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Quasi-periodic variations of the ~ 35 d period in Her X-1

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Abstract

Her X-1 shows a quasi-regular modulation of its flux on a ~ 35 d period, generally explained by the precession of the accretion disk which regularly blocks the view to the X-ray emitting regions near the magnetic poles of the neutron star. In tight synchronization a variation of the shape of the 1.24 s pulsation is observed, the physical origin of which is debated: precession of the neutron star or effects related to the the inner rim of the accretion disk are being discussed. Here we study the long-term behavior of the 35 d modulation using all observed "turn-ons" observed in the 40 years since the discovery of the source. The period of precession appears to change quasi-regularly on a time scale of a few years with an indication of a long-term period of repetition of ~ 15.5 years.

Introduction

Her X-1

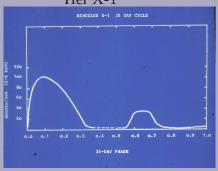

FIGURE 1: Scetch of 35 d flux modulation

The general 35 d flux modulation of Her X-1 is shown in Fig. 1: with a "Main-On" and a "Short-On", separated by two "Off" states. Being an eclipsing binary with an orbital period of 1.70 d, the flux is reduced to near zero every orbit for about six hours. Fig. 2 shows a mean light curve generated by folding many 35 d cycles (with phase 0.2 turn-ons) observed with the *RXTE*-All Sky Monitor (the folding is done such that eclipses fall on top of each other, see Klochkov et al. 2006). With the discovery of Her X-1 as a pulsating X-ray source by *UHURU* in 1972 (Giacconi et al. 1973) also the 35 d flux modulation was found and it was realized that the underlying clock was rather unstable. The timing behavior of this clock is usually described by the $(O-C)$-diagram, which plots the difference between the *observed* and the *calculated* (under the assumption of a constant period) turn-on times. For the constant period usually $P_{35} = 20.5 \times P_{orb}$ is used (e.g. Staubert et al. 1983, Staubert et al. 2006). An up-todate version of the $(O-C)$ diagram is shown in Fig. 3.
Here we report on two aspects of the turn-on clock: 1) the period of precession of the accretion disk is changing its value on time scales of a few years between values *above* and values *below* the mean period of 34.89 d. 2) There seems to be a long-term period of ~ 15.5 yrs modulating the precessional period in a nearly sinusoidal way.
We also point to the following three correlations of the turn-on clock with other clocks in the system:
1) All observed *Anomalous Lows* (AL) happened at a minimum in $(O-C)$ (with separations of ~ 5 yr or ~ 10 yr (see Fig. 3 and 4).
2) $(O-C)$ correlates strongly with the evolution of the 1.24 s pulse period (see Fig. 10).
3) The shape of the 1.24 s pulse profile varies with 35 d phase in strict coherence with $(O-C)$ (see Fig. 11).

Her X-1 – RXTE/ASM

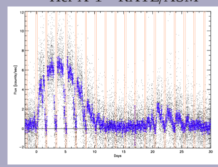

FIGURE 2: Folded 35 d light curve

Turn-On clock / the $(O-C)$ diagram

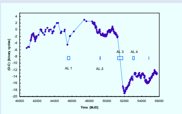

FIGURE 3: Turn-On history of Her X-1: $(O-C)$ diagram with respect to the ~ 35 d period.

Variations in the period of the 35 d modulation. The $(O-C)$ diagram: observed turn-on minus calculated turn-on, under the assumption of a constant period $P_{35} = 20.5 \times P_{orb} = 34.853$ d (Fig. 3). Note the strong change around AL3, which has been explained by an exceptionally low period of precession (Staubert et al. 2009). For the purpose of a rough turn-on ephemeris, one cyle during AL3 is suppressed in Figs. 4 and 5. For selected periods of time, mean 35 d periods were calculated (Fig. 5) and listed in the following Table (see also Still & Boyd 2004).

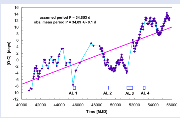

FIGURE 4: Modified $(O-C)$ diagram ("jump" at AL3 removed)

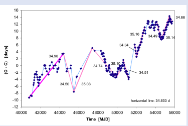

FIGURE 5: Modified $(O-C)$ diagram with piecewise linear fits: values are precession period in days.

Table of mean 35 d periods over selected time intervals

35 d cyc nos.	MJD	interval [years]	period [days]	+/- [days]
-15–84	40797–44260	9.5	34.98	0.01
88–119	44400–45470	3.0	34.50	0.01
119–174	45470–47400	5.3	35.08	0.01
174–247	47400–49935	7.0	34.74	0.01
247–267	49935–50637	1.9	35.10	0.03
267–283	50637–51189	1.5	34.51	0.03
301–307	51826–52032	0.6	34.27	0.17
307–331	52032–52877	2.3	35.16	0.04
341–365	53226–54063	2.3	34.85	0.03
367–381	54133–54616	1.3	34.49	0.04
381–405	54616–55460	2.3	35.14	0.02
405–413	55460–55737	0.8	34.66	0.04

Attempts to determine a long-term period in $(O-C)$

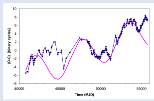

FIGURE 6: Modified $(O-C)$ diagram with fitted linear+sine function

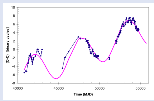

FIGURE 7: Same as Fig. 6, reduced data set used for the fit.

Fitting the $(O-C)$. Suppressing one cycle during AL3 leads to the modified $(O-C)$ diagram in Fig. 4, which allows to define a rough turn-on ephemeris by a linear fit: the overall long-term mean period is 34.89 ± 0.1 d.
The complete curve can roughly be modeled by combining a linear and a sinusoidal function. For this fit the selected data shown in Fig. 7 were used. The mangenta curve is the best fit function with a sinusoidal period of 5700 d~15.6 yr (also shown in Fig.6).
We note that the larger deviations of the observed data points from the sinusoidal fits appear to repeat to lie at the minima of the cosine curve.

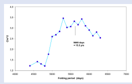

FIGURE 8: χ^2 distribution for the period search with the complete $(O-C)$ data set

Period search by folding. Fig. 8 shows the χ^2 distribution for the period search with the complete (modified) $(O-C)$ data set. A broad maximum is found around a trial period of 5660 d~15.5 yr.

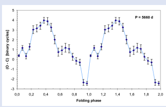

FIGURE 9: Profile of the long-term $(O-C)$ variation for a period of 15.5 years

Long-term profile for the variation of the period of accretion disk precession. Fig. 9 gives the profile found by folding the complete (modified) $(O-C)$ data with a period of 15.5 yr.

Correlation of $(O-C)$ with other obsarvables in the Her X-1 system

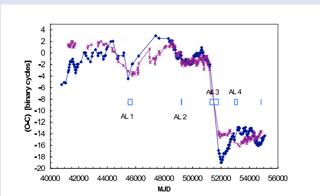

FIGURE 10: Turn-On history (blue squares) and inverted and scaled pulse period residuals (purple crosses).

Here we like to point to the following three correlations of the turn-on clock with other clocks in the Her X-1 the system:
1) All observed *Anomalous Lows* (AL) happened at a minimum in $(O-C)$ (with separations of ~ 5 yr or ~ 10 yr, see Fig. 3 and 4). *Anomalous Lows* (AL) appear only when $(O-C)$ is on the "downward-leg" towards a minimum (never at a maximum). The "downward-leg" is associated with a short precessional period, in turn probably associated with a smaller inclination of the accretion disk with respect to the orbital plane.
2) $(O-C)$ correlates strongly with the evolution of the 1.24 s pulse period. Fig. 10 shows $(O-C)$ together with a representation of the evolution of the pulse period (pulse period residuals against the linear spin-up trend, inverted and scaled to the modulation of $(O-C)$). This correlation can be understood as the result of strong feed-back mechanisms between the accretion process and the neutron star (Staubert et al. 2009).
3) The shape of the 1.24 s pulse profile varies with 35 d phase in strict coherence with $(O-C)$ (Fig. 11). It is evident that the two histories track each other quite closely. This suggests, that the variation of pulse shape may be associated with conditions in the accretion disk, most likely the inner edge of the accretion disk. If it is assumed that the variation in pulse profile shape is due to precession of the neutron star (Trümper et al. 1986, Shakura et al. 1999), then one needs to explain how the neutron star can change its period of precession (on rather short time scales of ~100 d) and how the accretion disk precession can be so tightly coupled to the precession of the neutron star (see discussion by Staubert et al. 2011).

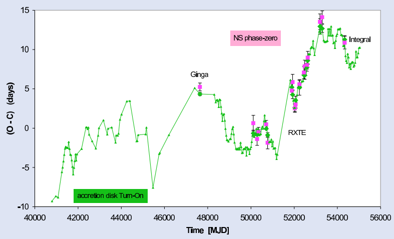

FIGURE 11: (O-C) values for all observed Turn-Ons (green) and for so far generated "pulse profile phase-zero" values from pulse profile fitting (mangenta).

Summary

The Her X-1 turn-on clock, as represented by the $(O-C)$ diagram, is not stable. However, it does not vary chaotically or according to a *random walk process* (as assumed early on e.g. by Staubert et al. 1983), but shows quasi-periodic variations on a time scale of a few years and a likely long-term modulation at a period around 15.5 yr.

The Her X-1 turn-on clock shows strong correlations to three other observables in the Her X-1 system: the appearance of *Anomalous Lows*, the evolution of the 1.24 s pulse period and with the reproducible changes of the shape of the pulse profiles with 35 d phase.

The combined physical modeling of the observed phenomena and their respective correlations should lead to an improved understanding of the physics at work in Her X-1, in particular, whether we can really assume that there is precession of the neutron star, and if so, what is the physical reason for it.

References

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