Timing and spectral variability of high mass X-ray pulsar GX 301–2 over orbital phases observed by Insight-HXMT

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ABSTRACT

We report the orbital X-ray variability of high mass X-ray binary (HMXB) GX 301–2. GX 301–2 undergone a spin up process in 2018–2020 with the period evolving from \( \sim 685 \) s to 670 s. The energy resolved pulse-profiles of the pulsar in 1–60 keV varied from single peaked and sinusoidal shapes to multi-peaked across different orbital phases. Pulse fractions evolving over orbit had negative correlations with the X-ray flux. The broad-band X-ray energy spectrum of the pulsar can be described with a partial covering negative positive cutoff power-law continuum model. Near the periastron passage of the pulsar we found a strong variation in the additional column density (\( NH_2 \)), which correlated with variation of the flux. Curves of growth for both Fe K\( \alpha \) and Fe K\( \beta \) lines were plotted to investigate the distribution of matter around neutron star. We have also found the evidence of two cyclotron absorption lines in the phase-averaged spectra in GX 301–2, with one line of 30–42 keV and the other line varying in 48–56 keV. Both two line’s centroid energies show the similar relationship with X-ray luminosity: positive correlation in lower luminosity range, and negative relation above a critical luminosity of \( 10^{37} \) ergs\(^{-1} \). We estimated the surface magnetic field of the neutron star in GX 301–2 at \( \sim (0.5–2) \times 10^{13} \) G. Two cyclotron line energies have a nearly fixed ratio of \( \sim 1.63 \) while having a low strength ratio (\( \sim 0.05 \)), suggesting that these two features may actually be one line.

Key words: stars: neutron – pulsars: individual: GX 301–2– X-rays: stars.

1 INTRODUCTION

GX 301–2 is a high mass X-ray binary system consisting of a neutron star in a 41.5 d eccentric orbit with a donor star of early type known as Wray 977 (White & Swank 1984). The donor star is massive (\( \sim 39–53 M_\odot \)) having a size of \( \sim 62 R_\odot \) and is at a distance of \( \sim 3 \) kpc (Kaper, van der Meer & Najarro 2006). Most recent Gaia measurement implies \( d=3.53^{+0.46}_{-0.52} \) kpc (Bailer-Jones et al. 2018). The stellar wind of this B1 hypergiant companion star is rather dense (\( M_\infty \sim 10^{-5} M_\odot yr^{-1} \)) and slow (\( \sim 300 \) km s\(^{-1} \)). This high stellar wind mass loss rate could propel the accretion rate onto the neutron star to an observed luminosity of \( L_x \sim 10^{37} \) erg s\(^{-1} \). The 5\( \times \)10\(^5 \) \( L_\odot \) luminosity of the Wolf-Rayet companion Wray 977 (Kaper et al. 2006) makes it among the most luminous stars in the Galaxy. The neutron star (NS) in this system has the mass of \( 1.85 \pm 0.60 M_\odot \) based on radial-velocity studies (Kaper et al. 2006) and is a rather slowly rotating pulsar (\( P_{\text{spin}} \approx 680 \) s, Nabizadeh et al. 2019; Abarr et al. 2020; Mönkkönen et al. 2020), compared to majority of accreting X-ray pulsars.

The neutron star in GX 301–2 shows strong orbital variability as it traverses through its binary orbit. One of the hallmark characteristics of this system is the recurrence of a pre-periastron flare at the NS. A densely emanating gas stream from the companion hypergiant Wray 977 is recurrently intercepted by the NS shortly before every periastron passage (Leahy 1991; Leahy 2002; Leahy & Kostka 2008). It results in intense X-ray flares with a 25% increase in the X-ray luminosity (Pravdo et al. 1995; Pravdo & Ghosh 2001). It is also evident that the continuum X-ray emissions of GX 301–2 modulated by the orbital period attain a peak around the orbital phase 1.4 d before the periastron (see Fig. 3 of Sato et al. 1986).

Leahy & Kostka (2008) have studied a ten year long orbital light curve of GX 301–2 with RXTE. These studies reveal that a simple model consisting of a gas stream plus stellar wind accretion onto the NS could explain the substantial changes in the orbital light curve suggesting bright, medium and dim intensity levels across the orbit. The orbital phase dependence of the X-ray flare and flux variation in GX 301–2 has been studied previously with EXOSAT (Haberl 1991), CGRO/BATSE (Koh et al. 1997), ASCA (Endo et al. 2002), RXTE/ASM (Leahy 2002), RXTE/PCA (Mukherjee & Paul 2004), BeppoSAX (La Barbera et al. 2005), and recently with XMM-Newton and MAXI (Islam & Paul 2014), INTEGRAL (Doroshenko et al. 2010; Yu & Wang 2016).

The broad-band X-ray spectrum of GX 301–2 can be explained by various phenomenological models with a power law modified by cutoff at higher energy. At lower energy the spectrum of GX 301–2 gets heavily absorbed (Fürst et al. 2011). This is due to the presence

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Fundamental cyclotron line energies from detected cyclotron scattering features (Staubert et al. 2019), with the pulsars. At present, there are more than 30 X-ray pulsars with resulting cyclotron scattering features in the energy spectra of X-ray sources, showing good calibration state and estimation of the instrumental background (Li et al. 2020).

GX 301–2 has been observed numerously by HE, ME and LE telescopes onboard Insight-HXMT satellite between August 3rd, 2017 and June 3rd, 2020 (i.e MJD: 57968 – 59003). These observations cover different orbital phases of the binary orbit (see Figure 1). A log of observations (information of OBSIDs) used in this paper is given in the table as the supplementary material. It should be noted that the LE telescope data of observations with OBSID: P0101309 have been analyzed and published by Ji et al. (2021), who have studied the source at 5.5–8.5 keV. In the following science analysis, we filtered data with the criterion: (1) pointing offset angle < 0.1°; (2) pointing direction above Earth > 10°; (3) geomagnetic cut-off rigidity value > 8 GeV; (4) time since SAA passage > 300 s and time to next SAA passage > 300 s; (5) for LE observations, pointing direction above bright Earth > 30°. The Insight-HXMT Data Analysis Software Package (HXMTDAS) V2.02 was used in this work.

We obtained the X-ray light curves of GX 301–2 in three energy bands: 1–10 keV, 10–30 keV and 30–60 keV (see Figure 2). The spin period of the neutron star in GX 301–2 is about 683 s. We made the barycentric correction of the light curves using the tool hxbary. For timing analysis, we corrected the photon arrival time for the binary motion, using ephemeris by Doroshenko et al. (2010). In the spectral analysis, we used well-calibrated energy bands of LE, ME and HE: 3–8.5 keV, 10–30 keV and 30–70 keV, respectively (Li et al. 2020). However, ME data in 21–24 keV was ignored due to the calibration uncertainties in this energy range. All uncertainties reported in this paper are at 90% confidence level. In the analysis and science presentation, we arranged all observations into two groups based on the orbital phase (Figure 1). For those having orbital phases in 0.2–0.9, we labeled them as apastron observations while others were labeled as periastron.

### 3 TIMING ANALYSIS AND PULSE PROFILES

The temporal analysis aims to derive the spin period of the neutron star in GX 301–2 at different observations. Then, one can obtain the pulse profiles for three energy bands (1–10 keV, 10–30 keV & 30–60 keV). The periodic signal was searched by folding the light curves, determining the chi-square ($\chi^2$) of the folded light curve and the $\chi^2$ values versus the periods. The $efsearch$ (a built-in function in HEAsoft) was used to search for the maximum of $\chi^2$ values. We have fitted the distribution with the theoretical distribution function given by Leahy et al. (1987). We have noticed that the sampling rate of our data was uneven. Consequently, the error was estimated from Equation 2 of Larsson (1996):

$$\sigma_f = \frac{\sqrt{2\text{arf}}}{\sqrt{NAT}}$$  (2)
Figure 1. Insight-HXMT observation log (magenta triangle on top) overplotted on the Swift/BAT orbital phase folded count rate. Orbital period and periastron passage are from Doroshenko et al. (2010). HXMT data covered most of the orbital phases. We label the phases 0.2–0.9 as the apastron, and other phases as periastron.

Figure 2. Count rates of GX 301–2 observed by three detectors of Insight-HXMT from August 2017 to June 2020.

Figure 3. The orbital demodulated spin period of the neutron star in GX 301–2 determined by Insight-HXMT. Orbital parameters are from Koh et al. (1997) and Doroshenko et al. (2010). The neutron star showed a long term spin evolution. From July 2018 to June 2020, the spin period evolved from 685 s to 670 s.

Figure 4. Pulse profiles of GX 301–2 obtained in three energy bands (i.e., 1–10 keV, 10–30 keV & 30–60 keV) from observations of LE, ME & HE detectors respectively. There are 25 good OBSIDs in which at least one complete pulse profile could be constructed without any gaps. These pulse profiles are shown in Figure 4.

where the parameter a was taken to be the value derived by Monte Carlo simulation (i.e. 0.469). N is the total number of data points, A is the sinusoidal amplitude and T is the total time length for the data. The intrinsic spin period values of GX 301–2 in several OBSIDs are presented in Figure 3. The spin period of GX 301–2 varied with time, reflecting the typical behavior in the wind accretion system. In addition, from 2017 – 2020, the neutron star of GX 301–2 showed a long-term spin up from the period of ∼685 s to 670 s.

The pulse profiles of GX 301–2 are obtained in three energy bands (i.e., 1–10 keV, 10–30 keV & 30–60 keV) from observations of LE, ME & HE detectors respectively. There are 25 good OBSIDs in which at least one complete pulse profile could be constructed without any gaps. These pulse profiles are shown in Figure 4.

The pulse profiles changes with the energy bands. In hard X-ray bands above 10 keV, the neutron star generally shows double peaks, sometimes as sinusoidal shapes. In low energy band, the mini-peaks appeared in all orbital phases, which made the double peak features disappear in some orbital phases. The energy resolved pulse-profiles of pulsar are also seen to be varying from single peaked and sinusoidal shapes to multi-peaked across different orbital phases. To study the pulse profile properties over the orbital phase, we calculated the pulse fraction (defined as $PF = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$) for all light curves and show the variation of $PF$ versus orbital phase in Figure 5. It is interesting that the mean pulse fraction at the orbital phase 0.85 – 0.99 was generally lower than that in other orbital phase for three energy bands, which is also consistent with the results reported by Endo et al. (2002) and Nabizadeh et al. (2019). The neutron star system approaching the periastron showed the X-ray flares, so that the pulse fraction may depend on the X-ray luminosity. In Figure 6, we also plotted the diagrams of three pulse fractions versus observed X-ray flux from 3 – 70 keV. The pulse fractions in three energy bands show negative correlation with X-ray flux, higher X-ray flux with the lower pulse fraction values.

4 SPECTROSCOPY OVER ORBITAL PHASES

Insight-HXMT pointing observations covered different orbital phases of GX 301–2 (see Figure 1). To understand the spectral properties and variations over the orbit, we obtained and analyzed the broad band x-ray spectra for different orbital phases. The spectra from 3–70 keV obtained by LE, ME and HE detectors are analyzed here.

The continuum spectra of GX 301–2 have been studied extensively (e.g., Fürst et al. 2018; La Barbera et al. 2005, and references therein). The X-ray spectrum of GX 301–2 at 3–70 keV can generally be described with a partial covered power-law model, corrected with a high energy cutoff. We implemented four kinds of phenomenological models to describe the continuum of GX 301–2 at first. Negative positive cutoff powerlaw or NPEx model (Mihara 1995), FDCut (Tanaka et al. 1986), HIGHECUT, newHcut (almost the same as highecut but being smoothed around the cutoff energy with a third-order polynomial; Burderi et al. 2000). We have
smoothed the in-continuity of HIGHECUT with an additional Gabs component.

The models included two absorption components: one is the Galactic ISM absorption with the column density \( NH_1 \) being fixed at \( NH_1 = 1.4 \times 10^{22} \text{ cm}^{-2} \). Another column density parameter \( NH_2,_{pcf} \) is the partial covering photoelectric absorption in the binary system which is expected to vary with the orbital phases. We applied \( t\text{bnew}^1 \) for both two components.

In the range of 6–7 keV, there exist complicated emission features in GX 301–2. These features are thought to be caused by fluorescence from neutral or ionized iron present in the material surrounding the neutron star. We added two Gaussian lines to fit the emission line features of Insight-HXMT spectra: Fe K\( \alpha \) (at \( \sim 6.4 \text{ keV} \)) and Fe K\( \beta \) (\( \sim 7 \text{ keV} \)) lines. Three parameters for these emission features were summarized in Table 1 including line centroid energy \( (E_{Fe}) \), line width \( (\sigma_{Fe}) \), and the equivalent width \( (eqw_{Fe}) \). The Fe K\( \alpha \) line around 6.4 keV can be detected in all orbital phases, while the Fe K\( \beta \) line around 7 keV could be detected by Insight-HXMT only in part of the pointing observations (also see Figure 8). In addition, as Ji et al. (2021) has confirmed, LE data is unable to constrain the line widths of the fluorescent lines. So, we fixed all these widths at 1 eV. Strong residuals at the lower energy side of Fe K\( \alpha \) sometime appeared in our data and can be explained by an extended Compton shoulder (CS) (Watanabe et al. 2003; Fürst et al. 2018; Ji et al. 2021). A box function was considered to describe this feature. However, in most of our observations, this feature is statistically insignificant and in principle, the energy resolution of LE telescope is not sufficient to fully resolve shape of the iron line complex. So, we did not fit this feature in the following analysis.

Absorption features around 30–60 keV appeared in most of the observations, especially for those near the periastron passage. These features should be attributed to the cyclotron resonant scattering features (CRSF) of the magnetized accreting neutron star. We used a multiplicative absorption model with a Gaussian optical depth pro-

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Figure 4. Background subtracted pulse profiles of GX 301–2 versus orbital phases. We showed pulse profiles in three energy bands: 1–10 keV, 10–30 keV & 30–60 keV, and the evolution of the profiles with the orbital phases from 0.03 to 0.99. See the text for details.

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\(^1\) http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/
Figure 5. Pulse fractions in three energy bands versus the orbital phase.

Figure 6. The relationships between pulse fraction and X-ray flux. In three energy bands, there exists the negative correlation between pulse fraction and X-ray flux.

file (Gabs in Xspec) to describe the cyclotron absorption line. In addition, a cross instrument calibration constant (CC) was added as the multiplicative components to calibrate the slight unequal flux between different telescopes of Insight-HXMT. Thus, the baseline model in our analysis can be described as:

$$CC \times NH_1(NH_2pcf \times (CRSFs) \times CONT + Gaussian).$$

With two Gabs components modeling the CRSFs, all of these models can obtain an acceptable fit in observations during the pre-
can be fitted with another Gaussian absorption feature. We adopt a very narrow absorption feature at \( \sim 22 \) keV, which can be fitted with a Gaussian absorption model. However, this narrow feature (\( \sigma \sim 1 \) keV) is more likely to be an artifact due to the poor calibration in 21–24 keV. We have ignored this energy range in our analysis.

We noticed wavy residuals between 10 and 30 keV in some observations. In view of these premises and to compare our results with Fürst et al. (2018), we continued our analysis of CRSFs with the NPEX model for all pointing observations. Spectrum parameters obtained in different orbital phases are summarized in Figure 9. Flux is calculated from the unabsorbed model in different energy ranges and hardness is evaluated from the ratio of flux in 8–20 keV over the one in 5–8 keV, i.e. \( \text{Flux}_{8-20} / \text{Flux}_{5-8} \). We have tried several kinds of hardness ratio (10–20/3–10, 30–70/3–5 etc.) and found that the definition has only a small effect on its behavior during the orbital motion.

In Figure 8, we showed the spectra from 3–70 keV obtained by three detectors LE, ME and HE for different orbital phases. In some observations, after fitting the spectrum with the cyclotron absorption line around 52–55 keV, there still exist an absorption feature in lower energies around 33 keV). We confirmed that this feature can be fitted with another Gaussian absorption feature. We adopt Monte Carlo Markov Chain (MCMC) method to estimate the error and detect any parameter degeneration. During the primary run, each chain was generated using 200000 steps (20 walkers) with the first 10000 steps being burnt. We found that in different orbital phases, the energy ratio of these two lines are fluctuating around a constant while the corresponding MCMC contour illustrate no apparent degeneration between these two parameters (see Figure 12). Thus, it is reasonable to claim that the correlations are intrinsic of the system.

We applied the NPEX with one or two absorption lines to fit all observed spectra from 3–70 keV based on Insight-HXMT observations. In the apastron phases, the S/N may be too low to distinguish the second line. In most situations, we took two cyclotron absorption lines in fittings. For some observations near the apastron, the S/N may be too low to distinguish two absorption lines (these features having very small strength), we took only one absorption line then. The model has given good fit to these spectra, with the reduced \( \chi^2 \) around 1 (see Table 1). All spectral parameters and their variations over the orbit are then collected and plotted in Figure 9. The spectral parameters really had some changes with orbital phases. X-ray flux and the intrinsic column density show nearly simultaneous variations over orbit, both of which have peaks around pre-periastron and post-periastron orbital phases as expected. The covering factor did not change within a narrow range \( \sim 0.95 – 1 \). The cutoff energy \( E_{\text{cut}} \) \( \sim 7 \) keV and photon index \( \Gamma \sim 1 \) did not show significant variation over orbit.

In all orbital phases, the Fe Kα line around 6.4 keV was detected, with the equivalent width evolving with the orbital phases. The iron line properties may be related to the column density in the accretion system, which will be discussed in §5.1. The cyclotron absorption lines were detected in the X-ray spectra of GX 301–2, which are at 48–56 keV and sometimes, another line at \( \sim 28 – 36 \) keV was also reported. In addition, line energies of these two CRSFs have some correlations. We will discuss it in §5.2.

5 DISCUSSIONS

5.1 Curve of growth

Theoretically, it is expected that the strength of spectral lines are positively correlated with the absorber optical depth. The equivalent width of Fe Kα line shows positive correlation with \( NH_2 \) which has been generally known as the curve of growth (see Torrejon et al. 2010; Gimenez-Garcia et al. 2015). Here we can probe the relation between the column density and iron lines observed in GX 301–2. In §4, we have obtained spectral properties over the orbit including two iron lines at 6.4 keV and 7 keV, their equivalent widths, and the corresponding intrinsic absorption column density \( NH_2 \) for each observation. \( NH_2 \) is around the level of \( 10^{24} \text{ cm}^{-2} \) at periapsis orbital phases, and \( NH_2 \sim (1–5) \times 10^{23} \text{ cm}^{-2} \) at other phases. In Figure 11, we present the hydrogen column density \( NH_2 \) versus the equivalent width (EqW) of both two iron lines: Fe Kα line and Fe Kβ line.

For the case of GX 301–2, we confirmed a strong correlation, and a power-law fit in Figure 11 leads to

\[
ev \propto NH_2^{1.06 \pm 0.20},
\]

with the Pearson coefficient (PC) of 0.75.

In addition, we also obtained the equivalent width of the Fe Kβ line in some observations of Insight-HXMT near the pre-periastron orbital phases. Thus we also plotted the \( \text{eqw} \) of Fe Kβ versus \( NH_2 \) in Figure 11. We found the curve of growth of the Fe Kβ line in GX 301–2. The correlation of \( \text{eqw}_{Fe,K\beta} \) versus \( NH_2 \) is not so strong,
Table 1. Spectral parameters of GX 301–2 fitted with NPEX based on some Insight-HXMT observations. X-ray flux is derived from 3–70 keV, while the hardness ratio is evaluated from the ratio of Flux$_{5–-20}$/Flux$_{5–-8}$.

| Observations | P010130900104 | P010130900107 | P010130900108 | P020101228407 |
|--------------|---------------|---------------|---------------|---------------|
| NH$_2$ (10$^{22}$ cm$^{-2}$) | 206.9$^{+8.2}_{-2.9}$ | 118$^{+6}_{-5}$ | 192$^{+9}_{-5}$ | 77$^{+15}_{-11}$ |
| PCF | 0.994$^{+0.03}_{-0.02}$ | 1.000$^{+0.04}_{-0.04}$ | 0.956$^{+0.03}_{-0.02}$ | 0.974$^{+0.012}_{-0.012}$ |
| $\Gamma$ | 1.492$^{+0.04}_{-0.01}$ | 1.022$^{+0.06}_{-0.11}$ | 0.774$^{+0.16}_{-0.10}$ | 1.15$^{+0.25}_{-0.25}$ |
| $E_{\text{eqv}}$ (keV) | 7.096$^{+0.437}_{-0.250}$ | 7.24$^{+0.10}_{-0.27}$ | 6.58$^{+0.06}_{-0.14}$ | 6.28$^{+0.31}_{-0.39}$ |
| $E_{\text{Ko}}$ (keV) | 6.425$^{+0.001}_{-0.002}$ | 6.434$^{+0.001}_{-0.002}$ | 6.49$^{+0.03}_{-0.27}$ | 6.35$^{+0.07}_{-0.18}$ |
| EqW$_{\text{FeKo}}$ (keV) | 1.68$^{+0.15}_{-0.15}$ | 0.492$^{+0.044}_{-0.035}$ | 0.808$^{+0.067}_{-0.04}$ | 0.16$^{+0.03}_{-0.12}$ |
| EqW$_{\text{Ko}}$ (keV) | 7.065$^{+0.02}_{-0.01}$ | 7.09$^{+0.02}_{-0.01}$ | - | - |
| EqW$_{\text{FeKo}}$ (keV) | 0.25$^{+0.12}_{-0.01}$ | 0.080$^{+0.007}_{-0.003}$ | - | - |
| $E_{\text{eqv1}}$ (keV) | 31.8$^{+0.7}_{-0.9}$ | 33.8$^{+0.7}_{-0.4}$ | 29$^{+5}_{-2}$ | 44$^{+25}_{-11}$ |
| $\sigma_{\text{eqv1}}$ (keV) | 5.7$^{+0.8}_{-0.4}$ | 6.9$^{+0.6}_{-1.0}$ | 11.9$^{+0.4}_{-0.2}$ | 3.8$^{+0.2}_{-1.1}$ |
| Strength1 | 5$^{+2}_{-2}$ | 7.3$^{+25}_{-1.8}$ | 19$^{+20}_{-1.0}$ | 11$^{+90}_{-1}$ |
| $E_{\text{eqv2}}$ (keV) | 53.5$^{+2.0}_{-1.2}$ | 56.24$^{+0.6}_{-0.7}$ | - | - |
| $\sigma_{\text{eqv2}}$ (keV) | 14.5$^{+1.9}_{-0.4}$ | 14.3$^{+1.6}_{-1.0}$ | - | - |
| Strength2 | 115$^{+30}_{-42}$ | 105$^{+9}_{-4}$ | - | - |
| Flux 10$^{-8}$ erg s$^{-1}$ cm$^{-2}$ | 1.13$^{+0.008}_{-0.008}$ | 1.27$^{+0.010}_{-0.004}$ | 0.19$^{+0.02}_{-0.02}$ | 0.268$^{+0.009}_{-0.004}$ |
| Hardness Ratio | 26$^{+3}_{-2}$ | 10$^{+2.3}_{-0.4}$ | 2.9$^{+0.4}_{-0.2}$ | 3.9$^{+0.7}_{-0.3}$ |
| Reduced-$\chi^2$ (df) | 1.1064 (287) | 1.1353 (287) | 0.9266 (292) | 0.7263 (292) |

The powerlaw fit in Figure 11 leads to

$$eqv \propto NH_2^{0.52_{-0.28}^{+0.28}}$$

with the Pearson coefficient of 0.51.

The derived correlation between the equivalent width of Fe lines and intrinsic column density is not completely consistent with the early work by Ji et al. (2021). This is due to the larger sample and broader energy band (3–70 keV compared to 5.5–8.5 keV) we have adopted. In other high mass X-ray binaries, this relation was also reported (Torrejon et al. 2010; Gimenez-Garcia et al. 2015). GX 301–2 has been studied extensively, and the cyclotron absorption line energies varied in a wide range from ~30 – 56 keV based on previous observations. Insight-HXMT detected the cyclotron lines both in periastron and apastron orbital phases, where two cyclotron absorption lines with a Gaussian profile are used, one line around ~26 – 35 keV, and the other around ~45 – 56 keV. Two possible absorption lines at ~35 – 40 keV and ~50 – 55 keV reported by NuSTAR (Fürt et al. 2018) were then confirmed by Insight-HXMT. This interpretation can explain the wide energy range and wild variability of the line parameters in previous study.

Combining about 40 pointing observation data, we analyze the CRSF line parameters systematically. From Figure 13, we found that the two centroid energies of CRSFs have a very strong linear correlation, indicating a fixed ratio between them. We confirmed the result is not due to the parameter degeneration during fitting process (see Figure 12). This ratio does not scale like 1 : 2 but is about 1 : 1.63, which is significantly greater than that derived by Fürt et al. (2018) but still too small compared to the value predicted by Mészáros (1992). It is suggested that there may exist two line forming regions (Fürt et al. 2018), situated at the surface of NS and 1.4 km above it respectively. This interpretation is based on the premise of Coulomb-radiation-dominated deceleration regime. The corresponding shock height can be calculated from Eq. (51) in Becker et al. (2012), assuming radius of the NS to be 10 km and a mass of 1.8$M_\odot$, we have:

$$h = 2.2 \times 10^4 \Lambda^{-1} L_{37}^{-5/7} B_{12}^{-3/7} \Lambda^{-1} \text{ cm.}$$

As the shock height should decrease with increasing luminosity, this regime will require a positive correlation of the CRSF energy with luminosity. This correlation was observed in low luminosity stage for both two CRSFs simultaneously (see left panel of Figure 13). Two forming region interpretation (Fürt et al. 2018) claimed that the higher energy absorption line around 50 keV was situated at the surface of NS, thus being unable to account for the strong correlation between the line energy and X-ray luminosity, unless the surface magnetic field of the neutron star also evolves during the orbital motion (should be impossible).

In addition, in more luminous range, we observed a negative correlation of the line centroid energy and X-ray luminosity for both

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The observed cyclotron absorption lines in fittings, at $\sim 30 - 40$ keV and $\sim 52 - 56$ keV while in the apastron phases, the S/N may be too low to distinguish/detect two absorption lines; in these cases, we took only one absorption line. The strength of the lower energy absorption is much smaller than the higher one near the periastron. Corresponding parameter values are in Table 1.

Figure 8. Spectrum examples of GX 301–2 from 3–70 keV combined with the LE, ME and HE data. From the top to bottom, the panels presented the spectra with fitted model components for three different observations with ObsID: P010130900104 (phase=0.988) (top left); P010130900107 (phase=0.957) (top right); P010130901801 (phase=0.624) (bottom left); P020101228407 (phase=0.587) (bottom right). For observations near the periastron, we took two cyclotron absorption lines in fittings, at $\sim 30 - 40$ keV and $\sim 52 - 56$ keV while in the apastron phases, the S/N may be too low to distinguish/detect two absorption lines; in these cases, we took only one absorption line. The strength of the lower energy absorption is much smaller than the higher one near the periastron. Corresponding parameter values are in Table 1.

Considering the uncertainty, we suggested the observed critical luminosity range in GX 301–2 of $(0.7 - 2.2) \times 10^{37}$ erg s$^{-1}$. Although during the spin-up event (MJD 58400-58600, only four available observations) GX 301–2 was considered having an accretion disc, observations in this stage still had only very low luminosity and thus low S/N for spectral analysis. Consequently, none of them were plotted on Figure 13. In a word, wind accretion may dominate the accretion process in our data, which generally should be a spherical symmetric process. According to Equation 7, given $\Lambda = 1$ for spherical symmetric accretion, we found that the energy of the CRSF on the surface of neutron star reaches the range of $\sim 90 - 200$ keV, suggesting a surface magnetic field of $(8 - 20) \times 10^{12}$ G in GX 301–2. Thus, the neutron star in GX 301–2 would be a strongly magnetized neutron star of typical magnetic field in the order of $10^{13}$ G (a little lower than the typical magnetar-like field suggested by Doroshenko et al. 2010). We concluded that the observed cyclotron absorption lines at energies of $30 - 56$ keV are likely to be produced at the height $> 10^5$ cm above the star surface, supporting the existence of a tall accretion column structure during periastron flare.

However, such a CRSF emission area height actually contradicts with Equation 6, which indicates an emission height tenfold lower...
Figure 9. Spectral parameters over the orbit of GX 301–2. Hardness is evaluated from the ratio $\text{Flux}_{5-20}/\text{Flux}_{5-8}$. NH$_2$ is the local column density in the binary system, showing peaks around the periastron orbital phases. PCF is the covering factor which is generally around 0.95–1. The photon index is around 1.2 while $E_{\text{cut}} \sim 7$ keV, showing no significant variations with orbit phases. The observed X-ray flux in the energy band of 5–70 keV in units of $10^{-9}$ erg cm$^{-2}$ s$^{-1}$ changes over the orbit, which correlates to the variation of NH$_2$. The equivalent width of Fe Kα line around 6.4 keV also show variation over the orbit. Fe Kβ line at $\sim 7$ keV was detected in some phases. In some observations, one or two CRSFs in $\sim 30$–55 keV were reported.
than what we have derived by the critical luminosity. This may make our interpretation self-contradicting. Here, we proposed another possibility that the parameter \( \Lambda \) may not be 1, because the result in Figure 11 has shown significant deviation from isotropic. However, there is no any conclusive evidence that could prove the existence of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either. Consequently, assuming a dipole magnetic field structure, we did a numerical calculation to obtain possible \( \Lambda \) of disc accretion either.

\[ \Lambda = \frac{t_{\text{ukov et al. (2015)}}}{t_{\text{blending of wind and disc accretion.}}} \]

\[ \text{We also compared our results with the model proposed by Mush-tukov et al. (2015). Assuming } \Lambda = 0.5 \text{ and equal flux for } X- \text{ and } O-\text{modes, the calculated critical luminosity for a NS with magnetic field of } \sim 5 \times 10^{12} \text{G is } 0.8 - 2.0 \times 10^{37} \text{erg s}^{-1}, \text{corresponding to } l_0/l_\odot = 0.5 \text{ and } 1.0 \text{ respectively (see Figure 7 of their paper). This result is also in good agreement with our observation. Considered the large uncertainty in } \Lambda \text{ and mixing polarization modes, the difference between their model and the one from Becker et al. (2012) may not be significant.} \]

\[ \text{We noticed that in most of the orbital phases, especially that near the periastron (see Figure 9), the strength ratio of these CRSFs fluctuates around } \sim 0.05. \text{ This result indicates that we may observe only one line but with a significant deviation from a simple empirical function, which is due to the superposition of CRSFs in different forming regions with different heights (Nishimura 2015). Such deviations have also been theoretically predicted by Schwarm et al. (2017) with MC simulations. Future numerical simulations and more detailed comparison between observations and simulated results could probe the physical origin of the very broad absorption feature.} \]

6 SUMMARY AND CONCLUSION

GX 301–2 is an interesting X-ray pulsars showing significant variation with the orbital phases both in light curves and spectral properties. Insight-HXMT has performed multiple pointing observations on this source covering different orbital phases, and found the timing and spectral variations over orbit in GX 301–2. The spin period of GX 301–2 showed variations, in addition, from 2017-2020, the neutron star of GX 301–2 underwent a long-term spin-up state with the period evolving from \( \sim 685 \text{ s} \) to \( 670 \text{ s} \). The pulse profiles changed in three energy bands and also varied with orbital phases. Pulse fractions from the bands of \( 3-60 \text{ keV} \) showed negative correlation with the X-ray flux.

The spectral parameters evolved over orbit in GX 301–2. The X-ray flux correlates to the column density, showing peaks near the periastron and apastron orbital phases. The Fe K\( \alpha \) line was detected in all orbital phases. In some orbital phases, the Fe K\( \beta \) line at \( \sim 7 \text{ keV} \) was also detected. The curve of growth for both two iron fluorescence lines were obtained, their equivalent width have a positive correlation with the column density.

Two CRSFs at \( \sim 30-42 \text{ keV} \) and \( \sim 50-56 \text{ keV} \) in GX 301–2 were confirmed by the Insight-HXMT observations. The cyclotron line energies showed slight variation over orbit and strong correlation with each other, having a fixed ratio \( \sim 1.63 \pm 0.01 \). The strength ratio between these two features stayed at \( \sim 0.05 \) during most of the phases. A simultaneous increase of line energy with X-ray luminosity for both two CRSFs was observed in low flux range, while in luminous states, both the two line energies showed a negative relation with the luminosity. The observed critical luminosity is around \( 10^{37} \text{ erg s}^{-1} \). Thus, if wind accretion does dominate GX 301–2, we estimated the surface magnetic field of the neutron star in GX 301–2 as \( (1-2) \times 10^{13} \text{ G} \). Another possibility is that GX 301–2 undergoes a blending of disc and wind accretion during periastron flare, with a magnetic field of \( \sim 5 \times 10^{12} \text{ G} \). The environment there is more complicated than we have postulated. In any case, GX 301–2 should be a highly magnetized neutron star, but its field is still lower than the typical field of magnetars (Doroshenko et al. 2010; Wang 2013). The observational phenomena indicated a strong coupling between two CRSFs. The two forming region interpretation proposed by Fürst et al. (2018) could not account for such a correlation between the line energies and luminosity. We proposed that we observed only one line but with a significant deviation from a simple empirical function. According to the observed critical luminosity, if wind accretion predominate, the line forming region may be high above the neutron star surface. The future simulated physical CRSF profile is expected to account for the strange line profile in GX 301–2.

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DATA AVAILABILITY

Data that were used in this paper are from Institute of High Energy Physics Chinese Academy of Sciences(IHEP-CAS) and are publicly available for download from the Insight-HXMT website. To process and fit the spectrum and obtain folded light curves, this research has made use of XRONOS and FTOOLS provided by NASA.
Figure 11. The equivalent width versus the hydrogen column density for two iron lines of GX 301–2: Fe Kα line at ∼6.4 keV (left) and Fe Kβ line at ∼7 keV (right). The equivalent width values of both two iron lines show positive correlation with the column density. Blue dashed lines represent the best fitted broken powerlaw functions. Data points being taken from the assumed disc accretion stage (MJD 58400–58600) were marked with blue crosses. Green dashed lines are the EqW-NH₂ relation derived by numerical simulation (assuming spherical symmetric, from Gimenez-Garcia et al. 2015), with the corresponding photon indexes of 0.5 and 2.0 respectively.

Figure 12. Probability distribution of CRSF and continuum parameters during fitting process generated by MCMC. There is no apparent parameter degeneration between CRSF centroid energies. In addition, there is only a very weak correlation between continuum parameters and CRSF energy.

REFERENCES
Abarr Q., et al., 2020, ApJ, 891, 70
Burderi L., Di Salvo T., Robba N. R., La Barbera A., Guainazzi M., 2000, ApJ, 530, 429
Becker P. A. et al., 2012, A&A 544, A123
Bailer-Jones C. A. L., Rybizki J., Fouesneau, M., Mantelet, G., Andrae R., 2018, AJ, 156, 58
Cao X. et al., 2020, Science China Physics, Mechanics, and Astronomy, 63, 249504
Chen Y., Cui, W., Li W. et al. 2020, Science China Physics, Mechanics, and Astronomy, 63, 249505
Doroshenko V., Santangelo A., Suleimanov V., Kreykenbohm I., Stauber R., Ferrigno C., Klochkov D., 2010, A&A, 515, A10
Endo T., Ishida M., Masai K., Kunieda H., Inoue H., Nagase F., 2002, ApJ, 574, 879
Fürst F. et al., 2011, A&A, 535, A9
Fürst F. et al., 2018, A&A, 620, A153
Gimenez-Garcia A. et al., 2015, A&A, 576, A108
Harding A. K., Kirk J. G., Galloway D. J., Mészáros P. et al. 1984, ApJ, 278, 369
Haberl F., 1991, ApJ, 376, 245
Ikhsanov N. R., Finger M. H., 2012, ApJ, 753, 1
Islam N., Paul B., 2014, MNRAS, 441, 2539
Ji L., et al., 2021, MNRAS, 501, 2522
Kaper L., van der Meer A., Najarro F., 2006, A&A, 457, 595
Figure 13. Left panel: Cyclotron absorption energy dependence of source unabsorbed luminosity in 5–70 keV. Positive correlation between CRSF energy and X-ray luminosity was observed in the low luminosity state, while above a critical luminosity around $10^{37}$ erg s$^{-1}$, the CRSFs energy correlate with the luminosity negatively. Blue dashed lines are broken powerlaw fittings, producing a best-fitting critical luminosity. Right panel: CRSF line energy correlation of GX 301–2. Two CRSFs have strong linear correlation especially at pre-periastron flare, which is not likely to be the consequence of parameter degeneration (also see Figure 12).

Figure 14. Calculated relation of $\Lambda$-critical luminosity and surface magnetic field strength-critical luminosity.

Koh D. T., et al., 1997, ApJ, 479, 933
Kreykenbohm I., et al., 2004, A&A, 427, 975
La Barbera A., Segreto A., Santangelo A., Kreykenbohm I., Orlandini M., 2005, A&A, 438, 617
Larsson S., 1996, A&A, 117, 197
Leahy D. A., 1987, A&A, 180, 275
Leahy D. A., 1991, MNRAS, 250, 310
Leahy D. A., 2002, A&A, 391, 219
Leahy D. A., Kostka M., 2008, MNRAS, 384, 747
Li X., Tan Y. et al. 2020, Journal of High Energy Astrophysics, 27, 64
Liu J., Soria R., Qiao E., Liu J., 2018, MNRAS, 480, 4746
Liu C. et al. 2020, Science China Physics, Mechanics, and Astronomy, 63, 249503
Mészáros, P. 1992, High-energy Radiation from Magnetized Neutron Stars (Chicago: University of Chicago Press)
Mihara, T. 1995, PhD thesis, Univ. of Tokyo
Makishima, K., & Mihara, T. 1992, Magnetic Fields of Neutron Stars
Mönkkönen J., Doroshenko V., Tsygankov S. S., Nabizadeh A., Abolmasov P., Poutanen J., 2020, MNRAS, 494, 2178
Mukherjee U., Paul B., 2004, A&A, 427, 567
Mushotuk A., Suleimanov V. F., Tsygankov S. S., Poutanen J., 2015, MNRAS, 447, 1847–1856
Nabizadeh A., Mönkkönen J., Tsygankov S. S., Doroshenko V., Molkov S. V., Poutanen J., 2019, A&A, 629, A101
Nishimura O., 2015, ApJ, 807, 164
Orlandini M. et al., 1998, ApJ, 500, 163-166
Orlandini M., dal Fiume D., Frontera F., Oosterbroek T., Parmar A. N., Santangelo A., Segreto A., 2000, AdSpR, 25, 417
Pravdo S. H, Day C. S. R., Angelini L. et al., 1995, ApJ, 454, 872
Pravdo S. H., Ghosh P., 2001, ApJ, 554, 383
Sato N., Nagase F., Kawai N., Kelley R. L., Rappaport S., White N. E., 1986, ApJ, 304, 241
Staubert R. et al. 2019, A&A, 622, A61
Suchy S., et al., 2012, ApJ, 745, 124
Schwarm F.-W. et al., 2017, A&A, 601, A99
anaka Y., 1986, IAU Colloq. 89: Radiation Hydrodynamics in Stars, Compact Objects, 255, 198
Torrejon J. M., Schulz N. S., Nowak M. A., & Kallman T. R., 2010, ApJ, 715, 947
Tsygankov S. S., Lutovinov A. A., Gilfanov M. R., Sunyaev R. A., 2004, AstL, 30, 540
White N. E., Swank J. H., 1984, ApJ, 287, 856
Zheng X., Liu J., Gou L., 2020, MNRAS, 491, 4802

APPENDIX A: DIFFERENT CONTINUUM MODELS

This paper has been typeset from a \LaTeX\ file prepared by the author.
Figure A1. Spectra of GX 301–2 in ObsID:P010130900701 from 3–70 keV fitted with four different continuum models. Top left: FDcut; top right: newHcut; bottom left: highEcut; bottom right: NPEX. Corresponding parameter values are shown in Table A1. All these continuum models with two Gabs can obtain an acceptable fit.
Table A1. Spectral parameters of GX 301–2 fitted with four different continuum models based on the Insight-HXMT observations for the Obs-ID:P010130900701.

| Models | FDcut (10^{22} cm^{-2}) | newHcut | highHcut | NPEX |
|--------|--------------------------|----------|----------|------|
| NH2    | 88.8^{+14}_{-13}        | 93^{+10}_{-9}  | 98^{+15}_{-19} | 101^{+18}_{-15} |
| PCF    | 0.99^{+0.10}_{-0.01}    | 0.993^{+0.006}_{-0.017} | 0.983^{+0.011}_{-0.017} | 0.994^{+0.006}_{-0.007} |
| Γ      | 1.235^{+0.001}_{-0.007} | 1.21^{+0.04}_{-0.04}   | 0.001^{+0.156}_{-0.001} | 1.30^{+0.13}_{-0.16}  |
| E_{fold} (keV) | 4.87^{+1.08}_{-1.10}   | 13.7^{+1.4}_{-2.0}    | 6.6^{+0.9}_{-1.3}   | 1.03^{+0.37}_{-0.32}  |
| E_{cut} (keV)  | 49.9^{+11.1}_{-15.8}   | 19.8^{+5.0}_{-8.0}    | 16.1^{+0.9}_{-0.8}  | 7.3^{+0.36}_{-0.41}   |
| E_{FeKα} (keV) | 6.435^{+0.022}_{-0.026} | 6.435^{+0.017}_{-0.020} | 6.435^{+0.013}_{-0.020} | 6.435^{+0.017}_{-0.021} |
| E_{FeKγ} (keV) | 6.773^{+15.3}_{-5.50} | 7.1^{+1.0}_{-1.5}     | 7.0^{+0.13}_{-0.38}  | 7.08^{+0.06}_{-0.31}   |
| E_{νcyc1} (keV) | 351^{+166}_{-18}       | 39.4^{+1.1}_{-1.4}    | 31.7^{+2.7}_{-2.4}   | 31.9^{+1.6}_{-1.4}    |
| σ_{νcyc1} (keV) | 6.2^{+2.8}_{-0.8}      | 4.1^{+1.6}_{-1.4}     | 5.1^{+0.9}_{-0.7}    | 5.7^{+0.7}_{-0.8}     |
| Strength1 | 174^{+10}_{-8.5}        | 6.5^{+14.8}_{-3.6}    | 16.9^{+15.5}_{-1.6}  | 7.6^{+7.4}_{-2.7}     |
| E_{νcyc2} (keV) | 49.3^{+11.7}_{-1.7}    | 50.1^{+2.9}_{-1.6}    | 46.9^{+2.3}_{-1.4}   | 51.6^{+1.3}_{-1.6}    |
| σ_{νcyc2} (keV) | 6.8^{+6.7}_{-0.5}      | 3.2^{+0.9}_{-2.9}     | 8.6^{+1.6}_{-2.0}    | 9.3^{+2.8}_{-2.8}     |
| Strength2 | 48.0^{+59.0}_{-7.5}     | 16.2^{+15}_{-11}      | 59^{+47}_{-16}       | 40^{+13}_{-16}        |
| Reduced-$χ^2$ (dof) | 0.8646 (269)            | 0.8645 (270)          | 0.8323 (267)         | 0.8732 (272)          |