiant energy, coming from one star, by the atmosphere of another star. For example, narrow high-excited emission lines can arise from the irradiated surface of the companion star in some X-ray binary systems. Observations of these lines lead to constraints on the mass of the compact object in such systems (Cornelisse et al., 2008). Also, analysis of the observed time delays between the light curve of the X-ray emission and its reprocessed optical echoes can constrain the binary inclination (O'Brien et al., 2002). In the case when the binary includes a pulsar with a companion occasionally getting into its beam pattern (BP), some part of the incident flux of the radiant energy can be reemitted in the form of periodical pulses. The properties of the pulses thus reflected have a number of specific features to be considered in the present paper.

It is known that reprocessing of the X-ray radiation of the pulsar by the atmosphere of a companion may result in emergence of reflected pulses in the X-ray as well as in the ultraviolet and optical ranges of the spectrum (Basko et al., 1974). Therefore, the objects for the study of which can be useful the results given below are, firstly, X-ray pulsars emitting due to the accretion of matter from the companion star (accretion-powered pulsars), and, secondly, pulsars in binaries emitting in the X-ray range due to their kinetic rotational energy (rotation-powered pulsars). Although these objects are obviously different in their physical characteristics and observational manifestations, it is their common property that is essential for us in this case: the presence of a compact X-ray source emitting in a limited solid angle $\Omega < 4\pi$ and rotating like a lighthouse. Observational data of properties of the X-ray

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radiation of accretion-powered pulsars can be found, for example, in catalogues Liu et al., 2006, 2007, and of properties of the X-ray radiation of rotation-powered pulsars — in the works (Kargaltsev and Pavlov, 2008; Becker et al., 2010).

The observation and interpretation of the reemitted pulses expand our possibilities of studying the properties of the source, companion and binary system in general (Avni and Bahcall, 1974). It would seem, besides, that the study of a quick-changing radiation flux can provide more information than the study of a stationary flux: in the first case we have a time-dependent function while in the second case we have one constant value only. An example of using observations of reemitted pulses is determination of the mass of the neutron star in Hercules X-1 system (Middleditch and Nelson, 1976). Another example is observed modulation of the radio emission of each pulsar by the radiation of the other in the double pulsar system PSR J0737–3039A/B (McLaughlin et al., 2004a,b). Basing on these observations could be determined the sense of rotation of each pulsar with respect to its orbital motion and some others parameters of this binary system, and also could be tested the rotating lighthouse model of pulsar emission (Freire et al., 2009; Liang et al., 2014).

Unambiguous interpretation of the results of observations of reemitted pulses in the binary systems under consideration is likely to be a challenging task as it is necessary to consider a whole number of factors influencing the properties of pulses (we do not discuss here the technical possibility of observation of such pulses). Firstly, this is the characteristics of incident radiation: the kind of the spectrum and the beam pattern. Secondly, this is the physical characteristics of the companion atmosphere, determining the reprocessing and reemission of the photons getting there. The entering of a considerable quantity of high-energy photons and pulsar wind particles into the atmosphere results in its heating and, consequently, in its restructuring, which should be taken into account. Thirdly, radiation propagation can be influenced by the gas-dynamic processes existing in a binary; it especially concerns X-ray pulsars. Finally, the properties of reemitted pulses depend on geometric parameters of the binary system.

The present paper considers the last, geometric, factor. It is considered on the basis of a model of the binary system that does not concern the details of the reprocessing and reemission of the photons. This model consists of a source rotating about its axis, a spherical reflective screen, and a distant observer. The following simplifying assumptions are made.

(1) The size of the source is negligible relative to the other length scales in the problem: the screen's radius, the distance between the source and the center of the screen, the distance between the screen and the observer. Therefore, the source can be considered as a point source. The source rotates about its axes with a constant period. In the considered model of the binary system this pointlike source represents the source of the X-ray emission.
(2) The screen reflects the radiation of the source and does not emit anything as it is. This screen represents a pulsar's companion. Due to the location of the screen all the points of its surface in the line-of-sight of the source occasionally get in the beam pattern of the source. The distance between the screen and the source is constant.
(3) Two kinds of the source BP are under consideration: in the first case of the BP every elementary area of the screen surface getting within its limits is exposed by the pulses which have infinitely narrow time spread while in the second case it is irradiated by the rectangular pulses. Having considered BP of the first type, we get the response of the screen to the incident δ-like pulse. This response is described by a certain impulse function. It is assumed that single pulses are reflected independently by the screen, so the response of the screen is linear. Then, if BP of the arbitrary type is represented as a set of δ-like pulses, the response of the screen in this case is described by properly summed up impulse functions, corresponding to these pulses (Avni and Bahcall, 1974). As an example such summing up is carried out for the BP of the second, rectangular, type, which can be regarded as the simple model of a fan beam pattern of the pulsar's emission.
(4) It is supposed that every elementary area of the screen's surface instantaneously reemits all the radiation reaching it so that the brightness of the area appears to be equal in all directions. The assumption about the instant reemission is a serious limitation of the model, especially in case when the question is not only about reflection, but also about the reprocessing of the radiation, — for instance, the reprocessing of the X-ray radiation into the optical radiation. The finite time of the reprocessing of radiation by the atmosphere of the companion results in a smearing of the reflected pulses and, accordingly, in the reduction of the effects which are discussed in this article. The examination of this influence is outside the scope of this paper because it requires adoption of a type of the pulsar's companion and detailed model atmosphere calculations.
(5) It is assumed that reflective screen is not rotating and the model binary is stationary (i.e. the source and the screen have no orbital motion). These assumptions prove to be justified if incident pulses have infinitely narrow time spread. But they may not be true in case when both the duration of incident pulses and the time of reprocessing of radiation in the atmosphere of the companion are finite (see Discussion, Note 3).
(6) The distance between the screen-source system and the observer is so great that the screen has point dimensions for him.

The model is described in detail in the next section.

The main conclusion provided by the consideration of this model is that the properties of the reflected pulses — their profile, and the moments of reaching the observer — substantially depend on the correlation between the light speed and the speed of the BP passing along the companion surface. In particular, at a certain correlation between these speeds the maximum amplitude of the reflected pulses is achieved. Thus, it may be concluded that if the source irradiating the companion rotates about its axis, it can have a certain influence on the reflected pulse radiation. This influence, however, is determined by the geometric parameters of the binary system only and does not depend on the way the reprocessing and reemission of the photons getting into the atmosphere proceed.

2. The model

Let us specify the parameters of the screen – source – observer system described in the Introduction.

Screen. The reflective screen is spherical with radius R. The sphere has no radiation of its own and does not rotate. We will assume the following reflecting properties of the screen surface: every its elementary area instantaneously reemits all the radiation falling on it so that its brightness appears to be the same in all directions (lambertian source). We will relate the Cartesian coordinate system (x, y, z) with the sphere placing the origin of this system in its center C (Fig. 1). We will also introduce the spherical coordinate system (r, θ, φ) with the same origin.

Source. Let the linear size of the radiation source be negligible relative to other length scales of the system, so that it can be