On the nature of the 35-day cycle in
HZ Her/Her X-1*

N. I. Shakura\textsuperscript{1,2}, D. A. Kolesnikov\textsuperscript{1}, and K. A. Postnov\textsuperscript{1,2}

\textsuperscript{1}Sternberg Astronomical Institute, Moscow State University, 119234
Moscow, Russia
\textsuperscript{2}Kazan Federal University, 420008 Kazan, Russia

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Abstract

Regular variations of the pulse period of Her X-1 with X-ray flux observed by
\textit{Fermi}/GBM are examined. We argue that these regular variations result from free
precession of the neutron star in Her X-1.

Among outstanding discoveries of the 1960s, the most bright is the discovery of
accreting black holes and neutron stars in close binary stars made by the \textit{Uhuru}
X-ray satellite. Her X-1 is one of the first X-ray pulsars discovered. It is a magnetized
accreting neutron star (NS) in a 1.7-day orbit with the Roche-lobe filling optical star
HZ Her \cite{1}. The NS mass is \( m_x = 1.4 \, M_\odot \), the NS spin period is \( P_x = 1.24 \, \text{s} \). The mass
of HZ Her is \( m_o = 2.0 \, M_\odot \).

The optical brightness of HZ Her demonstrates a significant modulation with the
orbital period of \( P_b = 1.7 \, \text{d} \). This modulation is due to a strong irradiation effect of the
donor star \cite{2,3}. The X-ray light curve of Her X-1 shows sharp eclipses because of the
high inclination of the binary system to the line of sight, about 90°.

In X-ray binaries similar to HZ Her/Her X-1, the mass transfer from the optical
component to the compact star occurs through the inner Lagrangian point to form a
turbulent near-Keplerian accretion disk around the compact object. Due to turbulent
viscosity, the matter in the disk loses the angular momentum and slowly approaches
the central object. The heat released during accretion is radiated from the disk surface.
In Her X-1, at a distance of \( \sim 100 \, R_{NS} \) from the center, the NS magnetic field breaks the
disk, and at lower distances the matter freely falls along the magnetic field lines towards
the NS surface and stops near the magnetic poles. Near the surface, the velocity of the
infalling matter is close to one third of the speed of light. During the collision, the huge
kinetic energy of the accreting plasma is transformed into heat and is radiated away in
X-rays.

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Soon after the discovery of the X-ray source in 1971 [1], a 35-d modulation of the X-ray flux from Her X-1 was discovered by the Uhuru satellite [4]. The 35-day X-ray cycle of Her X-1 comprises four states: (1) the Main-on lasting for \(\sim 7\) orbits with the highest X-ray flux; (2) the first low state lasting for \(\sim 4\) orbits; (3) the Short-on lasting for \(\sim 4\) orbits with the X-ray flux about three times as low as in the Main-on; (4) the second low-state lasting for \(\sim 4\) orbits (see, e.g., [5] for more detail and [6] for the recent update).

The 35-d X-ray cycle is associated with a tilted, retrograde precessing accretion disk. In the middle of the Main-on and Short-on, the disk is maximum open to the observer, and the central X-ray source is visible. During the low states, the outer parts of the tilted disk block the X-ray source. Recent observations by the SRG/eROSITA telescope during the low states of Her X-1 revealed the orbital variations of the X-ray flux [7]. The analysis of a large amount of the optical photometric data of HZ Her [8, 9] independently supports the presence of such a disk.

On the other hand, the model of free precession of the neutron star has been suggested as the possible explanation of 35-d X-ray cycle [10, 11, 12]. The EXOSAT observations showed that the X-ray pulse profiles of Her X-1 change during the 35-d cycle [13]. Later on, the Ginga and RXTE observations were used to study in detail the evolution of X-ray pulses with the 35-day phase [14, 15, 16].

The RXTE observations of Her X-1 suggest that the observed evolution of X-ray pulses could be explained by free precession of a NS with complex surface magnetic field [17]. The NS free precession is also able to explain the optical light curves of HZ Her [18, 19]. In this model, a more stable 35-day NS free precession period serves as a clock mechanism of the entire 35-day cycle via synchronization of the disk precession period by the action of gas streams forming the outer parts of the disk [20]. Possible synchronization mechanisms are further discussed in [18, 19].

As shown for the first time in [21], the NS free precession should be accompanied by small (about several microseconds) regular variations of the observed pulse period. These variations are clearly detected in the Fermi/GBM data[1].

The observable pulse frequency is a sum of non-periodical and periodical variations:

\[
\omega_o(t) = \omega_{ns}(t) + \frac{d\phi(t)}{dt}
\] (1)

As seen from Fig[1], the NS free precession should modulate the observed pulse frequency. The angle \(\phi\) can be found from sine and cosine theorem for spherical triangles:

\[
\cos \phi(t) = \frac{\sin b \sin \psi(t)}{\sqrt{1 - (\cos a \cos b + \sin a \sin b \cos \psi(t))^2}}
\] (2)

Here \(a = 50^\circ\) is the side of the spherical triangle connecting the NS spin and inertia axes, \(b\) is the side of the spherical triangle connecting the NS inertia axis and the magnetic pole, \(\psi(t)\) is the NS free precession angle linearly depending on time:

\[
\psi(t) = \Omega t + \psi_0
\] (3)

[1]https://gammaray.nsstc.nasa.gov/gbm/science/pulsars/lightcurves/herx1.html
Figure 1: Scheme of the NS free precession. The NS rotational equator is in the picture plane, the NS spin axis (R) is perpendicular to the figure plane. The dashed line indicates the path of the north magnetic pole (N) path of the freely precessing NS. The center of the dashed circle coincides with the NS principal momentum of inertia (I). The sides of the spherical triangle RNI are $a = 50^\circ$ and $b = 30^\circ$. $\psi$ is the free precession angle. The time derivative of the angle $\phi$ defines the pulse frequency variation.

Here $\Omega$ is the NS free precession angular frequency. The function $\omega_0(t)$ is shown in Fig. 2.

However, the Fermi/GBM pulse frequency measurements show high-amplitude irregular variations. Fig. 2 shows that the observed Fermi/GBM variations agree with theoretical behaviour of $\omega_0(t)$.

So far we have supposed only two-axial NS free precession. However, in Her X-1 a triaxial NS free precession is also possible [22].

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Figure 2: The measured pulsar frequency of Her X-1 as a function of time. Black dots show the Fermi/GBM measurements. Only points with errors smaller than 0.1 µHz are shown. The solid line indicates theoretical variation of the pulsar frequency due to NS free precession, Eq. 1. The slow drift of the pulsar frequency on timescale longer than 35 d can be due to possible irregular variations in the NS free precession parameters.
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