Study of Cyclotron Resonance Scattering Feature Variations in GX 301-2 Using INTEGRAL/IBIS (Post-print)

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Abstract

Using long-term hard X-ray monitoring observations of the high-mass X-ray binary GX 301-2 from 2003-2011 performed by INTEGRAL/IBIS, we have for the first time systematically studied its spectral properties at different accretion luminosities and orbital phases. A cyclotron resonant scattering feature (CRSF) at energies from 35-47 keV was detected in the hard X-ray spectra, suggesting a magnetic field of Sx10}Z 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 with 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 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 2x 1014 Gs, which contradicts the measured value based on the cyclotron line energy. A 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 such as GX 301-2 is briefly discussed, and GX 301-2 would be an accreting magnetar in the equivalence phase.

Full Text

Preamble

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

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Abstract: Using long-term hard X-ray monitoring observations of the high-mass X-ray binary GX 301-2 from 2003–2011 performed by INTEGRAL/IBIS, we have systematically studied its spectral properties across different accretion luminosities and orbital phases for the first time. A cyclotron resonant scattering feature (CRSF) at energies of 35–47 keV was detected in the hard X-ray spectra, suggesting a magnetic field of 5×10^{12} G. The variations of the CRSF show no relation to X-ray luminosity, while the line centroid energy of the CRSF has a positive correlation with the photon index and spectral cutoff energy, and there also exists a weak correlation between absorption depth and cutoff energy. These relations support the idea that the spectral cutoff in accreting X-ray pulsars is strongly affected by cyclotron resonant scattering. The correlation between the ratio of line width to 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^{13} G based on the cyclotron line energy. The line-forming region with a height at least larger than two neutron star radii, which contradicts the measured neutron star radius, is proposed to resolve this 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.

Keywords: GX 301-2; X-ray binaries; Neutron stars; Magnetic fields

Introduction

High-mass X-ray binaries (HMXBs) are X-ray sources composed of a nearly massive star and an accreting compact object (neutron star or black hole). A major portion of HMXBs that harbor X-ray pulsars are believed to be magnetic neutron stars with relatively strong magnetic fields of ~10^{12} G. Their X-ray emission can be powered by either an 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 changes in orbital phase and accretion 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 5.3 optical companion, Wray 977. Its distance is quite uncertain, with estimates between 1.8 kpc and 5.3 kpc. The latest estimate is about 3 kpc determined by interstellar absorption. The orbital period of the system is ~41.5 days with a high eccentricity of 0.5. The neutron star is an accreting X-ray pulsar with a spin period of 680–700 s, powered by a wind-fed direct accretion process that changes with orbital phases [7–8].

The cyclotron absorption line feature of GX 301-2 around 37 keV was first discovered by Makishima & Mihara (1992) based on Ginga observations, and then confirmed by Orlandini et al. (2000) using 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. 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 according to different measurements. Based on RXTE data, Kreykenbohm et al. (2004) reported a variable cyclotron line with energies from 30–38 keV according to phase-resolved spectra. La Barbera et al. detected CRSFs with centroid energies from 45–53 keV in different orbital phases using BeppoSAX observations (2005). Doroshenko et al. (2010) 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 variations of CRSFs from 28–43 keV, 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 the fact 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 in the data.

The CRSF centroid energy in GX 301-2 shows a large variation near 25 keV according to previous different observations, making 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. More observations need systematic studies of the centroid energy variation range in GX 301-2 with the same spectral line model in fittings.

In addition, what are the variation patterns 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 low-mass X-ray binary Her X-1, correlations between CRSF centroid energies and X-ray luminosities are discovered [15–17]. GX 301-2 has a different companion star and different accreting process (wind-fed direct accretion) from the Be X-ray transient and low-mass X-ray binary.

Thus, the relation between the CRSF and continuum spectral property in GX 301-2 should be studied in detail, which would help to understand the accreting processes and 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. This requires a highly magnetized neutron star with a magnetic field higher than the critical value in the so-called ejector and propeller phases. A possible way to spin down fast requires a magnetic field of ~4.4×10^{13} G. This proposed class of compact objects is renamed as accreting magnetars, which have been used to explain the nature of some superslow pulsation X-ray pulsars, e.g., 4U 2206+54 (P_spin ~ 5560 s), 2S 0114+65 (P_spin ~ 9700 s), and SXP 1062 (P_spin ~ 1060 s). GX 301-2 with a long spin period of ~700 s also needs a magnetar assumption. Detailed analysis of 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 normal neutron star systems and magnetars, which also needs more observations and theoretical work. Using the archived data of GX 301-2 collected by INTEGRAL observations in 2003–2011, we mainly concentrated on searching for CRSFs in the hard X-ray spectra of 18–100 keV and studying the correlations between the CRSF and continuum spectral parameters.

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 possible correlations between the CRSF and spectral parameters are presented for GX 301-2 in Section 4. We also study the spectral parameters and the CRSF versus the orbital phase in Section 5. We summarize our results in the last section, Section 6.

INTEGRAL Observations and Data Analysis

[Figure 1: see original paper]

The INTEGRAL is the currently operational space-based hard X-ray/soft gamma-ray telescope by ESA. GX 301-2 is observed with 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, which has a 12 (FWHM) angular resolution and arcmin source location accuracy in the energy band of 15-200 keV. The JEM-X aboard 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°), and 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 long-term monitoring of 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 offline scientific analysis (OSA) software, version 10.

The individual pointings in each satellite revolution (about 3 days) processed with OSA 10 are mosaicked to create sky images for source detection. We have used the energy range of 20–40 keV by the IBIS for 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 this 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 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.

Hard X-ray Spectral Properties of GX 301-2

We have extracted the X-ray spectra from 18–100 keV by 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 continuum spectral parameters and cyclotron line parameters.

With frequent observations by IBIS, covering a wide luminosity range and different orbital phases, we can study the variation patterns of the cyclotron scattering line feature.

The IBIS covers an energy range from 18–100 keV. A small telescope, JEM-X covering lower energy ranges from 4–30 keV, could also detect 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 can we 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 a very limited number of JEM-X spectra can be used to carry 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 JEM-X and IBIS data to present the spectral properties of GX 301-2 in hard X-rays. This spectrum is derived from revolution 176 when both JEM-X and IBIS detectors have detected GX 301-2 with a good significance level. In [Figure 2: see original paper], the combined spectrum from 4–100 keV obtained by both JEM-X (low energy) and IBIS (high energy) 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 JEM-X and IBIS can be good enough within ~6% (see samples in [21–22]). In the spectral fittings, the constant factor between JEM-X and IBIS is set to be one.

The spectral analysis software package used is 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 rollover (hereafter cutoffpl):

$$N(E) \propto E^{-\Gamma} \exp(-E/E_{\text{cutoff}})$$

Other simple spectral models like the single power-law model, the thermal bremsstrahlung model, and a blackbody plus 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., with larger reduced χ^2 values). Therefore, we just use the cutoff power-law model in the following spectral analysis.

The X-ray spectrum in [Figure 2: see original paper] is initially fitted with a cutoffpl model (in the top panel of figure). There are some features in residuals: one obvious feature around 6–7 keV is the Fe K line, and the other is the known cyclotron absorption feature around 30–40 keV. In the middle panel of [Figure 2: see original paper], we try to first fit the Fe K line with a Gaussian line profile. We have used a Gaussian line profile to fit the iron line feature:

$$F(E) = F_{\text{Fe}} \exp\left(-\frac{(E - E_{\text{Fe}})^2}{2\sigma_{\text{Fe}}^2}\right)$$

where $E_{\text{Fe}} = 6.4$ keV is the energy of the iron line, σ_{Fe} is the line width, and F_{Fe} is the line flux. After the fitting and fixing, 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:

$$f(E) = \exp\left[-\tau_{\text{cyc}} \exp\left(-\frac{(E - E_{\text{cyc}})^2}{2\sigma_{\text{cyc}}^2}\right)\right]$$

In the bottom panel of [Figure 2: see original paper], there are no obvious features after the cyclotron scattering line is added to fit the spectrum. Thus, the cutoffpl continuum model 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 IBIS. The fitted parameters can be compared with the ones using the combined spectrum from 4–100 keV. In the top panel of [Figure 3: see original paper], 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 , we can compare the spectral fitting results of the combined data and only the IBIS data. For one revolution, these two data sets give 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, especially the continuum parameters.

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 available data in different accreting luminosities (also see [Figure 4: see original paper]). This energy range is consistent with 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.

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 CRSFs and spectral properties. The correlations between the fundamental line energy of CRSFs and X-ray luminosity are reported in some X-ray pulsars, like the Be X-ray transients 4U 0115+63. A positive correlation between the energy of the fundamental line and the photon index is discovered in 4U 0115+63 during their outbursts, and in low-mass X-ray binary Her X-1 and GX 304-1 during the giant outburst in 2008.

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 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.

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 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 geometry near the surface of a neutron star. The variation pattern of 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 ($|r| > 0.5$) imply stronger correlation.

In [Figure 4: see original paper], we have presented the relationships among the centroid energy, the hard X-ray flux in the range of 18–100 keV, the photon index, and the exponential cutoff energy, and the depth of the cyclotron line versus the three spectral parameters. 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 positive correlations to the photon index ($r = 0.687$) and the cutoff energy ($r = 0.609$), and is similar to the case in the Be/X-ray pulsar 4U 0115+63. The relation of $E_{\rm cyc}$ versus cutoff energy is consistent with the common behavior found 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 CRSF is also changed; however, it seems to have no relation to the X-ray flux. While cutoff energy has the relationship to the depth, still showing a weak positive correlation to the cutoff energy ($r = 0.114$). Hence, the spectral cutoff energy relationship to the spectral index cutoff (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 pulsar GX 301-2 should be mainly induced by the cyclotron resonant scattering.

In the searching for CRSFs in different accreting X-ray pulsars with RXTE, Coburn et al. (2002) also found a correlation between the absorption depth and the ratio of the width to the energy in the phase-averaged spectra of 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:

$$\mathrm{Width}/E_{\rm cyc} \propto (\cos\theta)^{1/2}$$

where 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. While in a tall cylinder shape, the depth is largest when the line of sight is parallel to the magnetic field, which then predicts a positive correlation between the depth and the ratio of the width to the energy.

Kreykenbohm et al. (2004) analyzed the RXTE data and 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 [Figure 5: see original paper]. 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 IBIS. With the properties of the CRSF and its variation pattern, it is suggested that GX 301-2 has a cylindrical column accretion geometry.

CRSF versus Orbital Phase

[Figure 6: see original paper]

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

Using the orbital ephemeris provided by Koh et al. (1997), we divided one orbital circle into fourteen phase bins and re-combined the INTEGRAL data (in units of 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, cutoff energy, the centroid energies, and the absorption depth of the CRSF in GX 301-2. In [Figure 6: see original paper], we have presented the different spectral parameters versus the orbital phase.

The hard X-ray flux variation shows a flare around 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. 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 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 similar variation profiles to those of the photon index and the spectral cutoff energy 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.

Summary and Discussion

In this work, we have carried out data analysis on GX 301-2 with 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 previous reports by Ginga, RXTE, and Suzaku.

The variation patterns of 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 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, especially the high-energy cutoff, is strongly affected by cyclotron resonant scattering in GX 301-2. This characteristic is similar to other accreting X-ray pulsars, suggesting that there exist similar radiation processes in these X-ray pulsars independent of their companion stars and accreting processes.

In addition, a correlation between the ratio of line width to centroid energy and absorption depth in GX 301-2 implies a tall cylindrical 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 GX 301-2, the spin period has changed dramatically, showing 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 accretion rate). According to a standard model of the accreting disk, a critical period is defined by equating the corotational radius of the neutron star to the magnetospheric radius, which gives:

$$P_{\rm eq} \approx 5 \times 10^3\ {\rm s} \cdot \mu_{30}^{6/7} \dot{M}_{15}^{-3/7}$$

where μ_{30} is the dipole magnetic moment of the neutron star in units of 10^{30} G cm^3, and $\dot{M}_{15}$ is the mass accretion rate in units of 10^{15} g s ^{1}. This equation gives a magnetic field near 10^{13} G 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), which also implies a highly magnetized neutron star in GX 301-2 with $B \sim (2-3) \times 10^{13}$ G.

Independent of the wind-fed accreting models, the estimated magnetic field of GX 301-2 is located in the range of a typical magnetar. However, assuming that the cyclotron scattering line comes from the surface of the neutron star, the magnetic field of the star can be estimated by:

$$E_{\rm cyc} = 11.6 \text{ keV} \cdot \frac{B_{12}}{1+z}$$

where B_{12} is the magnetic field in units of 10^{12} G, and $z \sim 0.3$ is the gravitational redshift near the surface of the neutron star. Here we can take the maximum measured values $E_{\rm cyc} = 47$ keV, and derive the magnetic field of $\sim 5 \times 10^{12}$ G for GX 301-2, which is much lower than the magnetic field range for common magnetar candidates.

Why does such a large discrepancy between observations and theoretical expectations exist? It has been suggested that the line-forming region may reside in an accretion column with a significant height above the surface of the neutron star [37,6]. 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 $B \propto r^{-3}$, where r is the radius of the line-forming region, then assuming $B_{\rm surf} \sim 2 \times 10^{13}$ G and $B_{\rm line} \sim 5 \times 10^{12}$ G, one can derive a radius of line emission region $\sim 3.7 R_{\rm NS}$. If the surface magnetic field is near 10^{14} G, the requested emission region will be higher. Thus, the emission region must be located at a height at least larger than 2 $R_{\rm NS}$. The accreting and emission region will be like a cylinder column with a height $h \gg 2R_{\rm NS}$ in GX 301-2. This geometry is supported by our analysis results on GX 301-2: the correlation between the ratio of line width to centroid energy and absorption depth implies a tall cylindrical 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 quite different properties from isolated magnetar candidates (see discussions in [21]), anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs), which are 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. Magnetars born in 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 it will transfer into the spin-up process (a long-term spin-up trend is found in 2S 0114+65). After the spin-down phase, the magnetar candidate will stop until the accreting magnetar is located around the equilibrium spin period range (several hundred seconds). In this scenario, GX 301-2 is the successor of younger and fast-evolved superslow pulsation X-ray pulsars (like 4U 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 literature ([21] and references therein), we need to understand the nature of the magnetar definition. In , 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 derivatives, 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 an ultra-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 its main scientific objectives will be monitoring magnetar candidates, especially their spectral and temporal variations. Further studies on GX 301-2, especially on the spectral features and flares, even bursts, could improve our understanding of the nature of accreting magnetars and the magnetar family.

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Abstract: Using INTEGRAL/IBIS observations from 2003–2011, we systematically studied the spectral properties of the high-mass X-ray binary GX 301-2 across different accretion luminosities and orbital phases. A cyclotron resonant scattering feature (CRSF) at 35–47 keV was detected, indicating a magnetic field of 5×10^{12} G. CRSF variations show no correlation with X-ray luminosity, while the line centroid energy positively correlates with photon index and spectral cutoff energy, and absorption depth weakly correlates with cutoff energy. These results demonstrate that cyclotron resonant scattering strongly affects spectral cutoffs in accreting X-ray pulsars. The correlation between line width-to-energy ratio and absorption depth suggests a tall cylindrical accretion column on the neutron star surface. The long spin period requires a surface magnetic field $> 2 \times 10^{13}$ G, which contradicts the field derived from cyclotron line energy unless the line forms in an accretion column > 2 neutron star radii above the surface. This geometry is supported by CRSF variation patterns. GX 301-2 may be an accreting magnetar in the torque equilibrium phase.

Keywords: GX 301-2; X-ray binaries; Neutron stars; Magnetic fields

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Note: Figure translations are in progress. See original paper for figures.