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MODELLING OF LIGHT AND RADIAL VELOCITY CURVES IN X-RAY BINARY SYSTEMS

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Abstract. Synthesis methods for close binary systems allow one to reliably determine fundamental parameters of stars and relativistic objects (masses, radii, luminosities etc.). Our numerical models are designed to analyse light and radial velocity curves of various types of binary systems. In the present paper I focus on models developed for X-ray binaries. One of them was used for analysis of hard X-ray light curves (25-50 keV) of the unique object SS433 obtained by the INTEGRAL observatory. The orbital and precessional variability was computed in a model of a binary system containing a precessing accretion disk. I also present a model for a generic X-ray binary including a point X-ray source and an optical star. Heating of the optical star by the incident X-ray radiation is taken into account by model atmosphere calculations. The model allows one to compute absorption-line profiles and radial velocity curves of the optical component. Using this model the masses of relativistic objects in the X-ray binaries Cyg X-1, Her X-1, 2S 0921-630 and some others were refined.

1. INTRODUCTION

Binary stars are important, because they are numerous. Estimates show that about 50% of stars in our Galaxy are members of binary systems. The second reason why binaries are important is that they are the primary source of our knowledge of the fundamental stellar parameters. Also study of binary systems allows one to determine properties of very interesting astrophysical objects such as white dwarfs, neutron stars and black holes.

Classical methods for light and radial velocity curves analysis used simple models, like spherical stars for the light curves and two point masses for the radial velocities. This approach is not good for systems with non-spherical stars and totally fails for binaries with strong heating effects, such as X-ray binaries.

Synthesis methods for close binary systems allow one to determine the fundamental parameters of stars and relativistic objects for non-classical systems. Various computer codes were suggested by several authors. The most common one currently in use is the Wilson-Devinney code (Wilson 1971, 1979).

The main idea of the synthesis method is to create a grid of thousands of small elements on a distorted surface of a binary component and to compute the output stellar flux at each orbital phase by integration over the surface. Gravity darkening, limb darkening, heating effects, eclipses are taken into account.

Our team from Sternberg Astronomical Institute headed by prof. Cherepaschuk develops synthesis methods for light and radial velocity curves since the middle of 1970-th. We have our own set of computer codes for light and radial velocity synthesis for different binary models: Roche model at an eccentric orbit, a model with a spheroidal accretion disk, a model with a precessing thick accretion disk, a model for X-ray binaries etc. (Antokhina 1988, 1996, Antokhina and Cherepashchuk 1987, 1994, Antokhina et al. 2005). These models are being used for interpretation of observational data of various types of binaries.

In the current paper I present the results of analysis of the X-ray light curves for the massive X-ray binary SS433, obtained by the INTEGRAL observatory (Sect.2). Modelling theoretical absorption-line profiles and radial velocity curves for optical components in X-ray binary systems and deriving masses of relativistic objects is discussed in Sect.3.

2. MODELLING OF PRECESSIONAL AND ORBITAL VARIABILITY OF SS433

SS433 is a massive eclipsing X-ray binary system, consisting of a mass donor star and a compact object, surrounded by a supercritical precessing accretion disk with the narrow-collimated relativistic jets ($v = 0.26c$). This unique galactic X-ray binary exhibits several variabilities, including the precessional one (with the period $P_{prec} \simeq 162$ d) and the eclipsing one (with the binary orbital period $P_{orb} = 13.08$ d). SS433 has been extensively investigated in the optical, radio and X-ray domains (see reviews by Cherepashchuk (2002) and Fabrika (2004)). The main question is what is the mass of the relativistic object in this system. The value of mass defines if the compact object is a neutron star or a black hole. This information is crucial to understand how the relativistic jets are formed. In this system it is very difficult to directly measure the mass ratio of the components and hence their masses from spectroscopy. The spectrum contains strong spectral lines which are formed in the bright accretion disk. Spectral lines of the optical star are extremely weak and are hardy identified. Many attempts to determine the mass ratio from observations were undertaken during last decades, but the question about the mass of the compact object is still open.

A history of our attempts to get the mass ratio $q = M_x/M_v$ (here M_v is the mass of the "normal" star, M_x is the mass of the compact object) via light curve analysis by the synthesis methods began in the middle of 1980-th. Initially we analysed photometric light curves (V-bands) in the model contaning a precessional "thick" disk (Fig.1). Numerous calculations for a wide range of parameters of the binary allow us to obtain good light curve fits for two mass ratios values: $q = 0.4$ and $q = 1.2$. Both solutions correspond to the black hole hypothesis (Antokhina and Cherepashchuk 1985, 1987).

In the beginning of 1990-th we analysed the X-ray eclipses observed by the *Ginga* satellite in the 1-10 keV range (Brinkmann et al. 1989, Kawai et al. 1989, Kawai 1989) in the model of a thick precessing disk and thick non-relativistic jets in its centrum (Fig.2). The obtained limits of mass ratio $q = 0.15 - 0.25$ are consistent with the neutron star hypothesis. These results were in contradiction with the solution obtained from the optical data (Antokhina and Cherepashchuk 1985, 1987).

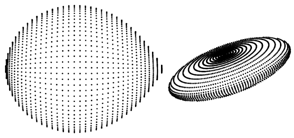

Figure 1: The geometrical model for SS433 with "thick" precessing disk.

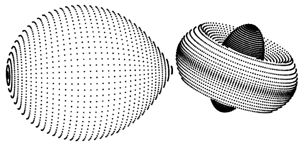

Figure 2: The geometrical model for SS433 with precessing disk and jets.

The discrepancy between the mass ratio values derived from the optical and X-ray photometry remained unresolved until the beginning of the observations of SS433 with the Gamma space observatory INTEGRAL. First INTEGRAL observations in 2003 showed that SS433 is a hard X-ray source with emission clearly detected up to 100 keV (Cherepashchuk et al. 2003). Strong precessional variability in hard X-ray domain is revealed with the amplitude $A_{pr} = L_{max}/L_{min} \sim 4$. The binary shows a wide, deep hard X-ray eclipse of the disk body by the optical star. Hard X-ray spectrum does not vary with the precessional phase. Our preliminary analysis showed that hard X-rays are produced in a hot extended corona located near the base of relativistic jets (Cherepashchuk et al. 2005).

The new studies of SS433 in hard X-rays using the INTEGRAL observations in 2003-2007 (Fig. 3) suggested the presence of a hot low density corona above the supercritical accretion disk in this source. The peculiar variability of the shape and width of the primary eclipse in hard X-rays was discovered. This implies that the primary eclipse is not purely geometrical and that the binary mass ratio as derived from the eclipse duration may be unrealistic.

To analyse hard X-ray eclipses of SS433 we used a geometrical model developed earlier to analyse the *Ginga* data (Antokhina et al. 1992) and the INTEGRAL light curve (Cherepaschuk 2005). In this model, a close binary system consists of an (opaque) "normal" star limited by the Roche equipotential surface and a relativistic object surrounded by an optically and geometrically thick "accretion disk". Relativistic jets are directed perpendicularly to the disk plane. The "accretion disk" includes the disk itself and an extended photosphere formed by the outflowing wind. The orbit is circular, the axial rotation of the normal star is assumed to be synchronized with the orbital revolution. The disk and "jets" are precessing in space and change the orientation relative to the normal (donor) star. The disk is inclined with respect to the orbital plane by the angle θ.

A cone-like funnel is located inside the disk and is characterized by the half-opening angle ω, thus the opaque disk body (see Fig.4) is described by the radius r_d and the angle ω. The central object is surrounded by a transparent homogeneously emitting spheroid with a visible radius r_j and height b_j which could be interpreted as a "corona" or a "thick jet" (without any relativistic motion). Here r_j, b_j and r_d are dimensionless values expressed in units of the binary separation a. The radius of the normal star is determined by the relative Roche lobe size, i.e. by the mass ratio $q = M_x/M_v$.

Only the "corona" is assumed to emit in the hard X-ray band, while the star and disk eclipse it in the course of the orbital and precessional motion. During precession

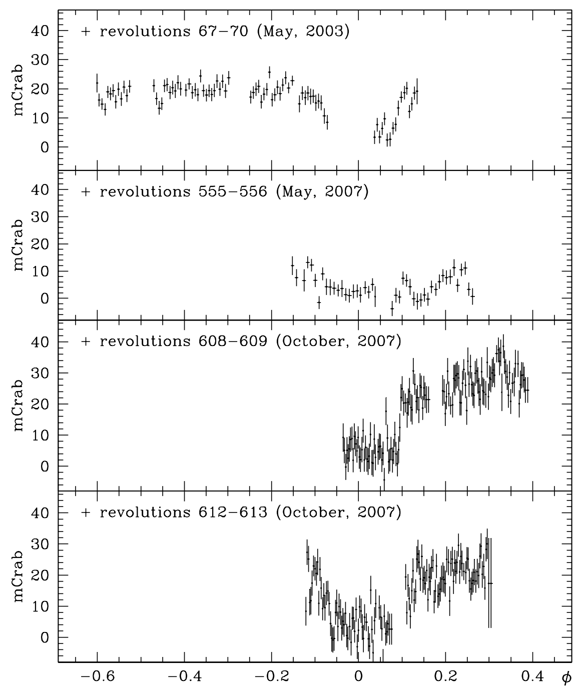

Figure 3: The INTEGRAL primary eclipses of SS433, observed in 2003-2007.

the inclination of the disk with respect to the observer changes, causing different visibility conditions for the "corona". Simulteneous analysis of the precessional and eclipse variability enables us to reconstruct the spatial structure of the region in the accretion disk center where the hard X-rays are produced.

The position of the components of the system relative to the observer is determined by the binary orbit inclination angle $i = 78.8°$, the disk inclination angle to the orbital plane $\theta = 20.3°$, and the precessional phase ψ_{pr}. Phase $\psi_{pr} = 0$ corresponds to the maximum disk opening of SS433 (T3 moment, maximum separation between the moving emission lines).

Free parameters of our model for the orbital and precessional variability of SS433 include: the binary mass ratio $q = M_x/M_v$, the disk parameters r_d, ω, the thick "jets" or "corona" parameters r_j, b_j. For each value of q from the range $0.05 - 1.0$, we found

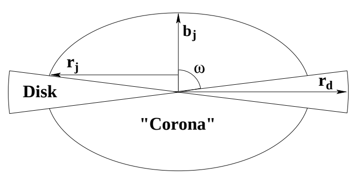

Figure 4: The geometrical model of the accretion disk and its "corona".

other parameters simultaneously fitting the orbital and precession light curves. The precession variability amplitude was assumed to be $A_{pr} \simeq 4$. The χ^2 criterion was used to evaluate the goodness of fits.

The minimum deviation of the model orbital light curve from the observed one is reached for the small mass ratio $q \sim 0.1$ and long X-ray emitting "jets" ($b_j > 0.5$) with the base radius varying in a wide range ($r_j = 0.05 - 0.25$). The main objection to the long "jets" comes from the impossibility to describe the observed precessional variability (see Fig.5). We conclude that at small mass ratio $q \leq 0.2$ our model does not simultaneously fit both orbital and precessional X-ray variability of SS433.

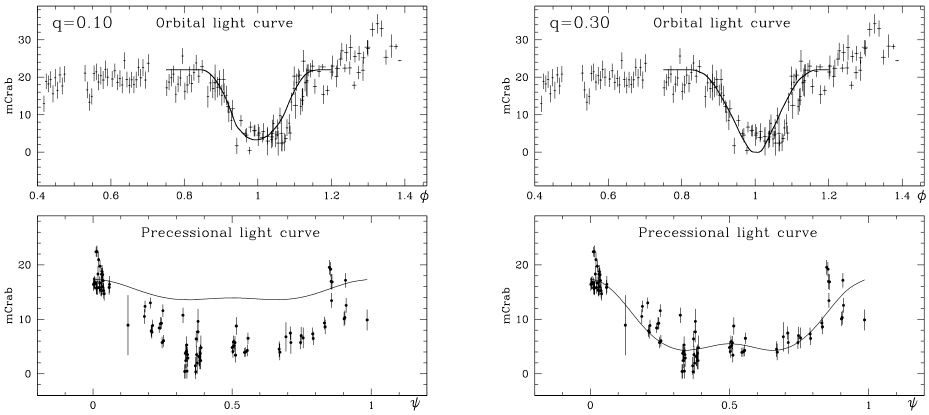

Figure 5: The orbital and precessional light curves of SS433 from INTEGRAL observation with $q = 0.1$ (left panel) and $q = 0.3$ (right panel). It is impossible to simulteneously fit the eclipse and precessional light curves for $q = 0.1$.

At $q = 0.3 - 0.5$ our model provides good fits to both the orbital and precessional light curves of SS433 (see Fig.5). The model parameters correspond to an extended corona comparable to the accretion disk in width ($r_j \sim r_d$) and with small vertical size ($b_j \sim 0.15 - 0.20$).

Using the mass function of the optical star found very recently by Hillwig and Gies (2008) $f_v(m) = 0.26M_\odot$ and the value of $q = M_x/M_v = 0.3 \div 0.5$ inferred from our analysis, we conclude that the masses of binary components of SS433 are $M_x = 4 \div 9M_\odot$, $M_v = 12 \div 20M_\odot$. The high mass of the relativistic object leaves no doubts that it is a black hole.

3. RADIAL VELOCITY SYNTHESIS FOR X-RAY BINARIES

The radial velocity curves of close binary systems provide important data on stellar masses. Usually these curves are considered in the framework of the simplest model, which implies that components of a binary system can be considered material points moving along Keplerian orbits. However, for most close binary systems such an assumption is not valid because very often the observed radial velocity curve does

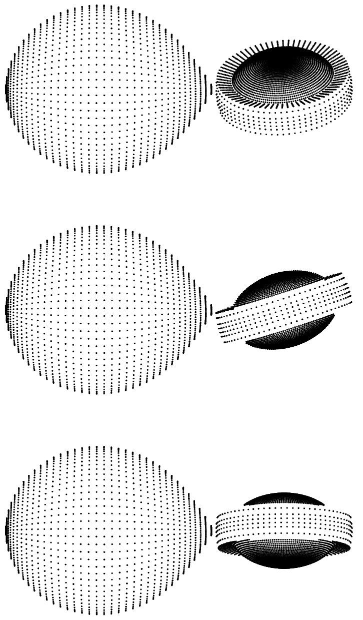

Figure 6: The model view of SS433 for the mass ratio $q = 0.3$ at different precessional phases.

not exactly correspond to the motion of the center of mass. This is due to the following reasons: (i) the distortion of stellar surfaces caused by mutual tidal forces, (ii) non-uniform surface temperature distribution depending upon local gravity and irradiation of stellar surfaces by other component (reflection effect).

The synthesis method gives a possibility to take into account the complicated shape of the components, to calculate physically sound radial velocity curves, and to obtain correct masses of the components. This is especially important for X-ray binaries, in which an additional complication is high level of X-ray heating.

Antokhina and Cherepashchuk (1994) suggested an algorithm for the calculation of the synthetic spectral line profiles and radial velocity curves of close binaries using Kurucz's computational data on stellar line profiles (Kurucz 1992). Later on a new refined computer code for synthesis of line profiles and radial velocities of optical stars in X-ray binary systems was suggested by Antokhina et al. (2005).

The model of a system is treated in the framework of Roche geometry. X-ray heating effects on the stellar surface (by incident radiation from the relativistic object) and calculation of absoption line profiles are done via solution of radiation transfer equiations. The tidal deformation of the optical star and its X-ray heating lead to variations of absoption line profiles with orbital phase. This variability can be used for independent determination of the basic system parameters such as mass ratio of the components q and orbital inclination i.

Fig. 7 shows the variations of the shape and intensity of a model line profile with orbital phase. We can clearly see the evolution of the stellar line profiles as the optical star turns the X-ray heated side toward the observer (at phase 0 the optical star is

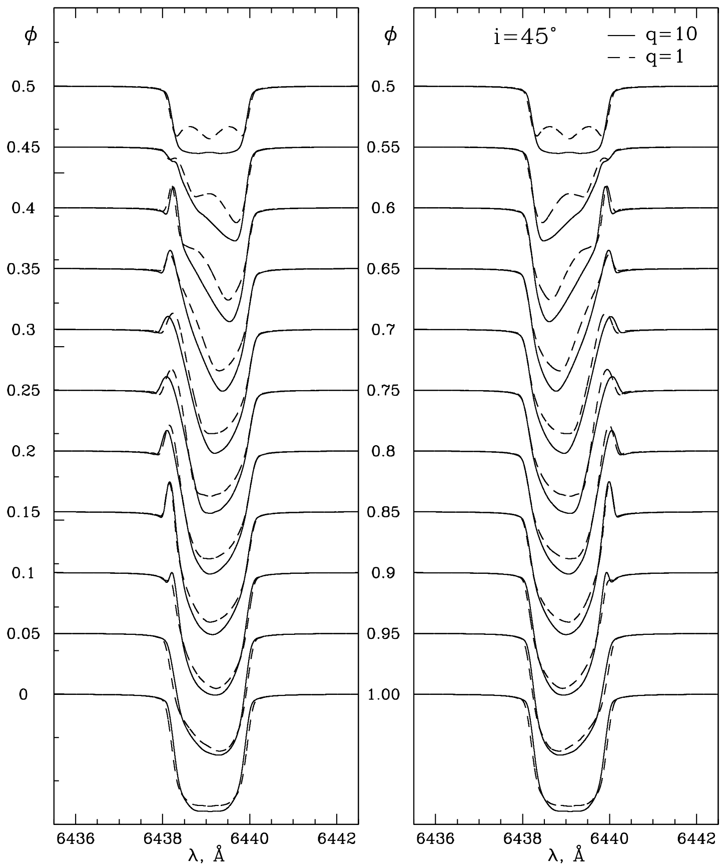

Figure 7: The variations of the CaI λ6439 line profiles in the spectrum of X-ray irradiated star during orbital period.

in front of the X-ray source and the unheated part of its surface is visible). Starting from about $\varphi = 0.1$, we begin to see the part of the star that is heated by external radiation. At $\varphi = 0.25$ (quadrature) the size of the stellar disk is maximal, and both unheated and heated parts of the star are visible. At phase 0.5 the observer can see the part of the star that is heated most by the incident X-ray radiation. After this phase the contribution of the emission feature begins to diminish.

Our method for computing absoption-line profiles for X-ray binary systems taking into account the heating of the stellar atmosphere by the external radiation can be applied to the analysis of the high resolution spectra of optical components in X-ray binaries. This provides additional opportunities for the reliable estimation of the physical parameters, first and foremost, the masses of neutron stars and black holes.

Using this approach, we refined the mass of the black hole in the X-ray binary Cyg X-1 (Abubekerov et al. 2004a) and the masses of neutron stars in the binaries Cen X-3, LMC X-4, SMC X-1, 4U 1538-52 and Vela X-1 (Abubekerov et al. 2004b). From the analysis of the high-quality radial velocity curve of the low-mass X-ray binary 2S 0921-63 (Jonker et al. 2005) we suggest the presence of a massive neutron star rather than a low-mass black hole (Abubekerov et al. 2006). Also we have obtained new estimates of the masses of the components of the Her X-1/HZ Her X-ray taking into account non-LTE effects in the formation of Balmer lines (Abubekerov et al. 2008).

We hope that applying our method to the interpretation of high-resolution spectra ($R \approx 50000$) obtained by large new-generation telescopes will make it possible to obtain more precise estimates of the masses of relativistic objects and to reduce the errors of these estimates.

Acknowledgments

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