**Insight-HXMT insight into switch of the accretion mode: the case of the X-ray pulsar 4U 1901+03**

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**Abstract**

We use the *Insight*-HXMT data collected during the 2019 outburst from X-ray pulsar 4U 1901+03 to complement the orbital parameters reported by *Fermi*/GBM. Using the *Insight*-HXMT, we examine the correlation between the derivative of the intrinsic spin frequency and bolometric flux based on accretion torque models. It was found that the pulse profiles significantly evolve during the outburst. The existence of two types of the profile’s pattern discovered in the *Insight*-HXMT data indicates that this source experienced transition between a super-critical and a sub-critical accretion regimes during its 2019 outburst. Based on the evolution of the pulse profiles and the torque model, we derive the distance to 4U 1901+03 as 12.4 ± 0.2 kpc.

**Keywords:** accretion, accretion disk – pulsars: general – pulsars: individual(4U 1901+03)

1. Introduction

Binary systems hosting neutron stars (NSs) are among the most powerful X-ray sources in our Galaxy. The binary systems with a massive stellar companion, usually an O or B star, are characterized as high mass X-ray binaries (HMXBs). The X-ray emission from HMXBs is due to the transfer of matter from the companion star and the accretion onto the NS. If NS in such system possesses strong magnetic field (of the order of 10^{12} G or even stronger), they exhibit themselves as X-ray pulsars (XRP; see Walter et al. [2015] for a recent review). The properties of emission registered during...
bright outbursts from the transient XRPs provide an insight into the physics of accretion and transfer of torque to the NS (Ghosh & Lamb 1979; Wang 1987; Zhang et al. 1996).

The high-mass X-ray binary 4U 1901+03 was discovered by Uhuru and Vela 5B in 1970-1971 (Forman et al. 1976; Fridhorsky & Terrell 1984). Galloway et al. (2005) reported results of the RXTE observations performed during an outburst in 2003 when the peak flux reached $8 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ in 2.5–25 keV. They detected a clear pulsatins with a spin period of $\sim 2.763$ s, and obtained the orbital ephemeris, where orbital period is 22.58 days, based on the Doppler effect caused by the motion in the binary system. After a long quiescence state, MAXI/GSC found a new outburst in 2019, with a peak flux of $\sim 200$ mCrab (Nakajima et al. 2019).

In this paper we report the results of the timing analysis of emission from 4U 1901+03, such as binary parameters, making use of the Insight-HXMT data as a complement to Fermi/GBM results (P. Jenke, in prep). The pulse profiles of the NS at different luminosity states are reported as well. In addition, we investigate the spin-up rate and the accreting torque during the outburst, and estimate the distance of the source according to theoretical torque models. The methods for the data reduction and analysis are presented in section 2. The obtained results are discussed in the frame of theoretical models in section 3.

2. Data analysis and results

To analyze the evolution of intrinsic spin frequency and flux during the recent outburst, we utilize the data from the Fermi/Gamma-ray Burst Monitor (GBM), the Swift/Burst Alert Telescope (BAT), and the Insight-Hard X-ray Modulation Telescope (Insight-HXMT).

Swift/BAT is a hard X-ray transient monitor providing near real-time coverage of the X-ray sky in the energy range 15–50 keV (Krimm et al. 2013). It provides the flux evolution of 4U 1901+03 in 15–50 keV during the whole outburst. For the Swift/BAT data, we selected the Daily light curves from MJD 58520 to MJD 58649. Also we performed multiple follow-up observations of the source with Insight-HXMT started from MJD 58573 to MJD 58644.8. With 36 observations carried out by the Insight-HXMT, the total exposure time is about 150 ks. The Insight-HXMT provides a broad band energy coverage in 1–250 keV (Zhang et al. 2014; Zhang et al. 2017). The time resolution of three instruments, the high energy instrument (HE) (Liu et al. 2019), the medium energy instrument (ME) (Cao et al. 2019), and the low energy instrument (LE) (Chen et al. 2019) on-board the Insight-HXMT are 2 $\mu$s, 20 $\mu$s, and 1 ms, respectively. The Insight-HXMT provides information about the flux and the temporal properties of 4U 1901+03. The frequency evolution and the frequency derivative could have continuous results in the case that the Fermi/GBM provides a continuous observation.

2.1. Data reduction

Scientific data for the timing and spectral results, are obtained from the reduction of the Insight-HXMT raw data. The methods of data reduction for the Insight-HXMT were introduced in previous publications (see e.g., Huang et al. 2018; Chen et al. 2018). We summarize the procedures of using the Insight-HXMT Data Analysis Software package (HXMTDAS) version 2.0.1 here:

1. Use the commands hepical, mepical, lepical in HXMTDAS to calibrate the photon events from the raw data according the Calibration Database (CALDB) of the Insight-HXMT.
2. Select the good time intervals (GTIs) for calibrated photons, using hegtigen, megtigen, and legtigen.
3. Extract the good events based on the GTIs using the commands hescreen, mescreen, and lescreen.
4. Generate spectra for selected photons using the commands hespecgen, mespecgen, and lespecgen.
5. Generate the background spectra based on the emission detected by blind detectors using the commands hebkgmap, mebkgmap, and lebkgmap.
6. Generate the response matrix files required for spectral analysis using the commands herpesgen, mespresgen, and lepresgen.

We apply strict criteria to create the GTI file used for spectral analysis. We set the parameters Earth elevation angle (ELV) greater than 10 degrees, the cutoff rigidity (COR) greater than 8 GeV, the offset angle from the pointing source (ANG_DIST) less than 0.04 degrees. We also exclude the photons collected 300 s before enter and after exit the South Atlantic Anomaly (SAA) region. However, in order to optimize the count statistics required for timing analysis, less strict criteria for filtering events are applied. Particularly, we select the time intervals when ELV $> 0$ and the satellite is not in the

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1https://swift.gsfc.nasa.gov/results/transients/index.html
SAA region. The total effective exposure time for Insight-HXMT after data screening is about 84.3 ks.

The arrival times of photons from the Insight-HXMT data are corrected to the Solar system barycenter using the HXMTDA8 commands hxbary. The coordinates of the source are taken as (J2000): RA=19h03m39.42s, Dec=+03d 12' 15.8'" [Halpern & Levine 2019].

2.2. Timing analysis

In Figure 1 the bolometric lightcurve of 4U 1901+03 based on the Swift/BAT data is presented. The count rate provided by Swift/BAT in 15–50 keV band was converted to match the flux calculated using spectra from Insight-HXMT. Due to dependence of spectral shape on the source flux, one conversion factor is not enough to make the Swift/BAT flux matches the Insight-HXMT fluxes well. Thus the conversion factors were estimated for different time intervals as $1.9 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ for the data before MJD 58580, $1.7 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ for the data between MJD 58580 and MJD 58597, $1.8 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ for the data after MJD 58597. These factors convert the Swift/BAT count rate in unit of cnt cm$^{-2}$ s$^{-1}$ to the flux in the units of erg cm$^{-2}$ s$^{-1}$. The background subtracted spectra from the Insight-HXMT data were analyzed in the 1–150 keV band. The more detailed spectral analysis based on the Insight-HXMT data is ongoing and will be published elsewhere.

The bolometric flux was estimated from fitting the broadband Insight-HXMT spectrum in 0.1–150 keV band as follows:

1. Fit each spectrum in 1–150 keV with a model TBabs*cutoffpl in XSPEC (v12.10.0c).
2. Expand the energy range to 0.1–150 keV for response matrix using the command energize.
3. Freeze the best fitted normalization value of the model cutoff power law.
4. Add cflux component in order to calculate an unabsorbed flux from the cutoffpl model in 0.1–150 keV energy band.

The photon index and the e-folding energy of exponential rolloff in the cutoffpl for the very first observation of Insight-HXMT are 0.46 and 7.08 respectively. The flux in 0.1–150 keV can serve as a good estimate for the bolometric flux of an XRP.

The preliminary orbital parameters of 4U 1901+03 are presented in the GBM Accreting Pulsar Histories project. Here we report the spin frequency obtained by the Insight-HXMT to complement the available Fermi/GBM measurements (P. Jenke, in prep). The spin period in each Insight-HXMT observation was calculated using an epoch-folding technique [Leahy 1987]. Uncertainty for the spin period were roughly estimated from the width of $\chi^2$ distribution for the trial periods. The observed frequencies obtained by the Insight-HXMT combine the intrinsic spin frequency of the NS and effect of the Doppler shift due to the binary motion (see black squares in Figure 2). As seen from Figure 2 the frequency evolution is modulated by an almost sinusoidal function. To calculate the intrinsic spin frequency of the NS we apply method described in Galloway et al. (2005). Here we outline the method of the corresponding calculations. The observed frequencies could be written as,

$$f(t) = f_{\text{spin}}(t) - \frac{2\pi f_{\text{doppler}} \sin i}{P_{\text{orb}}} (\cos l + g \sin 2l + h \cos 2l),$$  \hspace{1cm} (1)

where the first term $f_{\text{spin}}(t)$ is the intrinsic spin frequency of the pulsar, and the second term is the frequency modulation due to the binary motion. $f_0$ is a constant approximating $f_{\text{spin}}(t)$, $a_X \sin i$ is the projected orbital semi-major axis in units of light seconds, $i$ is the system inclination, $P_{\text{orb}}$ is the orbital period in unit of days, $g = e \sin \omega$, $h = e \cos \omega$ are functions of eccentricity $e$ and longitude of periastron $\omega$. And $l = 2\pi(t - T_{\text{orb}})/P_{\text{orb}} + \pi/2$ is the mean longitude. The reference time $T_{\text{orb}}$ is when the mean longitude $l = \pi/2$, where the NS is behind the companion.

The $f_{\text{spin}}(t)$ was described by a third order polynomial

\footnotesize
2https://gammaray.msfc.nasa.gov/gbm/science/pulsars.html
The residuals between frequency model and data are presented in the bottom panel. The blue line indicates the best fit polynomial function to the intrinsic frequency. The residuals between frequency model and data are presented in the bottom panel.

function,

\[ f_{\text{obs}}(t) = f_0 + \dot{f}(t-t_0) + \frac{1}{2} \ddot{f}(t-t_0)^2 + \frac{1}{6} \dddot{f}(t-t_0)^3 \] (2)

where \( f_0 \) is the frequency at reference time \( t_0 \). We arbitrarily select \( t_0 \) as the beginning of the Insight-HXMT observation of the source. And \( f, \dot{f}, \ddot{f}, \dddot{f} \) are the first, second, and third order derivatives of intrinsic frequency, respectively. Using Equation (1) we fit the joint data set consisting of the Fermi/GBM and Insight-HXMT data. In Figure 2, the observed frequency from the Insight-HXMT and Fermi/GBM data are plotted in black and red squares, respectively. The blue circles in the top panel correspond to the intrinsic frequency from the Fermi/GBM, while the residuals for the Insight-HXMT data set are presented with blue circles. The intrinsic spin frequencies for the black and red squares, respectively. The blue circles in the top panel correspond to the intrinsic frequency from the Fermi/GBM, while the residuals for the Insight-HXMT data set are presented with blue circles.

Table 1: Temporal parameters for 4U 1901+03

| Parameter | GBM results | GBM+HXMT results |
|-----------|-------------|-------------------|
| \( P_{\text{orb}} \) (days) | 22.5347777 | 22.534371(11) |
| \( a \chi \sin i \) (lt s) | 104.343 | 104.236(39) |
| \( e \) | 0.0150 | 0.01443(35) |
| \( \omega \) (deg) | 220.10 | 220.034(25) |
| \( T_{\pi/2} \) (MJD) | 55927.26871 | |
| \( f_0 \) (Hz) | - | 0.36204843(13) |
| \( f \) (Hz s\(^{-1}\)) | - | 1.833(16)e-11 |
| \( \dot{f} \) (Hz s\(^{-2}\)) | - | -1.89(11)e-18 |
| \( \ddot{f} \) (Hz s\(^{-3}\)) | - | -1.3e-26 |
| \( t_0 \) (MJD) | - | 58563.3290883878 |
| \( \chi^2/\text{dof} \) | - | 154/109 |

As can be seen, the shape of the pulse profiles evolves with energy. In hard energy band 27–150 keV covered by the HE instrument the profile remains narrow single peaked, while for the ME and LE instrument, the pulse profiles vary from double peak shapes to broad single peaked. The pulse profile depends on the flux as well. The averaged fluxes in time intervals T1, T2, and T3 are 4.7 × 10^-9 erg cm\(^{-2}\) s\(^{-1}\), 3.0 × 10^-9 erg cm\(^{-2}\) s\(^{-1}\), and 1.7 × 10^-9 erg cm\(^{-2}\) s\(^{-1}\), respectively. In the T1 interval, pulse profile in 10–30 keV range is double peaked. When the luminosity decreases, the pulse profile change to a broad single peaked in T2 and T3 intervals. For the profiles in 2–10 keV the variations are similar. Particularly, in the T1 interval a double peaked shape is detected. And single peaked profiles are detected in the T2 and T3 intervals.

The pulsed fraction of each profile are calculated by \( \Sigma (\text{flux per bin - minimum per bin}) \) divided by the total flux. In the time interval T1, the pulsed fractions for LE, ME, and HE are 0.12, 0.032, 0.015, respectively. Similarly, in the time interval T2, the pulsed fractions are 0.068, 0.032, 0.017. In the time interval T3, the pulsed fractions are 0.008, 0.02, 0.01. The pulsed fractions decrease with energy in the time interval T1, and T2. In
3. Discussion and conclusion

In this work, we investigate the temporal evolution of the coherent X-ray pulsations shown by 4U 1901+03 during its outburst in 2019, using the Fermi/GBM frequency results and the whole data set collected by the Insight-HXMT. The orbital parameters and the intrinsic timing parameters are obtained (see Table 1). The pulse profile evolution with luminosity and energy observed by the Insight-HXMT are presented as well. Using the long-term monitoring of the source we searched for a possible propeller effect reported by Reig & Milonaki (2016) 150 days after the outburst in 2003. However, we didn’t discover any sharp drops of the flux similar to another XRFs (Tsygankov et al. 2016). We also investigate the torque behavior during the outburst making use of the model in Ghosh & Lamb (1979) (GL model hereafter) and examine the correlation between the frequency derivative and the luminosity.

3.1. Accretion torque

The orbital parameters updated using the Fermi/GBM and Insight-HXMT data provide us an opportunity to analyze the spin-up behavior of 4U 1901+03 excluding the Doppler effect from orbital modulation. The spin evolution of the NS is driven by accretion torque during the outburst that can be written as:

\[ \dot{j} = \frac{df}{dt} = \frac{N}{2\pi I}, \]

where \( I \) is the effective moment of inertia of the NS, and \( N \) is the total torque. GL model assumes a magnetically-threaded disk having effects on the NS. Since the accreting materials have a torque onto the NS, the frequency derivative of the NS and the X-ray luminosity follows the correlation (GL model):

\[ \dot{j} = 5.0 \times 10^{-5} \mu_{30}^{2/7} n(\omega_z) R_6^{6/7} L_3^{-1} \left( \frac{M_{\text{NS}}}{M_\odot} \right)^{3/7} L_3^{-6/7} \text{Hz yr}^{-1}, \]

where \( \mu_{30} \) is the neutron star magnetic dipole moment in the disk plane (\( \mu = \frac{1}{2} BB^3 \)) in units of \( 10^{30} \text{G cm}^2 \), \( B \) is the magnetic field at the pole, \( R_6 \) is the radius of the NS in units of \( 10^6 \text{cm} \), \( I_{35} \) is the moment of inertia of the NS in units of \( 10^{35} \text{g cm}^2 \), \( M_{\text{NS}} \) is the mass of the NS in units of grams, the \( M_\odot \) is the solar mass in units of grams, and the \( L_3 \) is the luminosity in units of \( 10^{37} \text{erg s}^{-1} \). The dimensionless torque \( n(\omega_z) \) could be estimated as (GL model):

\[ n(\omega_z) \approx 1.39(1-\omega_z[4.03(1-\omega_z)^{0.173}-0.878])(1-\omega_z)^{-1}, \]

where \( \omega_z \) is the fastness parameter (Elsner & Lamb 1977),

\[ \omega_z \equiv \Omega_z/\Omega_K(R_m) \]

which is the ratio between the angular velocity of the NS and the Keplerian angular velocity at the magnetospheric radius.

As matter accreting on the NS, the angular momentum is carried from the Keplerian accretion disk to the NS. In the case of XRFs, the inner radius of the disk is the magnetospheric radius (\( R_m \)), where the accreting matter transfers the orbiting angular moment to the NS. Thus the angular momentum transported to the NS is \( M \sqrt{GM R_m} \). Multiple theories estimated the relation of \( R_m \) to the Alfv\( \text{e} \)n radius (\( R_\Lambda \)), where ram pressure of the spherical freely falling matter equals the magnetic pressure (Davidson & Ostriker 1973, Waters & Van Kerkwijk 1989):

\[ R_m = \xi R_\Lambda = \xi(2GM)^{-1/7} \mu^{4/7} M^{-2/7}, \]

where \( \xi \) is constant between 0 and 1 (Ghosh & Lamb 1979, Wang 1987, 1996). We use the \( \xi \) value from Ghosh & Lamb (1979), where \( \xi = 0.52 \). Substituting Equation (1) into Equation (6) one obtains:

\[ \omega_z = 1.19P^{-1} M_{17}^{-3/7} \mu_{30}^{6/7}(M_{\text{NS}}/M_\odot)^{-5/7}, \]

where \( P \) is the period of the X-ray pulsations in units of days, and \( M_{17} \) is the mass of the NS in units of \( 10^{17} \text{M}_\odot \).
where $P$ is the NS spin period in seconds and $M_{17}$ is mass accretion rate in units of $10^{17}$ g s$^{-1}$. The dimensionless torque $n(\omega s) \approx 1.4$ during the Insight-HXMT observation, indicating the NS in 4U 1901+03 is a slow rotator.

To analyze the correlation between frequency derivatives ($\dot{f}$) and bolometric flux ($F$) using the GL model, we calculate the representative $\dot{f}$ using the Fermi/GBM data covering time intervals with accurate flux measurements provided by Insight-HXMT. The frequency derivatives $\dot{f}$ were obtained as $\Delta f/\Delta t$ in each consequent time intervals (Doroshenko et al., 2018) using Fermi/GBM data corrected for the effects of the orbital motion. We select the midpoint of each time interval as representative time of the corresponding measurement. Since this time doesn’t necessarily coincides with the flux measurement time, we have to interpolate the $\dot{f}(t)$ using linear interpolation method to match the representative time of both measurements. The errors on $\dot{f}$ are derived as the propagating errors of calculating $\Delta f/\Delta t$ and linear interpolation. The results are shown in Figure 4. The fitting procedure reveals the correlation $D = 15.935 \times B_{12}^{1/6}$ [kpc] according to the Equation 4.

The GL model links the observed frequency derivative with the magnetic field strength and mass accretion rate onto the NS. According to Equation 4, the distance and the magnetic field correlation is plotted in black dashed line in Figure 5. The possible cyclotron resonance scattering features (CRSFs) are located at 10 keV (Reig & Milonaki 2016) and 30 keV (Coley et al. 2019). The fundamental cyclotron line energy is related to the magnetic field strength of the neutron star as $E_{cyc} = 11.6(1 + z)^{-1}B_{12}$ keV, where $z$ is the surface gravitational red-shift, and $B_{12}$ is the magnetic field in the unit of $10^{12}$ G (e.g., Staubert et al., 2019). We assume $z = 0.3$ for a typical neutron star mass of 1.4 $M_\odot$ and $R = 10^6$ cm. The magnetic field suggested by two different CRSFs are $1.1 \times 10^{12} \text{G}$ and $3.4 \times 10^{12} \text{G}$, respectively. Using these magnetic field strengths the distances to 4U 1901+03 according to the GL model can be estimated as 15.6 kpc and 13.0 kpc. They are consistence with an expected large distance greater than 12 kpc according to the optical observations (Strader et al., 2019). To verify which distance is more reliable, we take the evolution of pulse profiles during the outburst into account.

3.2. Critical luminosity

The evolution of pulse profiles during the outburst can be interpreted due to a transition of the source through the critical luminosity (Chen et al., 2008; Becker et al., 2012; Mushutkov et al., 2015; Weng et al., 2019; Ji et al., 2019; Doroshenko et al., 2019). In the bright state soon after the outburst peak, the profiles obtained with Insight-HXMT showed a two-peak pattern, implying a fan-beam emission geometry, when the X-ray luminosity is so high that the radiation pressure could stop the accreting matter above the surface via radiation-dominated shock (Chen et al., 2008). While at the low luminosity level, the profiles detected by Insight-HXMT suggest a pencil-beam geometry with pro-

Figure 4: The correlation between frequency derivatives and bolometric flux as seen by Insight-HXMT. The solid line is approximation with the GL model.

Figure 5: The distance – magnetic field diagram for 4U 1901+03. The solid line is the correlation following from the critical luminosity. The optical observation constrain the distance greater than 12 kpc (above the grey area). The red circle is the intersection with the torque model (shown with black dashed line), suggesting the distance of 12.4 ± 0.2 kpc. Vertical blue dashed line corresponds to the magnetic field derived from the cyclotron feature at 30 keV.
files having an one-peak pattern. Becker et al. (2012) argued that the critical luminosity at which the emitting pattern changes depends on the NS magnetic field as

\[ L_{\text{crit}} = 1.5 \times 10^{37} P_{12}^{16/15} \text{ erg s}^{-1}. \]  

(9)

The observed transition of the pulse profile shape happens around \( 4 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \), according to the Insigh-HXMT data. Using this value one can plot possible distances and magnetic field values satisfying Equation (9) (see solid line in Figure 5). The blue region corresponds to the uncertainty of the critical flux. The red circle in Figure 5 suggests the distance and the magnetic field based on both the torque model and critical luminosity. The resulting distance is \( 12.4 \pm 0.2 \text{ kpc} \) and the magnetic field is \( \sim 4.3^{+0.5}_{-0.2} \times 10^{12} \text{ G} \).

We note that the magnetic field values inferred from the possible cyclotron lines either at \( \sim 10 \text{ keV} \) or \( \sim 30 \text{ keV} \) are of the same order as derived above. Shi et al. (2015), Wang (1987) argued that the magnetic field is overestimated by the Ghosh & Lamb (1979), and the \( L_{\text{crit}} \) is highly uncertain (Becker et al. 2012; Mushtukov et al. 2015).

Nevertheless, the torque model and the variation of the pulse profile provide a new measure of the distance (\( 12.4 \pm 0.2 \text{ kpc} \)), which is consistent with the optical observation (Strader et al. 2019). Also further observation of the propeller effect will provide a new constraint to the distance and the magnetic field in 4U 1901+03.

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