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Monitoring of pulse period in Her X-1 with *Swift/BAT*: evidence of mass ejection

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Monitoring of pulse period variations in accreting binary pulsars is an important tool to study the interaction between the magnetosphere of the neutron star and the accretion disk. While the X-ray flux of the brightest X-ray pulsars have been successfully monitored over many years (e.g. with RXTE/ASM, CGRO/BATSE, Swift/BAT), the possibility to monitor their pulse timing properties continuously has so far been very limited. In our work we use Swift/BAT observations to study one of the most enigmatic X-ray pulsars, Hercules X-1. For the first time, a quasi-continuous monitoring of the pulse period and the pulse period derivative of Her X-1, is achieved over a long time (> 4 yrs). We argue that together with the long-term decrease of the orbital period in Her X-1 the measured pulse period behaviour requires the presence of mass ejection from the inner parts of the accretion disk along the open magnetic field lines. The mass ejection episodes probably take place during strong spin-down episodes which are associated with the low X-ray luminosity.

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1. Introduction

The persistent accreting pulsar Hercules X-1 was one of the first X-ray sources discovered by the *Uhuru* satellite in 1972 (Tananbaum et al. 1972; Giacconi et al. 1973) and since then it remains one of the most intensively studied X-ray pulsars. The mass of the optical companion is $\sim 2 M_{\odot}$ which places the system in the middle between high and low mass X-ray binaries. Other main parameters of the binary system are the following: orbital period $P_{\rm orb} \simeq 1.7$ days, spin period of the neutron star $P_{\rm spin} \simeq 1.24$ sec, X-ray luminosity of the source $L_{\rm X} \sim 2 \times 10^{37}\,{\rm erg\,s^{-1}}$ for a distance of ~7 kpc (Reynolds et al. 1997). The binary orbit is almost circular (Staubert et al. 2009) and has an inclination $i \sim 85-88^{\circ}$ (Gerend & Boynton 1976).

Like many other X-ray pulsars Her X-1 exhibits significant variation of the pulsation period. Alternation of spin-up and spin-down episodes on time-scales of several months in this system is superimposed on a background of systematic spin-up (e.g. Staubert et al. 2006; Klochkov 2007). The behavior of the pulsar's spin period on shorter time scales is not very well studied because such a study would require a continuous monitoring of Her X-1 with a sensitive X-ray detector. Only between 1991 and 2000 the *BATSE* instrument onboard *CGRO* provided the information about the source's pulse period on a regular basis.

In this work we present a continuous monitoring of the Her X-1 pulse period P and its local (measured at the time of the observation) time derivative $\dot{P}$ using the *Swift/BAT* instrument starting from 2005 (begin of scientific operation) to 2009. The data of the monitoring allowed us to explore for the first time the correlation between the *locally* measured $\dot{P}$ and the X-ray flux of the pulsar and compare the results with predictions of the accretion theory. The observed strong spin-down episodes are discussed in the frame of a model assuming ejection of matter from the inner part of the accretion disk along the open magnetic field lines.

2. Observations and data analysis

For our analysis we used the public archival data obtained with the **B**urst **A**lert **T**elescope (*BAT*, 150–150 keV, Barthelmy et al. 2005) onboard the *Swift* observatory (Gehrels et al. 2004). With its large field of view (1.4 sterad) the *BAT* instrument is originally designed to provide fast triggers for gamma-ray bursts and their accurate positions in the sky (~4 arcsec). Following such a trigger, the observatory points in the direction of the burst, which can be then observed with the X-ray and UV/optical telescopes onboard the satellite. While searching for bursts, *BAT* points at different locations of the sky, thus, performing an all-sky monitoring in hard X-rays (measurements of the X-ray flux are provided by the *Swift/BAT* team in the form of X-ray light curves for the several hundred bright persistent and transient sources[1]). If a bright pulsating source with a known period falls into the field of view of the instrument, the total count rate stored by *BAT* can be used to search for coherent pulsations of that source. We have used this strategy to measure the 1.24 s pulsations of Her X-1 during its so-called *main-on* states (when the X-ray flux of the source is high). Such states repeat every ~35 days and are believed to be caused by a precessing tilted accretion disk around the neutron star, see e.g. Gerend & Boynton 1976.

[1]http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/

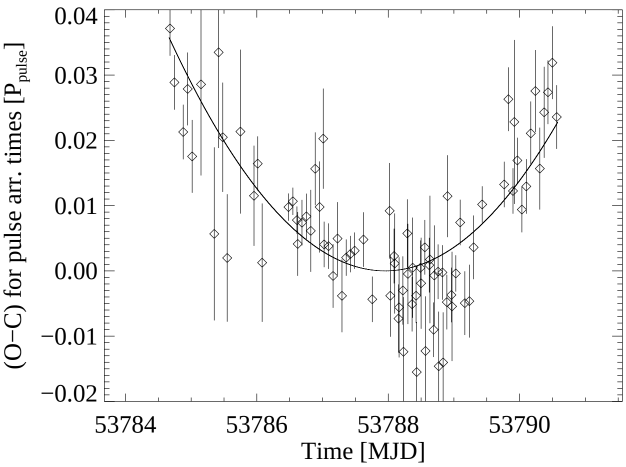

Figure 1: Estimated (observed) minus calculated (assuming a constant period) pulse arrival times of Her X-1 in units of its pulse period during one of its main-on states observed with *Swift/BAT*. Parabolic fit to the data shown with the solid line corresponds to a constant positive $\dot{P} \simeq 1.4 \times 10^{-12}$ s/s.

To determine the pulse period, we used the method similar to that described by Staubert et al. (2009) which includes two techniques for the determination of the period: *epoch folding* with χ^2 search (e.g. Leahy et al. 1983) and *pulse phase connection* (e.g. Deeter et al. 1981). The first one is used to establish the presence of the periodic signal from Her X-1 in the *BAT* data, determine the approximate period, and construct pulse profiles (by folding the data with the found period), while the second is subsequently applied to the pulse profiles to determine the precise value of the period and its time derivative.

For our analysis we used the total count rates measured by *BAT* with a time resolution of 64 msec. All times of the count rates were translated to the solar system barycenter and corrected for binary motion (using our newest orbital ephemeris presented in Staubert et al. 2009). Then we performed a period search using *epoch folding* in a narrow period interval around the expected pulse period (~1.237 s). If a strong periodic signal is present we determined the period and used it to construct X-ray pulse profiles for subsequent *pulse phase connection*.

A convenient way to explore the variation of the pulse period, often used in phase-connection technique, is to construct the so-called $(O-C)$ diagram showing the estimated (observed) pulse arrival time minus the calculated one assuming a constant period. An example of such a diagram measured with *BAT* during one of the Her X-1 main-on states is shown in Fig. 1. A straight line in the graph would correspond to a constant period defined by the slope of the line. The solid curve indicates the parabolic fit to the data corresponding to a constant positive $\dot{P}$.

3. Results

Using the method described in the previous section we determined the pulse period P and its time derivative $\dot{P}$ for most of the Her X-1 main-on states observed with *BAT*. For other parts of the 35 d cycle, i.e. outside main-ons, the flux was too low for such determinations. At the time of preparing this text the data are available for the time period from March 2005 to May 2009 that covers 45 35d cycles of the pulsar. For several cycles the *BAT* observations have relatively poor statistics due to gaps in the data. For such cycles only P, but no $\dot{P}$ could be determined.

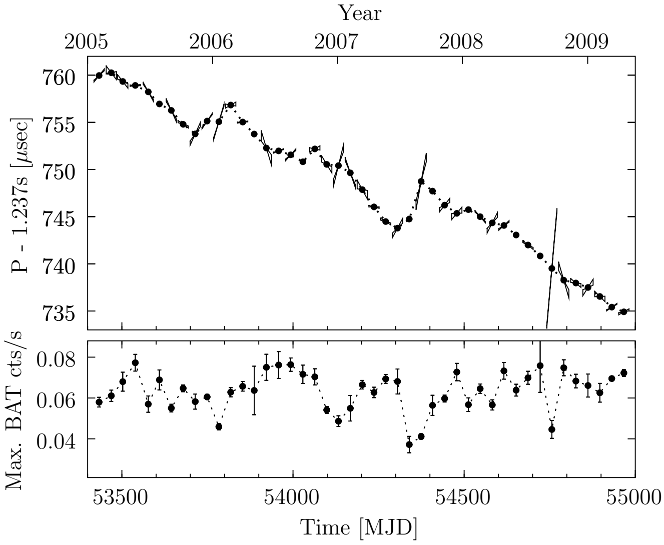

Figure 2: Top: Pulse period P of Her X-1 measured with *Swift/BAT* as a function of time. The cones around each point indicate the allowed range of the slope corresponding to the measured $\dot{P}$ and its uncertainties. Measurement errors of the period itself are smaller than the symbol sizes. **Bottom:** Maximum *Swift/BAT* count/rate in the respective main-on state.

The time evolution of the measured pulse period of Her X-1 is shown in Fig. 2 together with the X-ray flux in the respective main-on states. Where a corresponding value of $\dot{P}$ was measured, the 1σ-uncertainty range is indicated by the cones, the orientation of which reproduce the measured $\dot{P}$ value.

One can see, that for many points the locally measured $\dot{P}$ is substantially different from the one derived from P values of adjacent measurements (that is from the slope of the pulse period development). Thus, one can conclude that strong pulse period variations in Her X-1 occur on shorter time scales than the 35 d super-orbital period of the system.

Already in Fig. 2 one can notice that the strong spin-down episodes occasionally exhibited by Her X-1 and lasting from 1 to 3 main-ons are mostly coincident with drops in the X-ray flux. This behavior can also be demonstrated by plotting values of $\dot{P}$ versus X-ray flux (Fig. 3). The data indicate an anticorrelation as predicted by the basic accretion theory. Inspection of the linear Pearson's correlation coefficient gives the probability of $\sim 4\times 10^{-4}$ to find the measured correlation by chance.

The correlation is mainly driven by the group of four points with high spin-down rate and low flux (in the upper left part of the graph in Fig. 3). The rest of the points forms an uncorrelated "cloud" around $\dot{P} = 0$. This means that most of the time the pulsar is close to the equilibrium regime, when spin-up and spin-down torques are nearly balanced. Sometimes, however, it switches to strong spin-down accompanied by strong decrease of the X-ray flux. Such a behavior needs further explanation. In the next section we argue that the episodes of strong spin-down are associated with strong matter outflow from the inner parts of the accretion disk. The mass transfer rate through the accretion disk does not need to change significantly.

4. Evidence for the coronal mass ejection

If one assumes that the accretion disk carries some magnetic field, it can interact via reconnection with the neutron star's magnetosphere beyond the corotation radius R_c. This might imply that beyond R_c the field lines can sometimes inflate to become open (see also discussion in Lovelace

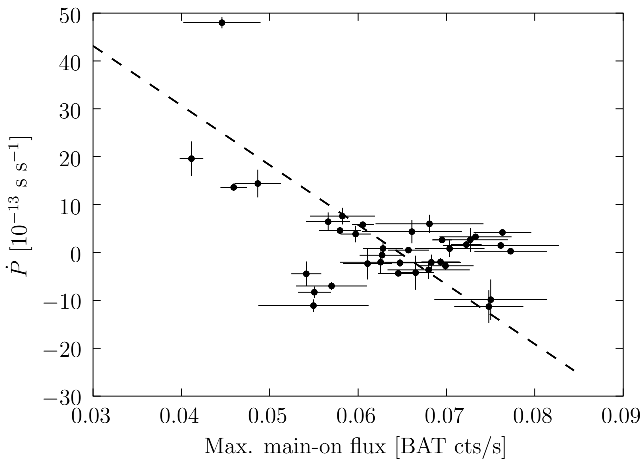

Figure 3: The locally measured time derivative of the pulse period, $\dot{P}$, in Her X-1 versus the maximum X-ray flux during the main-on state as determined from the *Swift/BAT* data. A linear fit (taking uncertainties of both variables into account) is shown with the dashed line.

et al. 1995). During such episodes, a substantial fraction of matter in the inner part of the accretion disk can escape the system in the form of a coronal wind ejection along the open field lines.

Such an ejection of matter should be reflected in a secular change of the system's orbital period which is indeed observed in Her X-1 (Deeter et al. 1991; Staubert et al. 2009). To assess the importance of coronal mass ejections for the orbital period evolution, we invoked general considerations of the non-conservative treatment of binary orbital parameters (see e.g. Grishchuk et al. 2001). First, we defined the non-conservativeness parameter in the standard way (e.g. Ritter & Kolb 1992): $\eta = -\dot{M}_x/\dot{M}_o \leq 1$, ($\dot{M}_o < 0$). Assume that the ejected mass carries away the specific angular momentum of the neutron star we express the fractional change of the orbital period through $\dot{M}_x/M_x$, q and η:

$$\frac{1}{3}\frac{\dot{P}_{\rm orb}}{P_{\rm orb}} = -\frac{\dot{M}_x}{M_x}\left[1-\frac{q}{\eta}-\left(1-\frac{1}{\eta}\right)\frac{q/3+1}{q+1}\right], \quad (4.1)$$

where M_x is the mass of the accretor, $\dot{M}_x$ is the accretion rate onto the neutron star, $q = M_x/M_{\rm opt}$ is the binary mass ratio.

It is convenient to normalize the mass accretion rate onto the neutron star $\dot{M}_x$ to the value that can be derived from the observed fractional change of the orbital period in the conservative case $(\dot{M}_x)_{\rm cons}$, so that $\dot{m} \equiv \dot{M}_x/(\dot{M}_x)_{\rm cons}$. In Her X-1 $q \simeq 0.63$ and one finds $(\dot{M}_x)_{\rm cons} \simeq 8\times10^{17}$ g s^{-1} for the measured $\dot{P}_{\rm orb} = -4.85\times10^{-11}$ s s^{-1} (Staubert et al. 2009). Then we can eliminate $\dot{P}_{\rm orb}/P_{\rm orb}$ from the left hand side of Eq. (4.1) to obtain the equation for η at a given $\dot{m}$:

$$\eta = \frac{q^2+2q/3-1}{(q^2-1)/\dot{m}+2q/3}. \quad (4.2)$$

From here we see that $\dot{m} < 1$ leads to $\eta < 1$, i. e. if one wants to decrease the mass accretion rate onto the neutron star to get smaller X-ray luminosity (as is the case of Her X-1, where the mean observed $L_x \sim 2\times10^{37}$ erg s^{-1} is 4 times smaller than the one following from the conservative mass exchange analysis, Staubert et al. 2009), a non-conservative mass exchange is required. Specifically, if we want to bring in accordance the observed $\dot{P}_{\rm orb}$ and $L_{\rm X}$ in Her X-1, we would need $\dot{m} \simeq 1/4$ and (from Eq. 4.2) $\eta \sim 0.1$, a fairly high non-conservative mass exchange.

In the frame of our model, the mass ejection from the system through the open magnetic field lines occurs most efficiently during strong spin-down episodes which are associated with small X-ray luminosity. Indeed, as we see in Fig 3, the observed X-ray flux is decreased by a factor of two during strong spin-down. From Eq. (4.2) it is easy to find that at a given q a fractional decrease in $\dot{m}$ leads to comparable fractional decrease in η, i.e. accretion indeed becomes more non-conservative during strong mass ejection episodes. During such episodes, the neutron star spin-down power $I\omega\dot{\omega}$ is spent to expel accreting matter from the inner disk radius $R_d \sim R_c$:

$$I\omega\dot{\omega} \sim \dot{M}_{\rm ej}\frac{GM}{R_c}\,. \tag{4.3}$$

This equation is satisfied for the observed parameters of Her X-1: ejected mass rate during strong spin-downs $\dot{M}_{\rm ej} \sim 0.5\dot{M}_x \simeq 10^{17}\,{\rm g\,s^{-1}}$, $\dot{P} \simeq 10^{-12}\,{\rm s\,s^{-1}}$, and $R_c \simeq 1.3\times10^8$ cm.

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