Testing accretion disk instabilities in X-ray binaries

Patrycja Bagińska[1], Agata Różańska[1], Agnieszka Janiuk[2] and Bożena Czerny[1]

1. Nicolaus Copernicus Astronomical Center
   Bartycka 18, 00–716 Warszawa, Poland
2. Center for Theoretical Physics
   Al. Lotników 32/46, 02–668 Warszawa, Poland

We study disk instabilities in black hole binaries in which X-ray novae outbursts were observed. Typically, one outburst occurs in each light curve, with total duration from 30 up to 400 days. The shape of an outburst can be very regular fast rise exponential decay (FRED) characteristic for ionisation instability mechanism that occurs in accretion disks, or irregular suggesting that, beside FRED, additional flickering occurs. We use the model which predicts time dependent evolution of ionisation instability in an accretion disk around black hole, assuming viscosity parameter to be proportional to the total pressure. We test it in detail for two objects: GX 339-4 and XTE J1818-245. The modelled light curves agree with the collected RXTE light curves, indicating that disk instability works in those objects.

1 Observations

Soft X-ray transients (SXTs) are the subclass of accreting low-mass X-ray binaries (LMXB) and they spend most of their lifetime in quiescent state as the faint sources. Those kind of objects can be discovered only during outburst phase when they become one of the brightest objects in the X-ray sky. SXTs include neutron star or black hole as a central object and K-type subgiant or dwarf as a secondary star. Typical timescales of outburst are: reccurence time of 0.5-50 yr, rise and decay of an outburst of 2-10 and even to 30-50 days respectively (Mineshige & Wheeler, 1989). Characteristic peak luminosity of SXT is 10^{38} erg/s (Tanaka, 1992) and in quiescence state the luminosity typically is 10^{33} erg/s or even less (Wu et al., 2010). We have found examples of FRED-type outbursts in the X-ray light curves of black hole binaries, obtained by RXTE satellites. In this paper we present data and careful modelling of two objects: GX 339-4 and XTE J1818-245. In data reduction we have used standard HEASOFT ftools [1] described in Blackburn (1995).

2 Ionisation Instability

X-ray novae outbursts are thought to be produced by disk ionisation instability mechanism. It is caused by partial ionisation of hydrogen which occurs in unstable zone located in outer parts of an accretion disk. As a result of instability, disk begins to oscillate between two states: hot and partially ionised state at high local accretion rate,

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[1] http://heasarc.gsfc.nasa.gov/ftools/

Name	M_{BH} [$M_\odot$]	Distance [kpc]	P_{orb} [h]	Outburst [MJD]	Total duration [days]	Rise [days]	Max. [days]	Decay [days]	Ref.
GX 339-4	5.8 ± 0.5	9.0 ± 3.0	42^h1	54120	120	30	15	75	1, 2
XTE J1818-245	$10 \pm 5[a]$	$2.8 - 4.3$	$--$	53595	85	5	1	79	3

Table 1: Observed parameters of two black hole X-ray binaries which exhibit FRED type outbursts probably caused by ionisation instability. [a] indicates that black hole mass is unknown. The distance measurement error was not specified so we assume that it is 10% of the given value. In column named Outburst we have information of the beginning of an outburst in the form of starting date. Presented parameter were taken from: 1) Özel et al. (2010), 2) Dunn et al. (2011), 3) Cadolle Bel et al. (2009)

and cold and neutral state of low local accretion rate. Viscous parameter is crucial in determining instability cycle, and this is known that two viscosity parameters are needed to explain data: α_{hot}, α_{cold}. Parameter α_{hot} forms timescale of an outburst and α_{cold} is responsible for separation between outbursts. Difference between both parameters determines amplitude (Janiuk & Czerny, 2011) of FRED. The timescale of this cycle activity strongly depends on primary star mass (in our case black hole mass). For detailed description see (Janiuk et al., 2004).

3 Model

We compute time evolution of an accretion disk taking into account ionisation instability. In the first step we calculate the stability curve i.e. the sequence of local solutions of the disk vertical structure, plotted on the surface density-temperature plane (the effective temperature is equivalent to the local accretion rate). In the next step this curve is used for solution of radial time dependent equation of motion, producing final total light curve. Results of modelling strongly depend on outer mean accretion rate, viscosity parameters and mass of the central object. In our models we use opacity tables of Alexander (Alexander et al., 1983) and Seaton (Seaton et al., 1994). For 25 masses from 3 to 15 $M_\odot$ and 12 mean accretion rates (from 10^{-9} to 10^{-7} $M_\odot$/yr) we generated the set of light curves showing the behaviour of accretion disk caused by ionisation instability. A constant viscosity model does not represent properly the observed amplitudes of outbursts in many sources (see: Janiuk et al., 2004, and references therein), and therefore we model the instability using different viscosity parameters in the cold and hot states for the disk ($\alpha_{hot} = 0.1$ and $\alpha_{cold} = 0.01$). In further analysis we fit only that instability models which fulfil the mass, luminosity and timescales criteria. For every observed object we have 1800 model computed.

4 Chemical composition

Abundances of metals in the disk are critical during creation of stability curve. We have done calculations for disks with different chemical compositions. We assume different metal abundances In case of solar abundance we have received stability curve which has double feature in instability part. This differs from typical S-curve solution for only hydrogen-helium disk. Double feature can be seen in models which contain larger abundance of metals (in our case this happens for $Z = 0.2$ and $Z = 0.02$). Only exception from that, is the example of helium-rich disk where doubleness did not appear at all, even with small metal abundance. Exemplary stability curves for different abundances are presented in left panel of Figure 1. For hydrogen-rich disk we have reached typical outbursts. For half hydrogen and half helium disks we

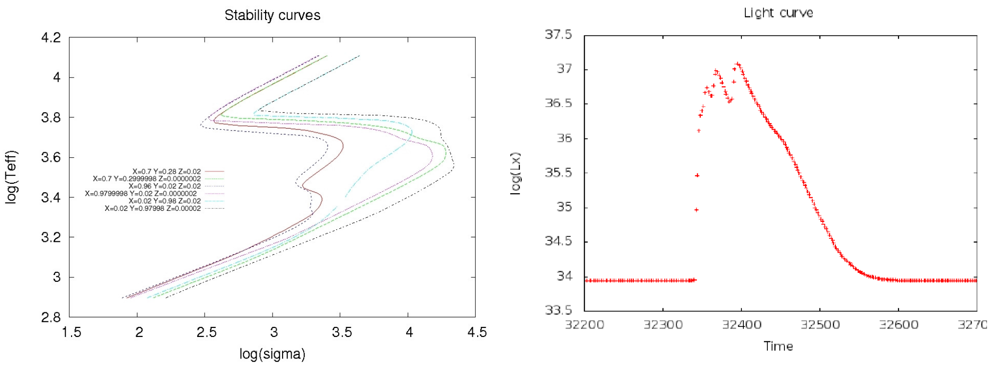

Fig. 1: Left panel displays stability curves i.e. effective temperature versus disk surface density, calculated for different chemical composition for mass $M = 7M_{\odot}$ at radius $R = 10^5 R_{\rm Schw}$. Right panel shows modelled light curve for solar chemical composition.

received symmetric and repeatable outbursts. For helium disks we have got almost FRED-type outbursts and finally for solar-type abundance we have got from chaotic outbursts (for $Z = 0.02$) through symmetric and FRED-like to regular changes in luminosity (for very low $Z = 0.0000002$). From our analysis we can conclude that changes in chemical composition of the disk influence the shape of modelled outburst. In further modelling we used models with solar abundance. The example of modelled light curve is presented in right panel of Figure 1.

5 Results and conclusions

We present the best fitted model to observational data for two SXT objects:

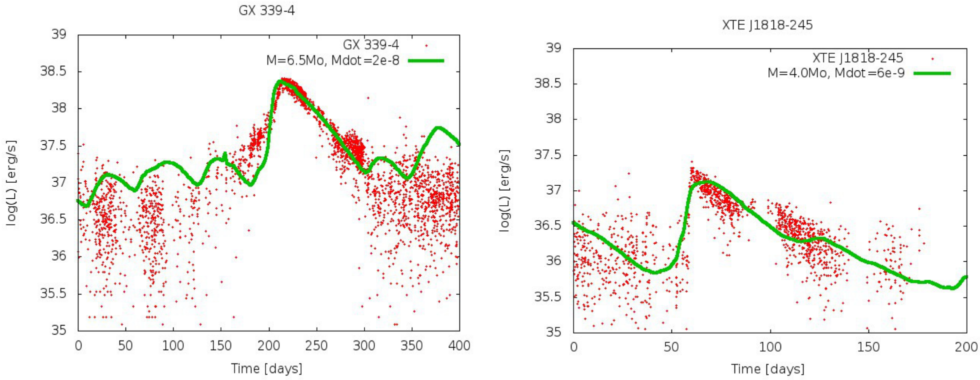

Fig. 2: Preliminary results of fitting our models to observational data for two objects: GX 339-4 and XTE J1818-245. Green solid line represents computed model while red points represent observational data.

GX 339-4 and XTE J1818-245. In case of GX 339-4 according to value of the mass from literature ($5.8 \pm 0.5 M_{\odot}$) we can assume that our fit ($6.5 M_{\odot}$) is consistent with previously determined mass. The mass of XTE J1818-245 was previously unknown and after fitting process we chose as the best fit mass: $M = 4M_\odot$. Figure 2 shows two examples of our analyse. According to the data presented in Table 1, and our best fitted model we conclude that our method allows us to estimate the mass of the central object and accretion rate on the outer part of the disk. This modelling also shows that the ionisation instability is very good explanation for the outbursts in those sources. We can also state that change of the chemical composition (higher amount of metals abundances) explains the stochastic variability pattern.

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