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The Study of Variations of Cyclotron Resonant Scattering Features in GX 301-2 by using the INTEGRAL/IBIS*

Yu Guangwen[1,2], Wang Wei[1]

(1. National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China, Email: wangwei@bao.ac.cn;
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: With long-term hard X-ray monitoring, observations on high mass X-ray binary GX 301-2 from 2003-2011 performed by INTEGRAL/IBIS, we first systematically studied its spectral properties in different accreting luminosities and orbital phases. The cyclotron resonant scattering feature (CRSF) at energies from 35-47 keV was detected in the hard X-ray spectra, suggesting the magnetic field of 5×10^{12} Gs. The variations of the CRSF show no relation to the X-ray luminosity while the line centroid energy of the CRSF has a positive correlation to the photon index and spectral cutoff energy, and there also exists a weak correlation between the absorption depth and cutoff energy. These relations support the idea that the spectral cutoff in accreting X-ray pulsars is strongly affected by the cyclotron resonant scattering. The correlation between the ratio of the line width to the centroid energy and absorption depth implies a tall cylindrical accreting column on the surface of the neutron star in GX 301-2. The explanation of the long spin period in GX 301-2 requires a strong surface magnetic field at least higher than 2×10^{14} Gs which is contradict with the measured value based on the cyclotron line energy. The line-forming region with a height at least larger than two neutron star radii is proposed to resolve the contradiction. This scenario is supported by the tall cylindrical accreting column on the neutron star surface in GX 301-2 according to the variation patterns of the CRSF. In addition, the possible evolution scenario of accreting magnetars like GX 301-2 is briefly discussed, and GX 301-2 would be an accreting magnetar in the equivalence phase.

Key words: GX 301-2; X-rays binaries; Neutron; Magnetic fields

1 Introduction

The high mass X-ray binaries (HMXBs) are X-ray sources composed of a nearly-type massive star and an accretion compact object (the neutron star or black hole). A major part of HMXBs which harbor X-ray pulsars are believed to be the magnetic neutron stars with a relatively strong magnetic field of 10^{12} Gs[1]. Their X-ray emission can be powered by the accretion disk (disk-fed) or direct accretion from the radiative wind (wind-fed) of the donor star. The high energy luminosity variation is generally due to the changes of the orbital phase and accreting rates.

GX 301-2 (4U 1223-62) is a high-mass X-ray binary system consisting of a neutron star and an early B-type optical companion Wray 977. Its distance is quite uncertain, with estimates between 1.8 kpc[2] and 5.3 kpc[3]. The latest estimate is about 3 kpc determined by the interstellar absorption[4]. The orbital period of the

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作者简介：于光雯，女，硕士. 研究方向：高能天体物理. Email：gwyu@bao.ac.cn
通讯作者：王　伟，男，研究员. 研究方向：高能天体物理. Email：wangwei@bao.ac.cn

system is 41.5 d with a high eccentricity of 0.5[5-6]. The neutron star is an accreting X-ray pulsar with a spin period of 680-700 s[7-8]. GX 301-2 is a variable X-ray source whose X-ray luminosity powered by the wind-fed direct accreting process which changes with the orbital phases.

The cyclotron absorption line feature of GX 301-2 around 37 keV was first discovered by Makishima & Mihara (1992)[9] based on the Ginga observations, and then confirmed by Orlandini (2000)[10] using the BeppoSAX observations. This Cyclotron Resonant Scattering Feature (CRSF) is produced by the resonant scattering of photons by electrons whose energies are quantized into Landau levels by the magnetic fields[11]. Therefore cyclotron resonance scattering features can be used to directly measure the magnetic field of the neutron star, and provide a useful way to understand the accretion geometry and physics near the surface of the neutron star. However, the cyclotron line centroid energy in GX 301-2 shows large variations and deviations by different measurements. Based on the RXTE data, Kreykenbohm et al. (2004)[12] reported the variable cyclotron line with energies from 30-38 keV according to the phase-resolved spectra. La Barbera et al. (2005)[13] detected the CRSFs with the centroid energies from 45-53 keV in different orbital phases with the BeppoSAX observations. Doroshenko et al. (2010)[6] detected a cyclotron scattering line at 46 keV in GX 301-2 with early INTEGRAL observations. Recently Suzaku broadband spectroscopy on GX 301-2 showed the variations of CRSFs from 28-43 keV[14], which is still consistent with early Ginga and RXTE results, but lower than the reported centroid energies by BeppoSAX and INTEGRAL. This discrepancy should result from that previous BeppoSAX and INTEGRAL results used a Gaussian line profile to fit the absorption dips, while other work applied the cyclotron absorption line profile into the data.

The CRSF centroid energy in GX 301-2 shows a large variation near 25 keV according to previous different observations, which makes it the largest variation scale in all accreting X-ray pulsars with CRSF measurements. Previous different missions reported different centroid energy ranges for CRSFs in GX 301-2 using different line profile models. Then more observations need systematical studies of the centroid energy variation range in GX 301-2 with the same spectral line model in fittings. In addition, what are this variation pattern of CRSFs and the relationship of CRSFs to continuum spectral properties in the supergiant X-ray binary GX 301-2? In the Be X-ray transient and the low-mass X-ray binary Her X-1, the correlations between CRSF centroid energies and X-ray luminosities are discovered[15-17]. GX 301-2 has the different companion star and the different accreting process (the wind-fed direct accretion) from the Be X-ray transient and the low-mass X-ray binary. Thus the relation between the CRSF and the continuum spectral property in GX 301-2 should be studied in detail, which would help to understand the accreting processes and the geometry in supergiant X-ray binaries.

The nature of accreting X-ray pulsars with long spin periods like GX 301-2 is not well understood. In the standard accreting and spin-period evolution scenario in X-ray binaries, the neutron star is very difficult to spin down to several hundred seconds[18] in the so-called ejector and propeller phases. A possible way to spin down fast requires a highly magnetized neutron star with a magnetic field higher than the critical value $B_{cr} = m_e^2 c^3/e\hbar = 4.4\times10^{13}$ Gs[19]. This proposed class of compact objects is re-named as accreting magnetars which have been used to explain the nature of some superslow pulsation X-ray pulsars, e.g. 4U 2206+54 (Pspin ~ 5560s[20-21]), 2S 0114+65 (Pspin ~ 9700s[22]), SXP 1062 (Pspin ~ 1060s[23]). GX 301-2 with a long spin period of ~700s, also needs a magnetar assumption[6]. Then detailed analysis on the X-ray spectral variations of GX 301-2 would help us to understand this magnetar candidate. There may exist common features and differences between the normal neutron star systems and magnetars, which also needs more observations and theoretical work.

Using the archived data of GX 301-2 collected by the INTEGRAL observations in 2003-2011, we mainly concentrated on searching for the CRSFs in the hard X-ray spectra of 18-100 keV and studying the correlations between the CRSF and the continuum spectral parameter. In Section. 2 of this paper, we show the information of the INTEGRAL observations and briefly introduce the data analysis. In Section. 3, we study the spectral properties and search for CRSFs of GX 301-2 in different luminosity ranges. A cyclotron absorption line model cyclabs is applied in our analysis. The study of the possible correlation between the CRSF and the spectral parameter are presented for GX 301-2 in Section. 4. We also study the spectral parameter and the CRSF versus the orbital phase in Section. 5. We summarize our results in the last section Section. 6 and discuss the implication of the results on the nature of GX 301-2.

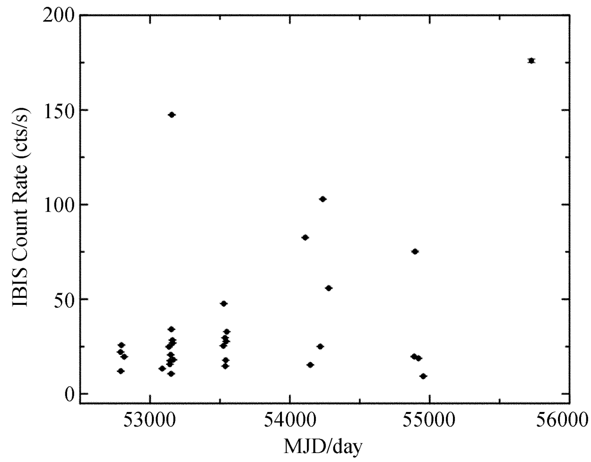

Fig. 1 The IBIS count rate variations of GX 301-2 in the energy range of 20 – 40 keV from 2003 – 2011. GX 301-2 is a highly variable source with the mean detected IBIS rate from 9–180 cts/s

2 INTEGRAL observations

The INTEGRAL is the currently operational space-based hard X-ray/soft gamma-ray telescope by ESA[24]. GX 301-2 is observed with the frequent pointing observational surveys on the Carina region from 2003–2011 by the INTEGRAL satellite. The hard X-ray data are obtained by the INTEGRAL Soft Gamma-Ray Imager[25] which has a 12′ (FWHM) angular resolution and arcmin source location accuracy in the energy band of 15–200 keV. The JEM-X aboard on the INTEGRAL is a small X-ray telescope covering about 4–30 keV, which could help to constrain the continuum of IBIS hard X-ray sources in low energy bands. However, JEM-X has a small field of view (off-source axis angle 5°), cannot detect GX 301-2 in most observational revolutions.

In this work, we used the available archival data for the IBIS observations where GX 301-2 is within ~10 degrees of the pointing direction with the corrected on-source time longer than 15 ks for each observation. In Table 1, the information of available INTEGRAL observations used in this paper is summarized. The INTEGRAL observations provided a long-term monitoring on GX 301-2 from 2003 – 2011. The archival data used in our work are available from the INTEGRAL Science Data Center (ISDC). The analysis is made with the standard INTEGRAL off-line scientific analysis (OSA[26]) software, version 10. The individual pointing in each satellite revolution (about 3 days) processed with OSA 10 is mosaicked to create sky images for the source detection. We have used the energy range of 20 – 40 keV by the IBIS for the source detection, significance levels and the quoted source fluxes for each revolution (see Table 1).

From Table 1, we can see that the source is variable in hard X-ray bands, which is typical for these class of wind-fed accreting X-ray binaries. The mean IBIS count rate of GX 301-2 (20–40 keV) in each revolution has a large variation range from <10 cts/s to ~180 cts/s. The spectral properties of GX 301-2 would vary with the different accreting luminosities and orbital phases. In following spectral analysis, we will extract the hard X-ray spectrum of GX 301-2 from 18–100 keV for each revolution. The spectral analysis processes then are made on these spectra to probe the variations of spectral properties of GX 301-2 in different luminosity ranges.

3 Hard X-ray spectral properties of GX 301-2

We have extracted the X-ray spectra from 18–100 keV by the IBIS in all observational revolutions for GX 301-2. These spectra will be fitted with a suitable continuum model, and then we will try to fit the cyclotron absorption line, deriving both the continuum spectral parameters and cyclotron line parameters. With frequent observations by the IBIS, covering a wide luminosity range and different orbital phases, we can study the variation patterns of the cyclotron scattering line feature.

Table 1 INTEGRAL/IBIS observations of the field around GX 301-2 within the off-axis angle 10°. The time intervals of observations in the revolution number and the corresponding MJD dates, and the corrected on-source exposure time are listed. Mean IBIS count rate in the energy range of 20–40 keV was also shown

Rev. Num	Obs Date (MJD)	On-source time(ks)	IBIS count rate(cts/s)	Rev. Num	Obs Date (MJD)	On-source time(ks)	IBIS count rate(cts/s)
76	52788.9–52790.1	71.2	22.16 ± 0.11	323	53527.2–53529.3	108.0	47.69 ± 0.09
77	52790.9–52791.4	31.7	12.01 ± 0.17	326	53536.0–53537.9	102.6	29.62 ± 0.11
78	52795.7–52796.5	35.5	25.74 ± 0.18	327	53538.8–53541.3	147.6	14.70 ± 0.08
85	52814.8–52816.1	99.1	19.62 ± 0.16	328	53541.8–53544.2	118.7	17.76 ± 0.09
176	53087.0–53088.6	116.0	13.37 ± 0.09	329	53544.7–53547.2	156.3	27.72 ± 0.08
192	53134.9–53137.5	205.1	24.94 ± 0.13	330	53548.0–53550.1	119.6	32.84 ± 0.09
194	53141.2–53143.5	172.1	15.68 ± 0.14	518	54110.5–54112.2	130.3	82.56 ± 0.18
195	53143.9–53146.5	204.7	17.50 ± 0.15	530	54145.6–54146.7	119.7	15.24 ± 0.15
196	53146.9–53149.5	204.5	20.65 ± 0.15	554	54217.5–54220.0	195.0	25.01 ± 0.13
197	53150.2–53152.5	177.3	10.65 ± 0.16	560	54235.4–54238.0	195.9	102.95 ± 0.14
198	53152.8–53155.4	202.1	34.07 ± 0.18	574	54277.6–54278.9	43.3	55.90 ± 0.16
199	53155.8–53158.5	199.7	147.42 ± 0.19	778	54888.9–54890.1	101.2	19.67 ± 0.20
200	53159.6–53161.5	140.7	28.41 ± 0.19	780	54895.1–54896.1	81.1	75.20 ± 0.25
201	53161.9–53164.4	176.6	26.86 ± 0.16	788	54919.2–54920.0	65.9	18.80 ± 0.26
202	53165.3–53167.4	136.3	18.04 ± 0.18	800	54954.3–54955.9	130.5	9.32 ± 0.18
322	53523.8–53526.1	141.3	25.42 ± 0.08	1058	55727.1–55727.7	17.1	176.05 ± 0.97

The IBIS covers an energy range from 18–100 keV. A small telescope, the JEM-X covering lower energy ranges from 4 – 30 keV could also detected the same source but requiring a much smaller off-axis angle. However, we have checked all available JEM-X data, only in a few revolutions we can extract a JEM-X spectrum for GX 301-2. A broader energy band spectrum from 4–100 keV could better constrain the continuum of GX 301-2. However, only very limited number of JEM-X spectra can be used to carried out statistical studies on spectral properties in the followings, for which we mainly used the IBIS data.

Here we will show one spectrum sample obtained by both the JEM-X and IBIS data to present the spectral properties of GX 301-2 in hard X-rays. This spectrum is derived from the revolution 176 when both JEM-X and IBIS detectors have detected GX 301-2 with a good significance level. In Fig. 2, the combined spectrum from 4–100 keV obtained by both JEM-X and IBIS for GX 301-2 is presented. The cross-calibration studies on the JEM-X and IBIS/ISGRI detectors have been made using the Crab observation data, and the calibration between the JEM-X and the IBIS can be good enough within ~ 6% (see samples in [21–22]). In the spectral fittings, the constant factor between the JEM-X and the IBIS is set to be one. The spectral analysis software package used is the XSPEC 12.6.0q.

Generally, the hard X-ray spectrum of accreting X-ray pulsars like GX 301-2 can be described by a power-law model plus a high energy exponential roll off (hereafter cutoffpl): $A(E) = KE^{-\Gamma}\exp(-E/E_{\mathrm{cutoff}})$. Other simple spectral models like the single power-law model, the thermal bremsstrahlung model, a blackbody plus a power-law model are also applied to fit the spectra of this source. However, these models cannot fit the hard X-ray spectra of GX 301-2 better than the cutoffpl model for the spectra from 4–100 keV, also for the cases from 18–100 keV (i.e., the larger reduced value of χ^2), therefor we just use the cutoff power-law model in the following spectral analysis.

The X-ray spectrum in Fig. 2 is initially fitted with a cutoffpl model (in the top panel of the figure). There are some features in residuals, one obvious feature around 6−7 keV is the Fe K_α line, the other is the known cyclotron absorption feature around 30−40 keV. In the middle panel of Fig. 2, we try to first fit the Fe K_α line and low energy band data points. We have used a Gaussian line profile to fit the iron line feature $A(E)=(K/\sqrt{2}\sigma_{\rm Fe})\exp(-(E-E_{\rm Fe})^2/2\sigma_{\rm Fe}^2)$, where $E_{\rm Fe}=6.4$ keV is the energy of iron line, $\sigma_{\rm Fe}$ is the line width, K is the line flux) and fixed $E_{\rm Fe}=6.4$ keV, and $\sigma_{\rm Fe}=0$. After the fittings, a broad absorption line feature from 30−50 keV appears in the residuals which are the cyclotron scattering line. Hence we have added the cyclotron scattering components to improve the spectral fittings. We have used the XSPEC model cyclabs to fit the cyclotron scattering line component[27]: $M(E)=\exp\left[-D_{\rm f}\dfrac{(W_{\rm f}E/E_{\rm cyc})^2}{(E-E_{\rm cyc})^2+W_{\rm f}^2}\right]$. In the bottom panel of Fig. 2, there are no obvious features after the cyclotron scattering line is added to fit the spectrum. Thus, the cutoffpl continuum model by using the cyclabs model plus a Gaussian iron line can well describe the spectrum of GX 301-2 from 4−100 keV. The fitted parameters are also shown in Table 2.

We also fitted the spectrum from 18−100 keV only obtained by the IBIS. The fitted parameters can be compared with the ones using the combined spectrum from 4−100 keV. In the top panel of Fig. 3, the spectrum is fitted with the cutoff power-law model. The absorption dip from 30−40 keV appears in the residuals. In the bottom panel, the cyclotron line feature is added to fit the spectrum. It is seen that no significant features in the residuals can be found.

From the best fitted parameters of the spectra for two energy bands shown in Table 2, we can compare the spectral fitting results of the combined data and only the IBIS data. For the one revolution, these two data sets give the similar spectral fitting results, for both continuum and cyclotron scattering features. Therefore, the spectral fitting parameters using only the IBIS data can well describe the hard X-ray properties of GX 301-2, specially the parameters

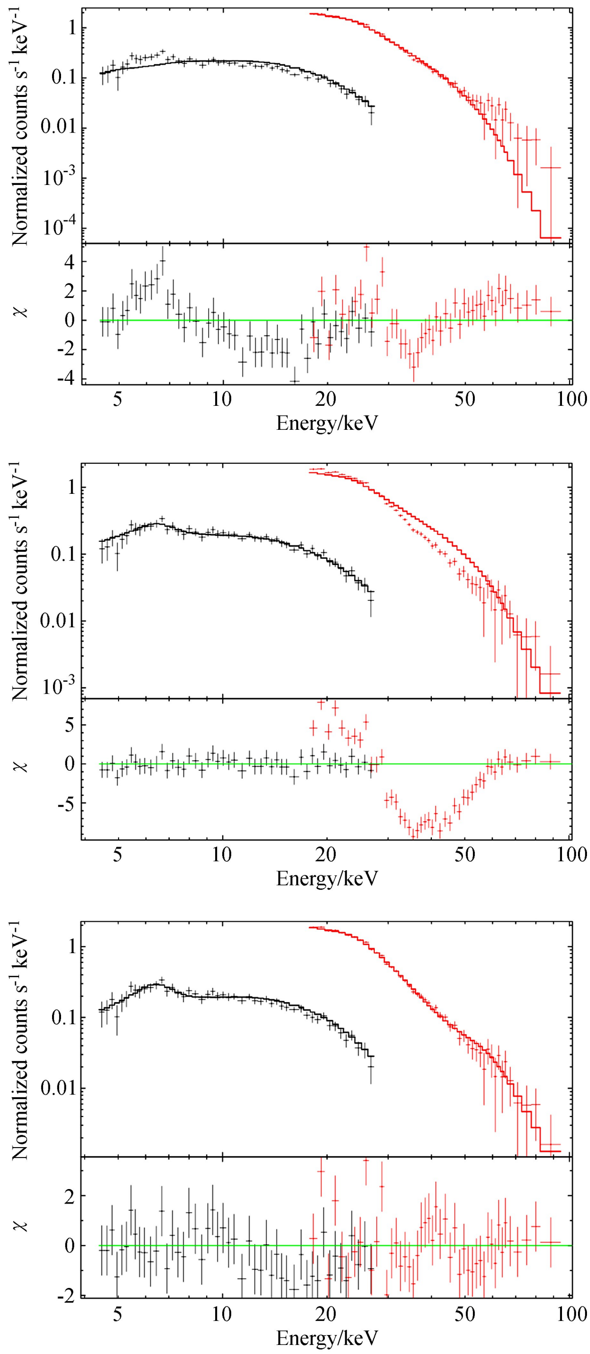

Fig. 2　The hard X-ray spectrum of GX 301-2 from 4−100 keV obtained by both JEM-X (low energy) and IBIS (high energy) for the observation revolution 176. In the Top, the spectrum is fitted with a power-law model anda high energy cutoff (cutoffpl). In the Middle, the spectrum is fitted with the cutoffpl plus a Gaussian line with the fixed Fe line energy at 6.4 keV. A strong absorption line feature from 30−50 keV is detected in residuals. In the Bottom, the spectrum is fitted with the cutoff using the cyclotron line model cyclabs plus a Gaussian line with the fixed Fe line energy at 6.4 keV. See the text for details

Table 2 The hard X-ray spectral properties (according to spectrum samples in Figs. 2-3) of the high mass X-ray binary GX 301-2. The flux is given in the unit of 10^{-10} erg $cm^{-2}s^{-1}$ within the range of 18-100 keV. The iron line flux K is in the unit of 10^{-5} photons $cm^{-2}s^{-1}$

4-100 keV	spectrum							
Model	Γ	E_{cutoff} /keV	E_e /keV	Width /keV	Depth	K	Flux	reduced χ^2 (d. o. f)
cutoffpl	−1. 89±0. 09	5. 2±0. 2					8. 3±0. 2	2. 983(94)
cutoffpl+Fe	−1. 38±0. 18	7. 8±0. 7				4. 4±1. 1	9. 0±0. 3	7. 722(93)
cutoffpl * cyclabs+Fe	−1. 34±0. 13	7. 7±0. 5	38. 5±0. 6	15. 3±2. 9	1. 1±0. 1	3. 8±0. 9	8. 6±0. 2	1. 066(90)

18-100 keV							
Model	Γ	E_{cutoff} /keV	E_e /keV	Width /keV	Depth	Flux	reduced χ^2 (d. o. f)
cutoffpl	−1. 68±0. 21	5. 5±0. 2				8. 3±0. 2	2. 892(44)
cutoffpl * cyclabs	−1. 36±0. 29	7. 5±0. 8	38. 3±1. 0	15. 4±3. 5	1. 0±0. 1	8. 5±0. 2	1. 238(42)

of the CRSF. Then we use the cutoff power-law model together with a cyclotron scattering line to fit the spectra derived in all available observational revolutions. The continuum spectral parameters and CRSF parameters are collected together for the next correlation studies.

In different accreting luminosities, one cyclotron scattering line feature is detected by the present INTEGRAL/IBIS observations. The detected line centroid energy in GX 301-2 varies from 35-47 keV according to all the available data in different accreting luminosities (also see Fig. 4). This energy range is consistent with the early Ginga, RXTE, and Suzaku results. The variation patterns of the CRSF may be related to the continuum spectral properties, which will be discussed in the next section.

4 Correlation studies of cyclotron resonance spectral features

The variations of CRSFs may be induced by some physical parameters in accreting X-ray pulsars, which can be statistically studied with the relations between the CRSFs and spectral properties. The correlations between the fundamental line energy of the CRSFs and the X-ray luminosity are reported in some X-ray pulsars, like the Be X-ray transients 4U 0115+63[15] and GX 304-1[16] during their outbursts, and a low mass X-ray binary Her X-1[17]. A positive correlation between the energy of the fundamental line and the photon index is discovered in 4U 0115+63 during the giant outburst in 2008[15]. In addition, with collecting observation data for different X-ray pulsars, a positive correlation between the energy of the fundamental CRSF and the cutoff energy in the accreting X-ray

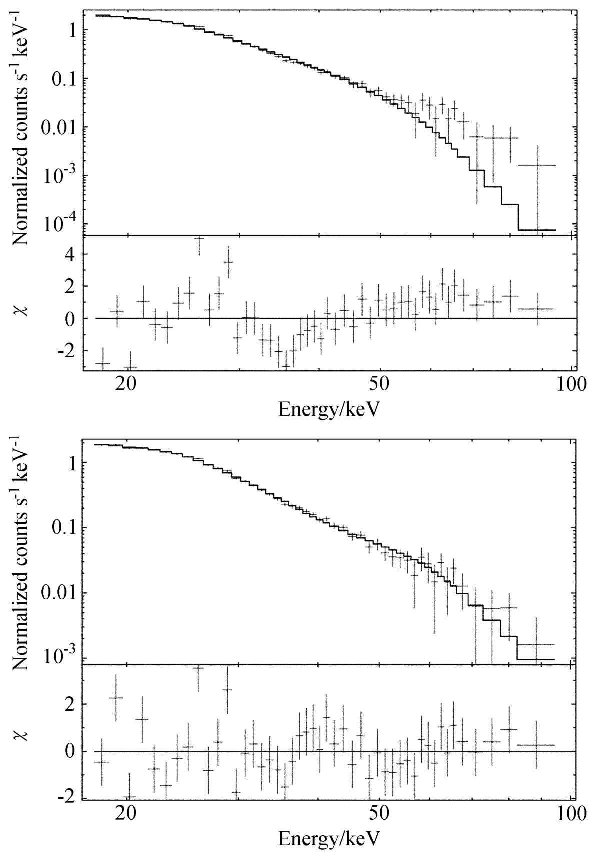

Fig. 3 The hard X-ray spectrum of GX 301-2 from 18-100 keV obtained by the IBIS for the observation revolution 176. In the Top, the spectrum is fitted with a power-law model and a high energy cutoff (cutoffpl). In the Bottom, the spectrum is fitted with the cutoffpl using the cyclotron line model cyclabs. See the text for details

pulsar continuum is found[28-30]. It is suggested that the spectral cutoff in accreting X-ray pulsars should be strongly affected by the cyclotron resonant scattering.

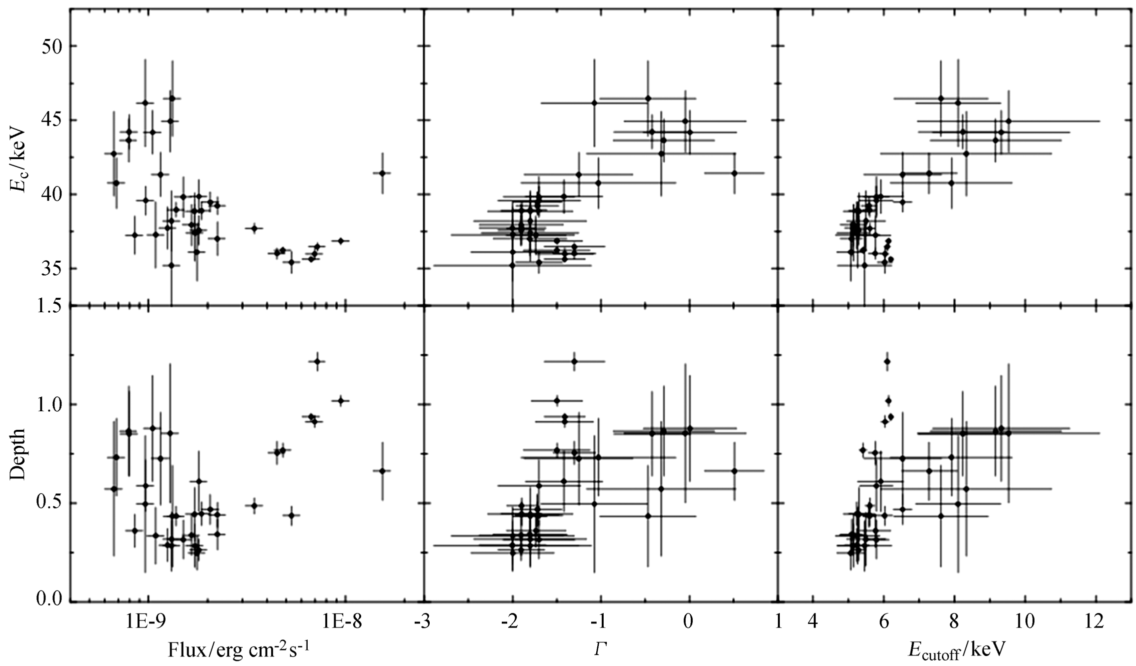

Fig. 4 The derived cyclotron energy E_c and the depth of the cyclotron line versus the three spectral parameters: the hard X-ray flux in the range of 18–100 keV, the photon index Γ and the exponential cutoff energy E_{cutoff}

The production of cyclotron resonant absorption line features near the surface of the neutron star is physically complicated, which will sensitively depend on the accretion states and the accretion geometry (e. g., [31-32]). Thus the detection of cyclotron scattering line features is not only used to identify a magnetized neutron star in binary systems but also important for studies on the accretion process and the geometry near the surface of a neutron star[32]. The variation pattern of the CRSFs and their physical origins need more studies with more observations in detail. With the derived spectral parameters of GX 301-2 by the IBIS long-term observations, we can first systematically study the variation patterns of the CRSF and probe the accreting geometry in the wind-fed accreting supergiant binary GX 301-2. In the following, we will use the Pearson product-moment correlation coefficient (hereafter r) to describe the correlation between spectral parameters, where $-1<r<1$, and larger $|r|$ values imply stronger correlation. Generally, there should exist the correlation between two parameters when $|r|>0.5$.

In Fig. 4, we have presented the relationships among the centroid energy E_c, the depth of the CRSF and three spectral parameters: hard X-ray flux from 18–100 keV, photon index Γ and cutoff energy E_{cutoff}. The centroid energy of the CRSF has no relation to the X-ray flux in GX 301-2, which is different from the Be/X-ray pulsars 4U 0115+63 and GX 304-1. But the line energy has the positive correlations to the photon index Γ ($r=0.609$) and the cutoff energy E_{cutoff}($r=0.687$). The relation of E_c versus Γ is similar to the case in the Be/X-ray pulsar 4U 0115+63[15]. The relation of E_c versus E_{cutoff} is consistent with the common behavior by collecting different accreting X-ray pulsars[28-30]. These correlations support the conclusion that the spectral properties of accreting X-ray pulsars in hard X-ray bands will be affected by the CRSFs.

The depth of the CRSFs is also changed, however, it seems to have no relation to the X-ray flux. While the depth still show a weak positive correlation to the cutoff energy E_{cutoff} ($r=0.509$), but no significant relationship to the spectral index Γ ($r=0.114$). Hence the spectral cutoff energy E_{cutoff} has the relationship to both the energy and the depth of the CRSF in GX 301-2. Then the high energy cutoff in the spectrum of the accreting X-ray pulsars GX 301-2 should be mainly induced by the cyclotron resonant scattering.

In the searching for the CRSFs in different accreting X-ray pulsars with the RXTE, Coburn et al. (2002)[30] also found a correlation between the absorption depth and the ratio of the width to the energy in the phase averaged spectra of the accreting X-ray pulsars. This relation can help to understand the accretion geometry of accreting X-ray pulsars. In an accreting column, one can find[33]: Width/$E_c \propto (kT_e \cos^2\theta)1/2$, where kT_e as the electron temperature along the magnetic fields is nearly constant, θ is the angle between the line of sight and the magnetic field. Generally, we assume that there exist two classes of accreting geometry patterns: a flat coin shape and a tall cylindrical shape. In the flat coin shape, the depth of CRSFs is largest when the line of sight is perpendicular to the direction of the magnetic field[34]. While in a tall cylinder shape, the depth is largest when the line of sight is parallel to the magnetic field[34], which then predicts a positive correlation between the depth and the ratio of the width to the energy. Kreykenbohm et al. (2004)[12] analyzed the RXTE data, derived this relation in the single source GX 301-2. With the present INTEGRAL observations, we derived the variation of the CRSFs in GX 301-2, then presented the relation between the ratio of the width to the energy and the absorption depth in Fig. 5. Though large error bars exist, the correlation between the ratio and depth ($r = 0.837$) is confirmed by our analysis with a larger data set from the IBIS. With the properties of the CRSF and its variation pattern, it is suggested that GX 301-2 has a cylindrical column accretion geometry.

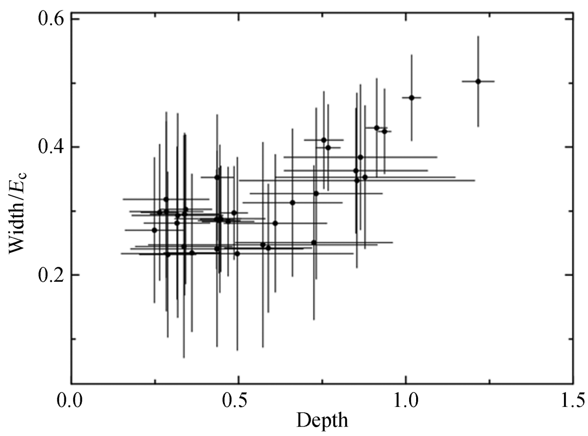

Fig. 5 The derived Width/E_c versus the depth of the cyclotron line for GX 301-2

5 The CRSFS versus the orbital phase

GX 301-2 has an orbital period of ~41.5 days, and its X-ray luminosity changes in one binary orbit. The INTEGRAL/IBIS performed a long-term observations on this source, covering the different orbital phases. Thus we can derive the orbital phase resolved spectra for GX 301-2, and study the variation of spectral properties versus the orbital phase.

Using the orbital ephemeris provided by Koh et al. (1997)[5], we divided one orbital circle into fourteen phase bins, and re-combined the INTEGRAL data (in units of the science windows, each has a duration of ~2000–4000 s) according to the defined phase bins. The data analysis processes were re-made for all data in each orbital phase, so that we can extract the hard X-ray spectrum of GX 301-2 for each orbital phase bin. Similar to the spectral fitting processes in Section 3, we have derived the best fitted continuum spectral parameters, like the X-ray flux, Γ and E_{cutoff}, the centroid energies and the absorption depth of the CRSF in GX 301-2. In Fig. 6, we have presented the different spectral parameters versus the orbital phase.

The Hard X-ray flux variation shows the flare around the orbital phase 0.9, which is still consistent with the orbital profile derived by the RXTE/ASM data in the range of 1.5–12 keV[35]. This flare occurs around the orbital phase just before the periastron passage of the neutron star in GX 301-2. The other spectral parameters also show the variations over the orbital phase. Specially, the mean centroid energy of the CRSF over the orbit varies from 37–44 keV, which is consistent with the variation range derived in different luminosities presented in Section 3. The flux variation has no correlations to the changes of other spectral parameters. But the centroid energy and depth of the CRSF still show the similar variation profiles to those of the photon index Γ and the spectral cutoff energy $E_{\rm cutoff}$ over the whole orbital phase. These correlations are similar to the relations found in Section 3. Hence the relations between the CRSF and continuum spectral parameters in GX 301-2 are confirmed with the orbital resolved spectral analysis.

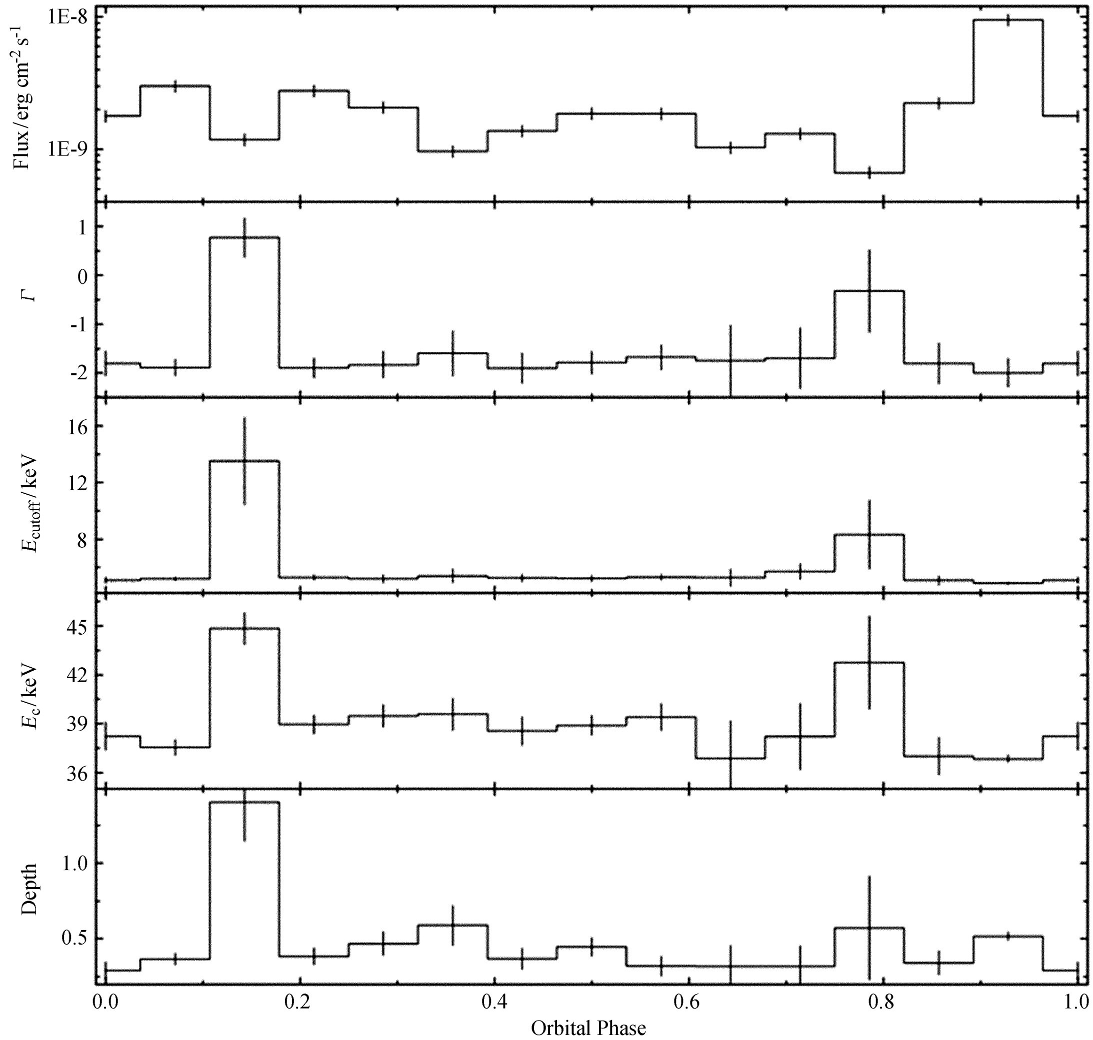

Fig. 6 The derived cyclotron line energy $E_{\rm c}$, the depth of the cyclotron line and the three spectral parameters: the hard X-ray flux in the range of 18−100 keV, the photon index Γ and the exponential cutoff energy $E_{\rm cutoff}$ versus the orbital phase

6 Summary and discussion

In this work, we have carried out the data analysis on GX 301-2 with the INTEGRAL/IBIS long-term observations. The cyclotron scattering line at energies from 35−47 keV in the X-ray spectra of GX 301-2 is confirmed by our analysis. The variation range of the line centroid energy is still consistent with the previous reports by Ginga[9], RXTE[12], Suzaku[14].

The variation patterns of the CRSFs and spectral properties of GX 301-2 are systematically studied over different luminosity ranges and orbital phases. The centroid energy of the CRSF has no relation to the X-ray luminosity, which is different from other accreting X-ray pulsars, like the Be X-ray transients. While the line centroid energy shows the correlation to the photon index and the spectral cutoff energy, and the absorption depth also has a weak correlation to the cutoff energy. These relations support that the spectral profile, specially, the high energy cutoff is strongly affected by the cyclotron resonant scattering in GX 301-2. This characteristic is similar to other accreting X-ray pulsars, suggesting that there exist the similar radiation processes in these X-ray pulsars independent of their companion stars and accreting processes. In addition, a correlation between the ratio of the line width to the centroid energy and absorption depth in GX 301-2 implies a tall cylinder accreting column on the surface of the magnetized neutron star. This special accreting geometry could help us to understand the nature of the neutron star in GX 301-2.

As shown in the introduction, GX 301-2 could be an accreting magnetar candidate. Since the discovery of the GX 301-2[36], the spin period changes dramatically, and shows both spin-down and spin-up trends in the last thirty years (see [12,14]). Therefore GX 301-2 is located in a torque equivalence phase, hence its equilibrium spin period can be estimated with the surface magnetic field of the neutron star and its average luminosity (the accreting rate). According to a standard model of the accreting disk[18], a critical period is defined by equating the corotational radius of the neutron star to the magnetospheric radius, which gives

$$P_{\rm cr} \approx 18\kappa^{3/2}\frac{M_{\rm NS}}{1.4M_{\odot}}^{-5/7}\left[\frac{\mu}{10^{30}\,{\rm Gcm}^3}\right]^{6/7}\left[\frac{\dot{M}}{10^{15}\,{\rm gs}^{-1}}\right]^{-3/7}{\rm s},$$

where $\kappa \sim 0.5-1$ is the geometrical parameter of the accretion flow, μ is the dipole magnetic moment of the neutron star, and $\dot{M}=\pi r_{\rm G}^2\rho_{\infty}V_{\rm vel}$ is the mass with which a neutron star interacts in a unit time as it moves through the stellar wind of the density ρ_{∞} with a velocity $V_{\rm rel}=\sqrt{V_{\rm NS}^2+V_{\rm w}^2}$, $r_{\rm G}=2GM_{\rm NS}/V_{\rm res}^2$ is the Bondi radius. This equation gives a magnetic field near 10^{15} Gs for the case of GX 301-2. Other stellar-wind accreting models in X-ray binaries can also estimate the equilibrium spin period (see discussions on some models in Doroshenko et al. 2010[6]), which also implies a highly magnetized neutron star in GX 301-2 with $B \sim (2-3)\times10^{14}$ Gs[6]. Independent on the wind-fed accreting models, the estimated magnetic field of GX 301-2 is located in the range of a typical magnetar.

However, if assuming that the cyclotron scattering line comes from the surface of the neutron star, the magnetic field of the star can be estimated by

$$[B/10^{12}{\rm G}] = [E_{\rm cyc}/11.6\ {\rm keV}](1+z),$$

Where $E_{\rm cyc}$ is the energy of the fundamental line. Here we can take the maximum measured values $E_{\rm cyc}=47$ keV, and $z \sim 0.3$, the gravitational redshift near the surface of the neutron star. Then we derived the magnetic field of $\sim 5\times10^{12}$ Gsfor GX 301-2 which is much lower than the magnetic field range for common magnetar candidates. Why a large discrepancy in observations and theoretical expectations exists?

It has been suggested that the line-forming region may reside in an accretion column with a significant height[37,6] above the surface of the neutron star. Then the measured magnetic field based on the cyclotron line energy is just the magnetic field strength near the line-forming region rather than the surface. Since $B_{\rm cyc}=(R/R_{\rm NS})^{-3}B_{\rm suff}$, where R is the radius of the line-forming region. Then assuming $B_{\rm surf}\sim 2\times10^{14}$ Gs, and $B_{\rm cyc}\sim 4\times10^{12}$ Gs, one can derive a radius of line emission region $R \sim 3.7$ RNS. If the surface magnetic field is near 10^{15} Gs, the requested emission region will be higher. Thus the emission region must be located in a height at least larger than $2R_{\rm NS}$. The accreting and emission region will be like a cylinder column with a height $>>2R_{\rm NS}$ in GX 301-2. This geometry is supported by our analysis results on GX 301-2: the correlation between the ratio of the line width to the centroid energy and the absorption depth implies a tall cylinder accreting column on the surface of the highly magnetized neutron star.

Then the high mass X-ray binary GX 301-2 could be very special, and can belong to a new class of compact objects—accreting magnetars. Accreting magnetars have the quite different properties from the isolated magnetar candidates (see discussions in [21]), anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs), which are the isolated systems without companion stars. Of course, the physical origin of magnetars in both accreting and isolated systems is unknown. An evolution scenario for accreting magnetars has been suggested[21]. Magnetars born in the binaries could spin down faster in the propeller phase than other normal neutron star binaries (fast spin-down trends observed in two systems, 4U 2206+54 and SXP 1062), then its spin period could spin down to slower than 10^4 seconds. After the spin-down phase, the magnetar candidate can transfer into the spin-up process (a long-term spin-up trend is found in 2S 0114+65[22]). This spin-up process will stop till the accreting magnetar is located around the equilibrium spin period range (several hundred seconds). In this scenario, GX 301-2 is the successor of the younger and fast-evolved superslow pulsation X-ray pulsars (like4U 2206+54 and 2S 0114+65), it has become an older accreting magnetar in the torque equivalence phase. Hence GX 301-2 becomes interesting and very unique in the family of accreting magnetars.

Though the idea of accreting magnetars is proposed in some literatures ([21] and references therein), we need understand the nature of the magnetar definition. In Table 3, we show the present understanding of both isolated and accreting magnetars in observations and theories. In observations both candidates have longer spin period values, larger spin period derivative and younger ages relative to other normal systems. We may need to search for more common features in two classes of magnetars. The well-known magnetar candidates as AXPs and SGRs require aultra-strong magnetic field to produce X-ray bursts, which can reflect magnetic field activity. How to detect the signals of magnetic field activity in accreting magnetar candidates is an intriguing question in studying accreting magnetars in the future. The Chinese hard X-ray telescope-Hard X-ray Modulation Telescope (HXMT) will be launched in the next year, one of main scientific objects will be the monitoring magnetar candidates, specially, their spectral and temporal variations. Further studies on GX 301-2, specially, on the spectral features and flares, even bursts could improve our understanding on the nature of accreting magnetars and the magnetar family.

Table 3 The resent classification of magnetar family: isolated and accreting magnetars

	Isolated magnetars	Accreting magnetars
Spin period(s)	2–12	>several hundred
Spin period derivative(s/s)	10^{-12}–10^{-10}	10^{-7}–10^{-6}
Characteristic age(yr)	10^4–10^5	10^4–10^6
X-ray spectrum	0.1–10 keV, kT~0.1–1 keV >10 keV, Γ~0.5–1.5	Power-law with high energy cutoff
X-ray luminosity(erg/s) (1–100 keV)	Quiescence 10^{35}–10^{36} Bursts>1037	10^{34}–10^{37}
Energy power	magnetic field decay/activity	wind-fed accretion

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用 INTEGRAL/IBIS 卫星研究 GX 301-2 中回旋共振散射线性质

于光雯[1,2]，王　伟[1]

（1. 中国科学院国家天文台，北京　100012；2. 中国科学院大学，北京　100049）

摘要：利用 INTEGRAL/IBIS 卫星 2003~2011 年对 X 射线双星 GX 301-2 的观测数据，系统研究了 GX 301-2 在不同吸积光度和轨道相位的谱性质，得到 GX 301-2 的回旋吸收线的性质与 X 射线光度无关，其能量在 35~47 keV 之间，且能量与光指数和截断能量正相关，回旋吸收线的深度与截断能量有弱正相关，这表明在吸积 X 射线脉冲星中，回旋共振散射线对截断能量有很大影响。而回旋吸收线宽度与能量比值和深度正相关，这表明在 GX 301-2 表面存在一个吸积柱。由 GX 301-2 的自旋周期得到表面磁场强度大约为 2×10^{14} Gs，与通过回旋吸收线得到的磁场强度不符，但可以用吸积柱模型很好地解释。

关键词：GX 301-2；X 射线双星；中子星；磁场

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