On the interplay between the heartbeat oscillations and wind outflow in the microquasar IGR J17091-3624

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Collaboration

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Heartbeat oscillations and wind in the IGR J17091

X-Ray binaries
Our model
Model of wind
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Schedule

- X-Ray binaries
- IGR-J-17091
- Model of accretion disk
- Observational data
- Comparison model-data
- Discussion and conclusions
Cygnus X-1

- First known black hole candidate, discovered by Uhuru X-Ray Satellite/ X-ray Explorer Satellite, SAS-A in 1971
- High-mass X-ray binary system about 6,070 light-years from the Sun that includes a blue supergiant variable star $M = 20M_{\odot}$
- X-ray spectrum of Cygnus X-1 can be characterized as a power law of the photon index $\gamma \sim 1.5 - 1.9$ (Liang Nolan 1984)
- Hard and soft states
GRS 1915+105

- Discover in 1992 by the satellite GRANAT
- Pseudo-superluminal jet expansion (Yadav et. al. 2006)
- Hearbeat variability (Neilsen et. al. 2011)
Heartbeat at the period between 5 and 70 seconds - possible by radiation pressure instability

Moderately bright transient X-ray binary

Peak flux level at 20 mCrab in the range 20 – 100 keV

Discovered by INTEGRAL/IBIS in 2003 (Kuulkers et. al. Astron. Telegram. 149)

Was searched in archival data of previous missions (TTM-Kvant, BeppoSAX)
Microquasar IGR-J-17091-3624

- Refined position of $IGR - J - 17091 - 3624$ provided by Kennea Capitani (2007)
- At the end of January 2011 Swift/BAT reported renewed activity of IGR-J-17091; 28 February 2011 started a long monitoring campaign
- 2011 outbursts increased to 120 mCrab (brightest outburst even observed from that object)
- RXTE/PCA data showed a continuous progression
- IGR-J-17091-3624 presents fast and ionized wind observed during the soft spectral state
- Similarities between IGR-J-17091-3624 and GRS-1915+105 - quasi periodic flare-like events at frequency 25-30 mHz (Altamirano et. al. 2011b, 2011c)
Binary object with black hole at mass $6M_\odot$ (Rebusco et. al. (2012))

Distance - more than 22 kpc ($6.6 \cdot 10^{22} cm$) (D. Altamirano et. al)

Radius of accretion disk - 
$R_{\text{max}} = 7.05 \times 10^{10} - 2.38 \times 10^{11}$ - estimation from orbital period measures (Wijnands et.al (2012))
The upper and lower panels of each frame show a light curve of IGR J17091–3624 and GRS 1915+105, respectively. Count rates are given in 1 s bins, per PCU, 2-60 keV and background subtracted (Altamirano et. al. 2012)
Our model - GLADIS code

- GLADIS Code - 1.5 D - model - approaching in radiation pressure instability
- $\alpha$ - disk.

- non-diagonal term of the stress tensor $T_{r\phi}$ proportional to total (gas + radiation) pressure $P$ (Shakura & Sunyaev)

$$T_{r\phi} = -\alpha p$$  \hspace{1cm} (1)
Physics of the model

We assumed the non-diagonal terms in stress tensor in cylindrical coordinates proportional to the total pressure with a constant viscosity $\alpha$, as introduced by (Shakura, Sunyaev (1973))

$$T_{r\phi} = -\alpha P,$$

(2)

where $P$ is pressure.

If we consider a thin disk that has an energy loss connected only with horizontal flows, local energy loss in the disk per unit volume per unit time is given by:

$$\frac{\partial F}{\partial z} = T_{r\phi} \partial_r v_\phi$$

(3)
and the dimensionless accretion rate is

$$\dot{m} = \frac{\eta \dot{M} c^2}{L_{Edd}} = \frac{\dot{M}}{\dot{M}_{Edd}}$$  \hspace{1cm} (4)$$

Here $\eta$ is efficiency of accretion, equal to $1/16$ in the pseudo-Newtonian approximation. The final formula for the viscous energy dissipation is:

$$\frac{\partial F_{tot}}{\partial z} = \alpha P \partial_r v_{\phi}$$  \hspace{1cm} (5)$$
Physics of the model - pressure

The equilibrium pressure consists of gas and radiation pressure

\[ P = P_{\text{gas}} + P_{\text{rad}} \]  \hfill (6)

where we assume that gas is an ideal gas of protons of mass \( m_p \)

\[ P_{\text{gas}} = \frac{\rho k_B}{m_p} T \]  \hfill (7)

and the radiation pressure is given by

\[ P_{\text{rad}} = \frac{4\sigma_B}{3c} T^4 \]  \hfill (8)
We consider here the model of vertically averaged disk (effectively, 1.5-dimensional model, as the motion in the angular direction is also accounted for). In the simplest possible stationary case, we close the equations by an energy conservation equation

\[ F_{\text{tot}} = Q_+ = Q_- \]  

(9)

where the total flux locally emitted from the surface of the accretion disk is given by the global parameters:

\[ F_{\text{tot}} = \frac{3GM\dot{M}}{8\pi r^3} f(r) \]  

(10)
where \( f(r) \) is given by the boundary condition on the inner edge of accretion disk. The vertically averaged viscous heating rate in the disk is

\[
Q_+ = \frac{3}{2} \alpha PH \Omega K
\]  

(11)

and the radiative cooling rate per unit time per surface unit is

\[
Q_- = \frac{4\sigma_B T^4}{3\kappa \Sigma}.
\]  

(12)

where \( \kappa \) is the electron scattering opacity which equal to 0.34 cm\(^{-2}\) g\(^{-1}\).
The outbursts of accretion disks may be induced by the two main types of instabilities which lead to the thermal-viscous oscillations - radiation pressure instability and ionization instability - more discussed in (Janiuk, Czerny 2011).

In our model we assume disk with radiation pressure which may leads to radiation pressure instability.

For our parameters disk is stable for $\dot{m} > 0.036$. 
1.5 D hydrodynamics - mass, angular momentum and energy conservation

In the time-dependent model we solve the full set of equations of hydrodynamics. We consider a model of thin disk, so in the conservation of mass (continuity) equation we neglect z-behaviour of density and velocity fields:

\[ \frac{\partial (\Sigma v_r)}{\partial r} + r \frac{\partial \Sigma}{\partial t} = 0 \]  

(13)

The mass conservation equation is

\[ \frac{\partial \Sigma}{\partial t} = \frac{1}{2\pi r} \frac{\partial (-2\pi r \Sigma v_r)}{\partial r} \]  

(14)

The angular momentum conservation is included in following equation

\[ \dot{M} \frac{d}{dr} (r^2 \Omega) = - \frac{\partial}{\partial r} (2\pi r^2 T_{r\phi}) \]  

(15)

We define \( \nu \) as the kinematic viscosity \( T_{r\phi} = \alpha PH = (3/2)\Omega \nu \Sigma \).
From mass and angular momentum conservation equations (14,15) and the kinematic viscosity definition we obtain the final formula on the evolution of the surface density of disk (Janiuk, Czerny 2002):

\[
\frac{\partial \Sigma}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( 3r^{1/2} \frac{\partial}{\partial r} \left( r^{1/2} \nu \Sigma \right) \right) \tag{16}
\]

\[
\nu_r = -\frac{3}{\Sigma} r^{-1/2} \frac{\partial}{\partial r} \left( \nu \Sigma r^{1/2} \right) \tag{17}
\]

We also have the energy conservation equation (Janiuk, Czerny 2002)

\[
\frac{\partial \ln T}{\partial t} + \nu_r \frac{\partial \ln T}{\partial \ln r} = \frac{4 - 3\beta}{12 - 10.5\beta} \left( \frac{\partial \ln \Sigma}{\partial \ln r} - \frac{\partial \ln H}{\partial \ln r} + \nu_r \frac{\partial \ln \Sigma}{\partial \ln r} \right) + \frac{Q_+ - Q_-}{(12 - 10.5\beta)PH} \tag{18}
\]
The mass loss rate (propably in the vertical direction) is equal to the ratio of the locally generated flux in the accretion disk, with a fraction determined by $f_{\text{out}}$, to the energy change per particle, $\dot{m}_z = F_{\text{tot}}(1 - f_{\text{out}})/(\Delta E/m_p)$. The local flux is given by the Equation 10 of the standard accretion disk theory

$$f_{\text{out}} = 1 - \frac{1}{(1 + A\dot{m}^2)} \quad (19)$$
We assume that this relation holds also in the hydrodynamical computations. The energy change per particle is on the order of virial energy, $\Delta E = B k T_{\text{vir}} = \frac{B G M}{r}$, with $B \sim 1$, so expressing the mass loss rate in terms of local variables, in the units of $[\text{g s}^{-1} \text{ cm}^{-2}]$, we have a final formula:

$$
\dot{m}_z(r) = B \frac{3}{4} \frac{1}{r} \Sigma v_r f(r)f_{\text{out}}
$$

(20)

with $f_{\text{out}}$ given by Equation 19.
Figure: *Chandra* ACIS-S HETG spectra for observation 12406 (*upper panel*) and 12405 (*lower panel*) in the 6-7.5 keV energy range. The wind components observed in observation 12406 are completely undetectable in observation 12405, if we assume that the wind density is a factor of 10 lower.
Figure: The time-line sketch created from the Swift/XRT and RXTE/PCA data analysis, showing the correlation of the wind and heartbeat presence in IGR J17091, superimposed to the Swift/BAT 15-50 keV light curve. The second Chandra observation (second green arrow) shows a fast, ionized wind, while the first XMM-Newton observation (first red arrows) and the first Chandra observation (first green arrow) lie in the heartbeat zone and does not show any detectable wind outflow. During the last XMM-Newton observation, the source is in hard state.
Obtaining the observational data

- SWIFT mission
- X-Ray data from thermal radiation of the disk - XRT
- 0.2 – 10 keV
- FITS files archives
- HEASOFT - High Energy Astrophysics SOFTware v.6.15
- XRT pipeline
- XSELECT extracting
Observational data

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SWIFT XRT observation no. 31921041

rate [counts/s]
time [s]

Heartbeat oscillations and wind in the IGR J17091
In order to characterise the wind in the Chandra observations, we prepared two tables with the photoionization code Cloudy C13.02. From the best fit values of the ionization parameter \( \xi = L_{\text{ion}} / n r^2 \), assuming the \( L_{\text{ion}} = 3.7 \times 10^{37} \) erg s\(^{-1} \), we get \( n_1 r_1^2 \simeq 1.5 \times 10^{34} \) and \( n_2 r_2^2 \simeq 5.8 \times 10^{33} \) cm\(^{-1} \) for the two wind components, respectively. The corresponding (spherical) mass outflow rates would be

\[
\dot{M}_{\text{wind}} \simeq 1.23 m_p f v \Omega n r^2
\]  

\( (21) \)

where \( m_p \) is the proton mass (the 1.23 correction factor comes from assuming cosmic elemental abundances), \( \Omega \) is the covering factor and \( f \) the filling factor. The absence of emission lines suggests \( \Omega/4\pi \simeq 0.5 \) 2012ApJ...746L..20K, so our estimated mass outflow rates are:

\[
\dot{M}_{\text{wind}1} \simeq 1.8 \times 10^{20} f_1 \ g \ s^{-1}  
\]  

\( (22) \)

\[
\dot{M}_{\text{wind}2} \simeq 1.2 \times 10^{20} f_2 \ g \ s^{-1}  
\]  

\( (23) \)
Filling factors $f_1$ and $f_2$ are difficult to estimate.

We can assume that extension of wind is comparable to launching radius and we have $N_H = fnr$

It leads to $r_1 \approx 1900r_g$ and $r_2 \approx 760r_g$ correspondingly to $n_1 \approx 5.1 \times 10^{15}$ cm$^{-3}$

Resulting filling factors are $f_1 \approx 0.0015$ and $f_2 \approx 0.0037$

Resulting wind components $\dot{M}_{wind1} = 2.7 \times 10^{17}$ and $4.2 \times 10^{17}$ and $\dot{M}_{wind2} = 2.7 \times 10^{17}$ and $4.2 \times 10^{17}$
For $\dot{M} > 0.04$ radiation pressure instability lead to outbursts.
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Regularity and grid

| $N_p$ | period | error | variance | duration of outburst | error | variance | $N_o$ |
|-------|--------|-------|----------|----------------------|-------|----------|-------|
| 25    | 441.163| 52.7  | 341.63   | 10.682               | 0.384432| 2.5209   | 44    |
| 30    | 684    | 77.9  | 397.3    | 29.2857              | 3.81897| 19.8076  | 27    |
| 40    | 1199   | 47.6  | 184.4    | 57.0582              | 2.8143 | 11.2537  | 16    |
| 50    | 1342   | 43.8  | 158.0    | 70.664               | 3.4465 | 12.8924  | 15    |
| 75    | 1381   | 21.1  | 76.0     | 76.6695              | 2.1083 | 7.8827   | 14    |
| 100   | 1402   | 18.5  | 64.2     | 78.5713              | 2.0588 | 7.42309  | 13    |

Resulting heartbeat outbursts modeled with different grids. First column $N_p$, gives the number of grid points. Last column, $N_o$, gives the number of outbursts in time interval of 20 ks.
Parameters of model displayed on the animations

- Mass $6M_\odot$
- Wind parameter $A$ between 0 and 100
- Accretion rate between 0.04 and 0.1 Eddington rate
Profile of density

Log density time = 0.01 s

-4

-3.5

-3

-2.5

-2

-1.5

-1

-0.5

0

-1

-1.1

-1.2

-1.3

-1.4

-1.5

-1.6

-1.7

-1.8

-1.9

-2

-2.1

-2.2

-2.3

-2.4

-2.5

-2.6

-2.7

-2.8

-2.9

-3

-3.1

-3.2

-3.3

-3.4

-3.5

-3.6

-3.7

-3.8

-3.9

-4

-5

1

1.5

2

2.5

3

Log [r (R_g)]
Profile of temperature
Grid of models

- Mass $6M_\odot$
- Wind parameter $A$ between 0 and 100
- Accretion rate between 0.04 and 0.1 Eddington rate
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Regularity and grid
Behaviour of disk
Profiles of density
Profile of temperature
Grid of models
With or without wind

Figure: Lightcurve without wind

Figure: Lightcurve with wind
Mass loss

To obtain the total mass loss in the wind, we integrate $\dot{m}_z$ over the disk:

$$\Delta \dot{M}_{\text{wind}} = \int_{R_{\min}}^{R_{\max}} \dot{m}_z 4\pi r dr$$

We assumed different $R_{\min}$ and $R_{\max} = 40000 R_{Schw}$ (for mass equal to 6 Solar masses, it gives $R_{\max} = 7.08 \cdot 10^{11}$ cm). The actual mass loss will be on this order, or somewhat smaller, as the wind particles may be accelerated to obtain kinetic energy not necessarily equal to the virial energy, but rather to have a velocity a few (2-3) times their escape velocity at the radius r. Here we therefore may calculate the upper limit for the wind column density, depending on our model parameter $A$. 

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Value of wind mass loss is changing in time due to outbursts. Averaging the solutions, we obtain total mass loss caused by wind at the level of $\Delta \dot{M}_{\text{wind}} = 3 \times 10^{16} - 2 \times 10^{17}$ g/s.
We calculate the wind density at $R_{max}$

$$\rho_{\text{wind}} = \frac{\dot{M}_{\text{wind}}}{4\pi R_{\text{max}}^2 v_{\text{esc}}}$$

(25)

where $v_{\text{esc}}$ is the escape velocity at $R_{max}$. In our best-fit model, the density of the wind is equal between $\rho_{\text{wind}} = 2 \times 10^{-16}$ and $gcm^{-3}$ and $7.2 \times 10^{-16}$. 
Column density of wind of protons

Assuming that wind consists of protons, we calculate the column density of the (spherically symmetric) wind:

\[ \int \rho_{\text{wind}}(\mathbf{r}) \, d\mathbf{r} = \rho_{\text{wind}}(R_{\text{max}}) R_{\text{max}}. \]  

(26)

Observable column number density of particle is given by formula

\[ N_H = \rho_{\text{wind}} R_{\text{max}} (f m_p)^{-1} \]  

(27)

Where \( f \) is the filling factor in principle unknown and constrained from the observations of wind and we finally obtain the estimated value at the range between \( N_H = 4.89 \cdot 10^{21} \) cm\(^{-2}\) and \( 1.62 \cdot 10^{22} \) cm\(^{-2}\).
For the radii below $\sim 70$ Schwarzschild radii, the dependence of $m_2(r)$ derived from Eq. (19) is a complicated function.

At larger radii it scales with radius as a simple power law with index $-1.8$.

After integration we have:

$$\dot{M}_{\text{wind}}(r, R_{\text{max}}) = 1.635 \times 10^{16} (R_{\text{max}}^{0.2} - r^{0.2}) \ [\text{g s}^{-1}]$$

(28)

First wind component with mass loss rate of about $\dot{M}_{\text{wind}1} = 2.5 \times 10^{16} \ \text{g s}^{-1}$ with launching up to $R_{\text{max}} \approx 4900 R_{\text{Schw}}$.

The second wind component, with $\dot{M}_{\text{wind}2} = 3.9 \times 10^{16} \ \text{g s}^{-1}$, should be launched up to $R_{\text{max}} \approx 5900 R_{\text{Schw}}$. 
The resulting wind mass loss rate and density, for assumed wind strength parameter \( A = 15 \) and several values of accretion rate, are summarized in table below. The column density is calculated assuming \( f_1 = 0.0015 \) wind extension \( R_{\text{max}} = 40000 R_g \).

\[
\begin{array}{|c|c|c|c|}
\hline
R_{\text{min}} & \dot{M}_{\text{wind}} [\text{g s}^{-1}] & \rho_{\text{wind}} [\text{g cm}^{-3}] & N_H [\text{cm}^{-2}] \\
\hline
3 & 2.18 \times 10^{17} & 2.0 \times 10^{-16} & 5.66 \times 10^{21} \\
70 & 8.84 \times 10^{16} & 3.9 \times 10^{-16} & 1.10 \times 10^{22} \\
150 & 7.68 \times 10^{16} & 5.0 \times 10^{-16} & 1.07 \times 10^{22} \\
350 & 6.04 \times 10^{16} & 7.1 \times 10^{-16} & 2.00 \times 10^{22} \\
2000 & 3.06 \times 10^{16} & 7.2 \times 10^{-16} & 2.04 \times 10^{22} \\
\hline
\end{array}
\]
Wind parameter and disk stability

- With $A = 300$, a stable disk solution is found in our simulations, while the mass loss rate $\dot{M}_{\text{wind}}$ is about $\sim 12$ times higher, than in the case of our heartbeat model with $A = 15$.
- Strong wind definitely stabilizes the heartbeat oscillations. There is a clear observable signature
- Taking the values of the wind velocities and mass loss rates such as those in the first *Chandra* observation, we obtain the observable wind launching zones of $950 – 4200$ and $380 – 4700$ Schwarzschild radii, for the first and second wind component.
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Spectral modeling

- Our wind density for accretion rate \( \dot{m} = 0.1 \) is included in the brackets of than results from the King et al., (2012), ApJL, 746, 20 obtained by spectral modelling
- Column density is modeled by the Fe absorption lines
- Fe XXV line 6.92 keV - outflow velocity 9300 km s\(^{-1}\)
- Fe XXVI line 7.32 keV - even higher velocity
Discussion

- Wind also exists in non-heartbeat and heartbeat states.
- In heartbeat states, it is ten times fainter.
- The mass outflow is $2.7 \times 10^{17}$ g s$^{-1}$ for the two wind components observed in the stable state, and about $2.5 \times 10^{16}$ g s$^{-1}$ in the heartbeat state.
- Wind ejection partially stabilized the disk.
- There are two components of wind.
- First component occurs between $\sim 380$ and $4700-5900$ $R_g$.
- Second component occurs between $\sim 950$ and $4200-4900$ Schwarzschild radii.
- Total mass loss rate $\dot{M}_{\text{wind}}$ in these two components will be of the order of $\lesssim 4 \times 10^{16}$ g s$^{-1}$ during the heartbeat oscillation.
- In non-heartbeat states, wind rate is $\lesssim 4 \times 10^{17}$ g s$^{-1}$.
Our final conclusions are as follows:

- The heartbeat oscillations of the X-ray luminosity of IGR J17091 detected during its outburst in 2011 are attributed to the radiation pressure instability of the accretion disk.
- The outflow launched from the disk on the cost of the part of the locally dissipated energy flux is plausible mechanism to regulate the amplitude of these oscillations.
- The strong outflow may stabilize the disk and suppress the heartbeat completely.
Our final conclusions are as follows:

- The observed properties of the wind detected from IGR J17091 in the state without the heartbeats allowed us to constrain the mass loss rate at large distances in the disk.
- The wind from the accretion disk, postulated by our model to stabilize the disk, is important in the innermost parts.
- In the spectroscopic observations, it may not always be detectable due to its high ionisation state or the velocities below the
- The MHD mechanism is rather driving the formation of a quasi-static, bound corona above the disk.
- We demonstrated that the observed winds are in good agreement with the scenario described by our model.
Thank you for attention