Diagnostics of very early stages of the classical nova explosion by the modeling of its X-ray emission

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Abstract. We present a spherically symmetric model of the interaction of classical nova ejecta with the matter of the companion star stellar wind. We compare its predictions with the data of observations of the unusual bright X-ray transient CI Cam and demonstrate that the outburst in 1998 can be explained as the X-ray emission at early stages of the classical nova explosion in the binary system. The X-ray outburst was observed almost immediately after the start of the motion of the ejecta (within 0.1-0.5 days) which give us the possibility to constrain two parameters of the explosions - the velocity and the mass of the ejecta. We show that the ejecta velocity was $\sim 2700$ km/s and remained at this value over $\sim 2$ day after the beginning of the explosion, that indicates the presence of the external forces acting on the ejecta. The mass of the ejecta was $\sim 10^{-7} - 10^{-6} M_\odot$.

1. Introduction
Classical nova can be a source of the standard ($\sim 2$–10 keV) and hard ($> 20$ keV) X-rays. The most popular model for the generation of the X-ray emission is shock wave model: an envelope (up to $\sim 10^{-4} M_\odot$, Prialnik and Kovetz 2005) expelled from the white dwarf (WD) surface moves in the dense stellar wind of the companion star with high velocities ($\sim 1000$-4000 km/s, Prialnik and Kovetz 2005) and forms the double shock wave structure (Figure 1). The forward shock can heat the matter up to $\sim 5$-80 keV ($h\nu \sim mU^2/2$). The reverse shock can also heat up the matter, but it is weaker and the radiation cooling in the ejecta is very effective; therefore in the following analysis we neglect it and consider the ejecta like a piston of the certain mass. To check the law of envelope expansion one needs observations of the first few hours or even minutes after the explosion beginning, i.e. long before of the maximum of the light curve in the optical band. Observations of the several Nova in hard X-rays in several days after the maximum in the optical band are not enough.

We argue that observations of the unusual X-ray transient XTE J0421+560/CI Cam can give us an opportunity to check models of the envelope expansion during the Nova outburst. More detailed studying can be found in the work of Filippova et al. (2008).

2. Outburst of the system CI Cam
The system XTE J0421+560/CI Cam was discovered as an X-ray transient on 31 March 1998 (Smith et al. 1998). Its properties were dramatically differed from the properties of the ordinary X-ray transients. The system spectrum contained emission lines, which are typical for the emission of the optically thin emission plasma with the temperature of $1$ – $10$ keV (Orr et al.
1998, Revnivtsev et al. 1999). A study of the system emission on the later stages of the evolution (Ishida et al. 2004, Boirini et al. 2002, Mioduzewski and Rupen, 2004) allowed to suggest that this bright outburst ($F_{\text{max}}$ 3–20 keV $\sim$ 2 Crab) is a classical Nova explosion.

An optical companion of the WD is B[e] star of the B4 III-V type (Barsukova et al. 2006). Using parameters from this work we calculate the position of the WD in the binary system at the moment of the explosion: the orbital phase was $\varphi_{\text{orb}}=0.2\mbox{-}0.34$ and the distance between stars was $r = (5.47 - 7.54) \times 10^{12}$ cm (Figure 2, the hatched region).

3. Numerical method

We use a spherically symmetric Lagrangian code with the staggered mesh and artificial viscosity (more detail description can be found in Janka et al. 1993). We take into account the radiation cooling of the matter heated by the shock wave in the optically thin regime.

To obtain the simulated mean temperature of the emission we calculate the ratio of fluxes in the 3–5 and 5–20 keV energy bands, which corresponds to the certain temperature in the model of the one temperature optically thin plasma emission.

For the simplest estimations the volume averaged distribution of the stellar wind density relative to the WD position can be approximated by the constant near WD, which transforms to the $n \sim r^{-2}$ dependence of the density on the distance at $r > r_c$. 

Figure 1. Scheme of the shock waves. D - velocity of the forward shock. U - velocity of the ejecta (read the text).

Figure 2. The companions position in the beginning of the outburst. The hatched region corresponds to the possible position of the white dwarf; grey rings are stellar wind.

Figure 3. Light curve of the system CI Cam in the 3 - 20 keV energy band. Dashed line corresponds to the law of $L_\lambda \sim t^4$.

Figure 4. Dependence of the emission mean temperature on the time.
4. Ejecta velocity
The constant temperature during the first ∼2 days (Figure 4) indicates that the velocity of the ejecta at this time was constant. For the strong shock wave its temperature equals to $kT_1 = 2\mu m_p D^2 \gamma^{-1} \left(\frac{\gamma+1}{\gamma+1}\right)$, where $\gamma$ is an adiabatic index of the stellar wind. For the observed $kT_1$∼10 keV we obtain $D_\sim$ 2900 km/s and, for the constant density, $U_\sim$ 2640 km/s. For the following calculations we adopt $U_\sim$ 2700 km/s. The difference between the mean temperature behind the shock wave and the temperature on the shock wave is illustrated in Figure 5 for different initial densities of the stellar wind (dash-dotted line - $n_0 = 10^{9}$ cm$^{-3}$, long dashed line - $n_0 = 5 \times 10^{9}$ cm$^{-3}$, dashed line - $n_0 = 10^{10}$ cm$^{-3}$). It is clear that if the radiation cooling is low, than our estimations are valid.

5. Density of the stellar wind near WD
Observations indicate that during the rising part of the outburst flux rose as $L_{3-20\text{keV}} \sim 1.1 \times 10^{23} t^{3} d_{2\text{kpc}}^{2}$ erg (Figure 3). If the piston moves with the constant velocity in the medium with the constant density than the luminosity increases as an emissive volume: $L = \Lambda n^{2} \frac{4\pi}{3} (D^3 - U^3) t^3$, so we can estimate the stellar density near WD $n_0(r < r_c) \sim 8.6 \times 10^{9} d_{2\text{kpc}} U^{-3/2} \frac{10^{13}}{2700 \text{km/s}} cm^{-3}$ and $r_c = D t_{\text{peak}} \sim 1.9 \times 10^{13} (t_{\text{peak}}/0.75 \text{day}) D_{3000 \text{km/s}} cm$.

6. Temperature on the later stages of the expansion
When the piston transfers its kinetic energy to the surrounding matter it starts to decelerate and the shock wave begins to move in the Sedov regime where the temperature on the shock wave depends on time as $T \sim t^{-0.66}$ (in the medium with $n \sim r^{-2}$), which is close to the observed law $T \sim t^{-0.7-0.6}$. We find that the mean temperature behind the shock wave in the Sedov regime is also can be approximated by the law of $T \sim t^{-0.6}$, i.e. the shock wave was in the Sedov regime on 4-10 days after the explosion.

7. Mass of the shell
We calculate models where the shell expands freely (Figure 6). These calculations demonstrate, that to have a constant temperature during first 1-2 days after the outburst the shell should be massive, but in order to be decelerated on the later stages of the expansion, the shell should be light enough and first 1-1.5 days should move under the external pressure. From our calculations it follows that several models can describe observations equally well (Figure 7). In these models the time of pushing varies between 1 and 1.5 days, the mass of the shell should be about $10^{-7} - 10^{-6} M_\odot$. 

![Figure 5](image1.png)

Figure 5. Dependence of the mean temperature on time for different initial densities of the stellar wind. Thin solid line - temperature on the shock wave.

![Figure 6](image2.png)

Figure 6. Dependence of the mean temperature on time for different mass of the shell.
Figure 7. Models of the best approximation the observed temperature. Points - observations.

Figure 8. Light curves: solid line - spherically symmetric case, dashed line - disk like structure, points - observations.

8. Light curve approximation
The light curve predicted by one of our best models is presented in the Figure 8. The discrepancy in the decay phase can be result of the non-spherical symmetry of the stellar wind; particularly, it can be followed from the disk-like dense stellar wind of the B[e] star in the equatorial plane. We calculate the qualitative light curve on the phase of the luminosity decay assuming that emission comes from the dense disk with the constant height but dynamics of the shock wave is the same as in the spherically symmetric case. The slope of the luminosity decline in this model is very close to the observed one (Figure 8).

9. Conclusions
(i) the X-ray outburst of the CI Cam system in 1998 can be explained by the model of the classical Nova explosion in the dense stellar wind;
(ii) we have measured the velocity of the shell on 0.1-0.5 day (during first several hours) after outburst \( \sim 2700 \text{ km/s} \);
(iii) the velocity remained approximately constant during first 1-1.5 days, which indicates an importance of the external force acting on the ejecta, e.g., the radiation pressure from the surface of the WD;
(iv) the estimated mass of the ejecta is about \( 10^{-7} - 10^{-6} M_\odot \).

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