Variations and correlations in cyclotron resonant scattering features of Vela X-1 studied by INTEGRAL

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ABSTRACT

Long-term hard X-ray monitoring observations of high-mass X-ray binary Vela X-1 from 2003–2011 have been carried out by the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL). I systematically analysed the average hard X-ray spectra of Vela X-1 from 3–200 keV, with the main aims of detecting cyclotron resonant scattering features and studying their pattern of variation with accreting luminosity and orbital phase. The cyclotron scattering lines of Vela X-1 at \( \sim 22–27 \) and \( 49–57 \) keV are confirmed in the average spectra of Vela X-1. However, in flare states with hard X-ray luminosity higher than \( \sim 5 \times 10^{36} \text{ erg s}^{-1} (3–100 \text{ keV}) \), the fundamental line cannot be detected. This feature suggests that a fan-like beam radiation pattern is expected in high-luminosity ranges of Vela X-1. Variations of the cyclotron line energies and depths are discovered, which may change with continuum spectral properties. Both cyclotron line energies show no correlations with X-ray luminosity. The fundamental line energy shows no significant correlations with photon index and exponential cut-off energy, while the first harmonic energy shows a positive correlation with photon index and exponential cut-off energy. The energy ratio of two cyclotron lines, always higher than 2, has a weak correlation with photon index and cut-off energy. These relations support the idea that the X-ray spectral properties of accreting X-ray pulsars are affected by cyclotron resonance scattering. In the case of Vela X-1, the broader and deeper first harmonic would play the main role in causing the spectral variations. The positive correlations between the ratio of line width to energy and the corresponding depth for both lines support a cylindrical column accretion geometry in Vela X-1.

Key words: stars: individual: Vela X-1 – stars: magnetic field – stars: neutron – X-rays: binaries.

1 INTRODUCTION

Vela X-1 is a persistently emitting and eclipsing high-mass X-ray binary (HMXB) with a B0.5 Ia supergiant companion, the distance of which is determined as \( \sim 1.9 \) kpc (Nagase 1989). Its X-ray luminosity variability shows an orbital period of 8.96 d (van Kerkwijk et al. 1995). This source contains a neutron star with a pulsation period of \( \sim 283 \) s (McClintock et al. 1976). The spin period and the derivative have changed erratically since its discovery, as expected from the wind-fed direct accretion system (Bildsten et al. 1997).

Cyclotron resonance scattering features (CRSFs) can be used to determine the magnetic field of the neutron star directly and additionally reflect the accretion geometry and emission properties near the surface of the neutron star. An absorption-line feature around 55 keV was first reported in Vela X-1 from High Energy X-Ray Experiment (HEXE) observations (Kendziorra et al. 1992).

In addition, Makishima & Mihara (1992) found a possible absorption feature around 32 keV from Ginga data and Choi et al. (1996) reported the line feature around 23–24 keV, also using the Ginga data. Kretschmer et al. (1997) reported two absorption features at \( \sim 23 \) and \( \sim 45 \) keV using the broad-band data from HEXE. With Rossi X-Ray Timing Explorer (RXTE) data, a detailed pulse phase-resolved analysis (Kreykenbohm et al. 2002) confirmed the existence of two cyclotron scattering lines at around 25 and 55 keV and also reported a variation with pulse phase. However, some other researchers only found the cyclotron scattering feature around 55 keV using Beppo Satellite per Astronomia a raggi X (BeppoSAX) data (e.g. Orlandini et al. 1998). With recent INTEGRAL data, Schanne et al. (2007) found two possible absorption lines at \( \sim 27 \) and 55 keV. Kreykenbohm et al. (2008) reported an absorption line at \( \sim 53 \) keV using INTEGRAL/Imager on Board the INTEGRAL Satellite (IBIS) data. More recently, detailed analysis of Suzaku observational data by Maitra & Paul (2013) and Odaka et al. (2013) reported the detection of CRSFs at \( \sim 25 \) and 50 keV. Thus there exist two cyclotron scattering lines in Vela X-1 with existing observations from...
different missions, but an understanding of the variability pattern of CRSFs still requires more observational data and detailed studies.

Previous observations of accreting X-ray pulsars studied the correlations between CRSFs and luminosities/spectral properties mainly in Be X-ray transients (see Klochkov et al. 2012; Li, Wang & Zhao 2012). However, the variation pattern and possible correlations of CRSFs in wind-fed accreting X-ray pulsar systems like Vela X-1 have never been studied in detail. Given the different companion star and accreting processes, the relationships between CRSFs and continuum spectral properties may be different or have some common characteristics. In this work, I use all the available observed data for Vela X-1 collected by INTEGRAL from 2003–2011 to study the variations of the spectral properties of this source in hard X-ray bands systematically. The main scientific aims are to search for CRSFs in the hard X-ray spectra of 3–200 keV and to study their variation with long-term monitoring data, in order to study in detail the relations between CRSFs and continuum spectral properties in Vela X-1 in different luminosity ranges. These correlations will help researchers to understand the accretion geometry and processes near the surface of a strongly magnetized neutron star in a wind-fed accreting X-ray binary.

The article is organized as follows. In Section 2, the INTEGRAL observations are briefly introduced. The spectral properties of Vela X-1 in different accretion states are studied and cyclotron scattering lines are searched for in different luminosity ranges in Section 3 and possible correlations between CRSFs and the spectral parameters of Vela X-1 over wide luminosity ranges are approached. In Section 4, the spectral variations of Vela X-1 over its orbital phases are also presented. In the last section, Section 5, a brief summary and discussion are presented.

2 INTEGRAL OBSERVATIONS

Vela X-1 was observed with frequent pointing observational surveys of the Vela region from 2003–2011 by the INTEGRAL satellite. I use mainly the observational data obtained by the INTEGRAL Soft Gamma-Ray Imagery (IBIS–ISGRI; Lebrun et al. 2003), which has a 12-arcmin (FWHM) angular resolution and arcmin source location accuracy in the energy band 15–200 keV. The Joint European X-Ray Monitor (JEM-X) on board INTEGRAL is a small X-ray telescope (Lund et al. 2003) that can be used to constrain the continuum spectrum below 20 keV, combined with IBIS.

In this work, I use the available archival data for the IBIS observations, where Vela X-1 is within ~10° of the pointing direction. The INTEGRAL observations showed long-term monitoring of Vela X-1 from 2003–2011. The total observations include 1670 science windows (the duration of each science window is about 2000 s). The archival data used in our work are available from the INTEGRAL Science Data Center (ISDC). Analysis is performed with the standard INTEGRAL off-line scientific analysis software (OSA: Goldwurm et al. 2003), version 10.

Individual pointing observations processed with OSA 10 are mosaicked to create sky images for the source detection. I have used the energy range of 20–40 keV from IBIS for source detection. Fig. 1 also shows a light-curve sample of Vela X-1 obtained by IBIS. Vela X-1 is a strongly eclipsing binary; the eclipses are observed by IBIS with a count rate decreasing to near zero, which lasts about 1.7 d, consistent with the report by Watson & Griffiths (1977). Other than eclipses, Vela X-1 is also a highly variable hard X-ray source. From the hard X-ray count rate variations of Vela X-1 presented in Fig. 1, I define three accreting states based on the average luminosities: flare states, with mean count rate higher than 100 count s−1; active states, with mean count rate in the range ~30–100 count s−1; and low states, with mean count rate below ~30 count s−1 (not including the eclipse data).

3 HARD X-RAY SPECTRAL PROPERTIES OF VELA X-1 IN DIFFERENT ACCRETING STATES

The hard X-ray spectra of Vela X-1 from 3–200 keV obtained with JEM-X and IBIS are extracted for different accreting states. Cross-calibration studies on the JEM-X and IBIS/ISGRI detectors have been carried out using Crab observation data and the calibration between JEM-X and IBIS/ISGRI can be good enough within ~6 per cent (see the samples in Jourdain et al. 2008 and Wang 2013). In the spectral fittings, the constant factor between JEM-X and IBIS is set to be 1. The spectral analysis software package used is XSPEC 12.6.0q (Arnaud 1996).

Generally, the hard X-ray spectrum of accreting X-ray pulsars like Vela X-1 can be described by a power-law model plus a high-energy exponential roll-off (hereafter cut-off model): \[ A(E) = KE^{-\gamma} \exp\left(\frac{-E}{E_{\text{cut-off}}}\right). \] Other simple spectral models like the single power-law model and the thermal bremsstrahlung model are also applied to fit the spectra of Vela X-1. However, these models cannot fit the hard X-ray spectra of Vela X-1 from 3–200 keV, so I will use the cut-off power-law model (similar to Orlandini et al. 1998 and Kreykenbohm et al. 2008) in the following spectral analysis. After the continuum fittings of the spectrum, dips in the residuals still exist, such as the absorption feature around 55 keV, which is a known cyclotron scattering line. I therefore add cyclotron scattering components to improve the spectral fittings. I also use the XSPEC model cyclabs to fit the cyclotron scattering line component (Mihara et al. 1990):

\[ M(E) = \exp\left[ -D_1 \left( \frac{W_l (E/E_{\text{cyc}})}{E - E_{\text{cyc}}} \right)^2 \right]. \]

For some cases, the iron line at 6.4 keV is needed to fit the feature around 6–7 keV in JEM-X spectra. I take a Gaussian iron line profile in the fits: \[ A(E) = \left(\frac{K}{\sqrt{2\pi}\sigma_e}\right) \exp\left[-\left(E - E_{\text{Fe}}\right)^2/2\sigma_e^2\right], \] where \(E_{\text{Fe}} = 6.4\) keV is the energy of iron line, \(\sigma_e\) is the line width and \(K\) is the line flux. In addition, a systematic uncertainty of 1 per cent for the IBIS–ISGRI energy channels is added in the spectral analysis. I tried to obtain the spectra from 3–200 keV of Vela X-1 at different luminosities for statistical studies as in Section 3.1, so that I combined different science windows with similar IBIS count rate level into a single spectral analysis. I then divided the IBIS count rates for all science windows (e.g. IBIS count rates in Fig. 1) into several count-rate levels according to the following definition: in the range \(>\)0–100 count s−1 (low and active states) the science windows are combined with a bin of 10 count s−1, i.e. 10–20 count s−1, 70–80 count s−1 and so on; for count rates higher than 100 count s−1 (flare states), the science windows are combined according to six count rate bins: 100–120, 120–140, 140–160, 160–180, 180–200 and >200 count s−1.

Then the spectral extractions are carried out for each group of science windows in the data analysis. In Figs 2–4, I present the samples of the hard X-ray spectrum for Vela X-1 in three accreting states. In Table 1, the best-fitting spectral parameters of the three accreting states are also displayed. In the following, the hard X-ray spectral properties of Vela X-1 in the three accreting states are described according to the analysis in this work. In Fig. 2, one hard X-ray spectrum from 3–200 keV in flare states is presented. The spectrum is first fitted with a power law plus a high-energy cut-off (the left panel of Fig. 2). There is an obvious
Figure 1. The hard X-ray count-rate variations of Vela X-1 from 20–40 keV derived by long-term monitoring observations by IBIS–ISGRI from 2009 November–2010 April. Vela X-1 is a highly variable X-ray source with strong eclipses. In the observed interval, I detected four eclipses with a duration of ∼1.7 d. Vela X-1 generally has a mean count rate of ∼40–50 count s$^{-1}$. Sometimes it shows flare states with a mean rate higher than 100 count s$^{-1}$.

Figure 2. The hard X-ray spectrum sample from 3–200 keV of Vela X-1 in the flare state obtained by JEM-X and IBIS. Left: the spectrum is fitted with a cut-off power-law model. Right: the spectrum is fitted with a cut-off power-law model plus a cyclotron scattering line around 55 keV.

absorption dip in the spectrum from 50–60 keV, which should be due to the cyclotron resonance scattering. Thus, in the right panel of Fig. 2, a cyclotron scattering line component is added into the spectral fittings. The fitted spectral parameters are collected and presented in Table 1. In flare states, the first harmonic of CRSFs in Vela X-1 varies from 51–57 keV. However, the fundamental line feature around 25 keV is not detected in flare states. The disappearance of the fundamental line is interesting and needs more study. This non-detection cannot be due to the low significance, since, in flare states, Vela X-1 was detected generally with a very high
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Figure 3. The hard X-ray spectrum sample from 3–200 keV of Vela X-1 in the active state obtained by JEM-X and IBIS. (1) The spectrum is fitted with a cut-off power-law model. (2) The spectrum is fitted with a cut-off power-law model plus a cyclotron scattering line around 56 keV. (3) The spectrum is fitted with a cut-off power-law model plus a cyclotron scattering line at 56 keV with an Fe Kα line at 6.4 keV. (4) The spectrum is fitted with a cut-off power-law model plus two cyclotron scattering lines at ∼25 and 56 keV, with an Fe Kα line at 6.4 keV.

Figure 4. The hard X-ray spectrum sample from 3–200 keV of Vela X-1 in the low state obtained by JEM-X and IBIS. Left: the spectrum is fitted with a cut-off power-law model. Middle: the spectrum is fitted with a cut-off power-law model plus a cyclotron scattering line around 50 keV. Right: the spectrum is fitted with a cut-off power-law model plus a cyclotron scattering line around 50 keV, with an Fe Kα line at 6.4 keV.

detection significance level >400σ from 20–40 keV. I also try to derive an upper limit for the depth for the fundamental line in the flare states, which is ∼0.05 (2σ).

In the active states, two cyclotron scattering line components are detected in hard X-ray spectra of Vela X-1. Fig. 3 displays a hard X-ray spectrum of Vela X-1. The spectral fitting processes are divided into four steps (see also Fig. 3 and Table 1): (1) the continuum is fitted by a cut-off power-law model; (2) a resonant scattering line around 56 keV is added; (3) the Fe Kα line at 6.4 keV is fitted; (4) there still exists an absorption-line feature around 25 keV that is the fundamental line, then finally the spectrum is fitted with a cut-off power-law plus two resonant scattering lines with the fixed Fe Kα line.

The reported fundamental cyclotron lines in active states are determined at energies distributed from 22–27 keV. The surface magnetic field of the neutron star in Vela X-1 can be estimated by using the formula

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

where \( E_{\text{cyc}} \) is the energy of the fundamental line (here I take \( E_{\text{cyc}} = 27 \text{ keV} \)) and \( z \) is the gravitational redshift near the surface.
of the neutron star. I then obtain a magnetic field of $\sim 2.3 \times 10^{12} G$ for the neutron star in Vela X-1. For the neutron star in Vela X-1, I can take a mass of 1.9 $M_\odot$ (Quaintrell et al. 2003) with a radius of 10 km; I then estimate $B \sim 3 \times 10^{12} G$.

The first harmonic of the CRSFs in Vela X-1 is determined at energies distributed from 50–58 keV in active states. In addition, when comparing fitted parameters of two cyclotron line features, I find that the fundamental line is generally narrower and shallower than that of the first harmonic in Vela X-1, i.e. the width of the fundamental line is around 4 keV with a depth of around 0.1–0.3 and the width of the first harmonic is around 9 keV with a depth of $\sim 1$. This special feature may imply a large viewing angle with regard to the magnetic field in the case of Vela X-1 (see the theoretical calculations by Nishimura 2011). The line-width ratio width$_2$/width$_1 \sim 2$ is still consistent with the predictions of theoretical Doppler broadening (Mészáros & Nagel 1985).

In Fig. 4, I presented a hard X-ray spectrum in the low state of Vela X-1. The fitted spectral models and spectral parameters are also displayed in Table 1. In the low states, the fundamental cyclotron scattering line of CRSFs is not detected in the average spectra of Vela X-1, which may be due to the low detection significance levels of the source (lower X-ray flux levels). The first harmonic line energies determined are around 50–57 keV, with a line width and depth around 8 keV and 1–2 respectively, values that are still similar to the fitted parameters in the active states.

### 3.1 Variations of CRSFs versus continuum spectral parameters

The production of cyclotron resonant absorption-line features near the surface of a neutron star is complicated in physics and will depend sensitively on accretion states and accretion geometry (e.g. Araya & Harding 1999; Nishimura 2011). In addition, the fundamental line energy may also change in different accretion luminosity states and the relativistic cyclotron scattering line energy would have non-harmonic line spacing (Araya & Harding 2000). Therefore, detection of cyclotron scattering line features is not only used to identify a magnetized neutron star in binary systems but also important for studies of accretion processes and geometry near the neutron star surface (Becker et al. 2012; Nishimura 2011). The variation pattern of the CRSFs and their physical origin require detailed studies with frequent observations. The correlation studies for the cyclotron resonant absorption-line features should be helpful in understanding the spectral properties and production mechanism of CRSFs near the surface of a magnetized neutron star.

In this subsection, using the INTEGRAL spectral analysis results in different accreting luminosities of Vela X-1. I will study systematically the relationships between cyclotron scattering lines and three continuum spectral parameters: hard X-ray flux, photon index and cut-off energy. Moreover, I not only show the fundamental line but also the first harmonic, which is a stronger absorption feature in Vela X-1. In the following, we used 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, a correlation should exist between two parameters when $r > 0.5$.

In Fig. 5, I present the relationship of the fundamental line energy $E_1$ and depth versus three continuum spectral parameters. $E_1$ shows no significant correlations with the X-ray flux and the spectral parameters $\Gamma$ and $E_{\text{cut-off}}$. However, a very weak relation of $E_1$ versus the cut-off energy $E_{\text{cut-off}}$ ($r = 0.49$) may exist. This uncertainty may be due to the small number of data points, so I will study this relation again in the following analysis. The depth has no relationship to the three spectral parameters, but may become lower when the flux is higher than $10^{-8}$ erg cm$^{-2}$ s$^{-1}$.

The first harmonic energy $E_2$ and depth versus the continuum spectral parameters are shown in Fig. 6. $E_2$ also has no relation to the X-ray flux, but shows positive correlations with $\Gamma$ ($r = 0.53$) and $E_{\text{cut-off}}$ ($r = 0.58$). Moreover, the absorption depth of the first harmonic also has positive correlations with $\Gamma$ ($r = 0.85$) and $E_{\text{cut-off}}$ ($r = 0.88$), but no relation to the accreting luminosity.

Furthermore, I present relations between the energy ratio of the absorption lines $E_2/E_1$ and three continuum spectral parameters in Fig. 7. The ratio is independent of the X-ray flux and $\Gamma$ and $E_{\text{cut-off}}$ (maybe due to the small number of data points). The derived energy ratio is generally higher than 2, suggesting an absorption-line-forming region with a large polar cap or a greater height, so that the fundamental line would be formed at a higher site and the first harmonic primarily around the bottom (see the simulations by Nishimura 2011).

### Table 1. The best-fitting spectral parameters of Vela X-1 in three different luminosity ranges in the hard X-ray bands from 3–200 keV. The spectra were fitted with different models as defined here: (1) cut-off power-law model cut-offpl; (2) cut-off power law plus a cyclotron scattering line cut-offpl*cyclabs; (3) cut-off power law plus a cyclotron scattering line, with an Fe Kα line fixed at 6.4 keV; (4) cut-off power law plus two cyclotron scattering lines, with an Fe Kα line fixed at 6.4 keV. The width of the Fe Kα line is also fixed at zero in the fits. The continuum flux is given in units of $10^{-9}$ erg cm$^{-2}$ s$^{-1}$ and the Fe line flux in units of $10^{-2}$ photon cm$^{-2}$ s$^{-1}$.

| Model | $\Gamma$ | $E_{\text{cut-off}}$ (keV) | $E_1$ (keV) | Width$_1$ (keV) | Depth$_1$ | $E_2$ (keV) | Width$_2$ (keV) | Depth$_2$ | Line flux | Flux | Reduced $\chi^2$ (d.o.f) |
|-------|----------|---------------------------|------------|----------------|-----------|------------|----------------|-----------|-----------|------|------------------------|
| Flare |          |                           |            |                |           |            |                |           |           |      |                        |
| 1     | $-0.12 \pm 0.03$ | $10.1 \pm 0.1$            | $55.4 \pm 0.9$ | $9.5 \pm 1.8$ | $1.4 \pm 0.1$ | $25.1 \pm 0.4$ | $24.2 \pm 0.4$ | $0.6(79)$ |          |      |                        |
| Active|          |                           |            |                |           |            |                |           |           |      |                        |
| 1     | $-0.34 \pm 0.02$ | $9.2 \pm 0.1$             | $57.0 \pm 0.8$ | $9.3 \pm 1.8$ | $1.2 \pm 0.1$ | $9.2 \pm 0.2$ | $1.7(79)$ |          |      |      |                        |
| 2     | $-0.11 \pm 0.03$ | $11.1 \pm 0.2$            | $56.9 \pm 0.8$ | $9.2 \pm 1.8$ | $1.2 \pm 0.1$ | $1.2\pm 0.2$ | $9.2 \pm 0.2$ | $1.7(78)$ |          |      |                        |
| 3     | $-0.17 \pm 0.03$ | $10.9 \pm 0.2$            | $56.2 \pm 0.7$ | $9.3 \pm 1.8$ | $1.2\pm 0.1$ | $1.2\pm 0.2$ | $9.1 \pm 0.2$ | $1.7(78)$ |          |      |                        |
| 4     | $-0.14 \pm 0.03$ | $11.1 \pm 0.2$            | $25.5 \pm 0.9$ | $3.7 \pm 1.7$ | $0.06 \pm 0.01$ | $25.2 \pm 0.4$ | $24.2 \pm 0.4$ | $0.6(79)$ |          |      |                        |
| Low   |          |                           |            |                |           |            |                |           |           |      |                        |
| 1     | $-0.51 \pm 0.04$ | $8.4 \pm 0.1$             | $50.8 \pm 0.7$ | $7.9 \pm 1.7$ | $0.9 \pm 0.1$ | $4.3 \pm 0.3$ | $2.8(82)$ |          |      |      |                        |
| 2     | $-0.24 \pm 0.05$ | $10.2 \pm 0.3$            | $50.7 \pm 0.7$ | $8.1 \pm 1.7$ | $0.9 \pm 0.1$ | $4.2 \pm 0.3$ | $1.7(79)$ |          |      |      |                        |
| 3     | $-0.31 \pm 0.06$ | $9.9 \pm 0.3$             | $50.7 \pm 0.7$ | $8.1 \pm 1.7$ | $0.9 \pm 0.1$ | $4.2 \pm 0.3$ | $0.7(78)$ |          |      |      |                        |
Coburn et al. (2002) found that a positive correlation exists between absorption depth and ratio of width to energy in the phase-averaged spectra of accreting X-ray pulsars. This indicates that the accretion geometry of an accreting X-ray pulsar is a tall cylindrical-shaped accretion column rather than a flat coin shape (Kreykenbohm et al. 2004). In Fig. 8, I also presented the ratio of width to energy of both $E_1$ and $E_2$ versus the corresponding depth from different observations of Vela X-1. A weak positive correlation between $W_2/E_2$ and $\text{Depth}_2$ is found ($r = 0.55$), but I could not find a relationship between $W_1/E_1$ and $\text{Depth}_1$ (the ratio of $W_1/E_1$ is nearly constant, with large uncertainties). The properties of cyclotron resonance scattering features like $E_2$ therefore suggest that Vela X-1 should have a cylindrical column accretion geometry. These correlations will be studied again to provide a further check in the following analysis.

4 SPECTRAL VARIATIONS OVER THE ORBITAL PHASES

Using long-term monitoring observations of Vela X-1 with INTEGRAL, I try to derive the spectral variation with orbital phase (orbital period of ~8.96 d). Strong eclipses in the orbital phase of Vela X-1 exist (also see Fig. 1). During the eclipses (about 1.7 d), INTEGRAL did not detect the source and no spectral information can be obtained. For the other orbital phases, I divided the phase into 30 bins. The science windows of the INTEGRAL observations are re-combined according to the time intervals of the different orbital phase bins. The data analysis was redone for all science windows in each phase bin and I extracted the spectrum for the data of each phase bin with JEM-X and IBIS.
Similarly to Section 3, I fit the hard X-ray spectrum with a cut-off power-law model plus cyclotron scattering line features, to obtain the best-fitting spectral parameters. For the orbital phase just before and after the eclipse, the cut-off power-law model cannot fit the spectrum below 5 keV very well. An additional hydrogen absorption component is required to fit the spectrum below 5 keV. The large column density values of $\sim (1–6) \times 10^{23}$ cm$^{-2}$ suggests an enhanced wind density just before and after the eclipses. In the other orbital phases, the absorption component is not needed in the spectral fittings, implying an upper limit of $\sim 10^{23}$ cm$^{-2}$ (2$\sigma$) for the column density. Kaper, Hammerschlag-Hensberge & Zuiderwijk (1994) suggested absorption component structures resulting from the presence of a photoionization wake in Vela X-1 from optical spectroscopy of the companion. This absorption density variation versus orbit was also recently reported by the Monitor of All-sky X-ray Image (MAXI: Doroshenko et al. 2013), which suggests that a denser stream-like region trailing the neutron star of Vela X-1 exists. However, the absorption density variation versus orbit (see Fig. 9) derived by INTEGRAL still supports the standard smooth-wind model (Castor, Abbott & Klein 1975).

Finally, I derived all best-fitting spectral parameters for the data in 30 orbital phase bins. In Fig. 9, the variations of the continuum spectral properties and two cyclotron scattering line features with orbital phase are presented. The parameters of both cyclotron scattering line features show variations relative to the continuum spectral parameters over the orbital phases. So, similarly to the correlation studies in Section 3.1, here I also present the relationships between cyclotron line features and three continuum spectral parameters.

For the fundamental line of Vela X-1, the energy $E_1$ and depth have no correlations to the continuum parameters, flux, $\Gamma$ and cut-off energy $E_{\text{cut-off}}$. In Fig. 10, I present only the relation of depth versus X-ray flux. The depth shows no correlation with hard X-ray flux ($r = 0.29$). In the higher flux region, e.g. above $\sim 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, the depth becomes significantly smaller than in the lower flux region, which may indicate no detection of the fundamental line in the flare states (Section 3).

The fitted parameters of the first harmonic of CRSFs versus X-ray flux, $\Gamma$ and $E_{\text{cut-off}}$ are displayed in Fig. 11. Both the cyclotron energy $E_2$ and the absorption depth have no relation to the hard X-ray flux, while $E_2$ has strong positive correlations with photon index $\Gamma$ ($r = 0.56$) and cut-off energy $E_{\text{cut-off}}$ ($r = 0.76$). The absorption depth shows no significant correlation to $\Gamma$ and a very weak positive correlation with $E_{\text{cut-off}}$ ($r = 0.49$). The correlations $E_2$ versus $E_{\text{cut-off}}$ and depth versus $E_{\text{cut-off}}$ support the idea that the high-energy cut-off in the hard X-ray spectra of accreting X-ray pulsars is attributed to cyclotron resonant scattering.

Fig. 12 also presents the ratio $E_2/E_1$ versus three continuum spectral parameters. The ratio is still generally larger than 2 and shows no relation to the hard X-ray flux. However, $E_2/E_1$ shows a positive correlation with photon index $\Gamma$ ($r = 0.52$) and cut-off energy $E_{\text{cut-off}}$ ($r = 0.56$).
Figure 9. The spectral variations of Vela X-1 over the whole orbital phase. No spectral information is derived during the eclipse phase of Vela X-1. The starting point is derived as the time just after the eclipse, which is taken as MJD 52975.075 here.

Figure 10. The derived depth of the fundamental line versus the hard X-ray flux in the range 3–100 keV.

In Fig. 13, the ratios of width to line energy versus absorption depth for two cyclotron scattering line features are studied once more. Though large uncertainties exist, I can still find positive relationships between the ratio and depth for each cyclotron line: $W_1/E_1$ versus $\text{Depth}_1$ ($r = 0.63$) and $W_2/E_2$ versus $\text{Depth}_2$ ($r = 0.69$). With more data analysis, the assumption of a cylindrical column accretion geometry near the surface of the magnetized neutron star in Vela X-1 is confirmed.

5 SUMMARY AND DISCUSSION

In this work, I have carried out long-term hard X-ray monitoring observations of Vela X-1 using INTEGRAL from 2003–2011. After detailed analysis of the spectral properties of Vela X-1 in different luminosity ranges and orbital phases, I found some new results, which are summarized here as follows.

1. Cyclotron resonant scattering features are detected in Vela X-1 for different accreting states. In the average spectra of Vela X-1, the fundamental absorption line varies from 22–27 keV and the first harmonic is determined at 47–58 keV. I obtain a surface magnetic field of $\sim 3 \times 10^{12}$ G for Vela X-1 using the reported fundamental line energy.
Figure 11. The derived cyclotron energy \( E_2 \) and depth of the first harmonic versus three spectral parameters: hard X-ray flux in the range 3–100 keV, photon index \( \Gamma \) and exponential cut-off energy \( E_{\text{cut-off}} \).

Figure 12. The energy ratio of the first harmonic to the fundamental line \( E_2/E_1 \) versus three spectral parameters: hard X-ray flux in the range 3–100 keV, photon index \( \Gamma \) and exponential cut-off energy \( E_{\text{cut-off}} \). The ratio has no correlation with hard X-ray flux, but shows positive correlations with \( \Gamma \) and the cut-off energy \( E_{\text{cut-off}} \).

(2) The fundamental absorption line cannot be detected in the flare states, with an upper limit of \( \sim 0.05 \) (2\sigma) for the depth. Above a critical X-ray flux \( \sim 1.2 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \), corresponding to a luminosity from 3–100 keV of \( \sim 5 \times 10^{36} \text{ erg s}^{-1} \), only the first harmonic around 50–57 keV could be detected in average spectra of Vela X-1. In the active states, when Vela X-1 has a lower luminosity, both the fundamental absorption line and the first harmonic are detected. When the hard X-ray luminosity is below \( \sim 5 \times 10^{35} \text{ erg s}^{-1} \), the fundamental absorption line again cannot be detected, maybe due to the lower detection significance levels of the source.

(3) The cyclotron line energies and depths at different accretion luminosities and orbital phases are studied. The fundamental line energy shows no significant correlations with X-ray luminosity, photon index and high-energy cut-off, while the first harmonic energy shows positive correlations with photon index and cut-off energy. These positive correlations suggest that the first harmonic dominates effects on the spectral profiles of Vela X-1 in hard X-ray bands. The line energy ratio \( E_2/E_1 > 2 \) shows a weak positive correlation with photon index and cut-off energy. The absorption depth of the fundamental line has no significant correlations with flux, \( \Gamma \) and \( E_{\text{cut-off}} \), but in the high-flux region above \( 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \) the depth becomes much smaller. The absorption depth of the first harmonic shows no relation to X-ray flux, \( \Gamma \) and \( E_{\text{cut-off}} \).

(4) Positive correlations exist between the ratio of line width to energy and the depth for both cyclotron scattering lines. This supports the suggestion that the persistent wind-fed accretion source Vela X-1 has a cylindrical column accretion geometry similar to the
other supergiant X-ray pulsar GX 301-2 (Kreykenbohm et al. 2004) and some Be X-ray transient sources during their outbursts (see Li et al. 2012).

(5) Change of the absorption density with orbital phase in Vela X-1 is also detected. Enhanced absorption is observed near the eclipse and the density variation profile versus orbit phase is still consistent with a standard smooth-wind model.

With long-term observations, I confirmed CRSFs at about 25 and 55 keV in the hard X-ray spectra of Vela X-1. More importantly, I found large variations of the fitted parameters of CRSFs (especially the cyclotron energies). These variations may relate to the accretion process and geometry, which could be connected to X-ray continuum properties like luminosity, photon index or spectral cut-off energies. For some X-ray pulsars, the possible relationship between the energy of the fundamental line and the bolometric luminosity is reported. A negative correlation between the energy of the fundamental line and the luminosity is found in Be transient 4U 0115+63 during outbursts (Li et al. 2012), while a recent work by Müller et al. (2013) showed that there is no correlation between the fundamental line energy and luminosity in this source. However, a positive correlation between the cyclotron line energy and luminosity is found in other X-ray pulsars like Her X-1 (Vasco, Klochkov & Staubert 2011) and GX 304-1 (Klochkov et al. 2012). Becker et al. (2012) suggested a critical X-ray luminosity in these accreting X-ray pulsars, which could explain the bimodal dependence of the CRSF centroid energy on X-ray luminosity. Moreover, a positive correlation between the energy of the fundamental line and photon index was also discovered in 4U 0115+63 during the giant outburst in 2008 (Li et al. 2012). In addition, collecting observation data of different X-ray pulsars, a positive correlation between the energy of the fundamental CRSF and the cut-off energy in the canonical X-ray pulsar continuum is found (Makishima et al. 1999; Kreykenbohm et al. 2002; Coburn et al. 2002). The physical origins of these correlations are still not well understood, but are generally believed to provide strong constraints on production models of CRSFs and accretion geometry near the surface of the magnetized neutron stars in HMXBs.

The existence of the correlations between cyclotron scattering energies and spectral photon index and cut-off energies suggests that the spectral properties of accreting X-ray pulsar Vela X-1 would be strongly affected by the cyclotron resonance, similarly to other X-ray pulsars. Previous work on the statistical relation between cut-off energies and fundamental line energies for 10 accreting X-ray pulsars has inferred that the spectral cut-off should be caused primarily by the cyclotron resonance (Makishima et al. 1999; Kreykenbohm et al. 2002; Coburn et al. 2002). These 10 X-ray pulsar systems included Be X-ray transients and wind-fed supergiant X-ray binaries. This correlation was derived using different types of X-ray pulsars and different sources. For the single source case of Vela X-1, I still confirmed the correlation. In addition, these relations are more complicated due to the existence of two cyclotron scattering lines.

The fundamental line energy has no relation to the cut-off energy, but the first harmonic energy shows a strongly positive correlation with the cut-off energy. The possible explanation would be that the first harmonic is broader and deeper than the fundamental line in the spectrum of Vela X-1 and is always detected significantly, but the fundamental line sometimes disappears, e.g. in the flare state. Therefore, the first harmonic will dominate the cause of the spectral cut-off in Vela X-1.

Generally, the fundamental cyclotron resonance is thought to have a much larger electron–photon interaction cross-section than the higher harmonic resonances, which will lead to a broader fundamental line with a larger depth (as in the case of typical X-ray pulsar 4U 0115+63; see Li et al. 2012). However, some X-ray pulsars with longer spin periods also show broader and deeper first harmonics, like Vela X-1 and 4U 2206+54 (Wang 2009). Some physical conditions may cause this special case in Vela X-1. Nishimura (2011) modelled cyclotron lines by considering the superposition of series of cyclotron line spectra emerging from different heights of a line-forming region and simulated the profiles of fundamental and first harmonic lines considering different viewing angles. The simulation results found that at larger viewing angles the expected fundamental line profile will be shallow and narrow and also suggested that, in the case of Vela X-1, the fundamental line tends to be formed around a higher site at the larger line-forming region, while the first harmonic line is formed primarily around the bottom. Thus the predicted energy ratio of $E_2/E_1$ is higher than harmonic ratio 2.

In the analysis of the cyclotron line features of Vela X-1 at different luminosities, I have found that, above a critical hard X-ray luminosity $\sim 5 \times 10^{36}$ erg s$^{-1}$ from 3–100 keV, the fundamental line cannot be detected for smaller absorption depths. This feature is also detected in the giant outbursts in Be/X-ray pulsar A0535+26, when its X-ray luminosity is higher than $\sim 10^{37}$ erg s$^{-1}$ (Maisack et al. 1997). Non-detection of the fundamental line in high luminosity ranges may suggest that the accreting radiation in Vela X-1 is strongly beamed (Poutanen & Gierliński 2003); pencil-like and fan-like beam patterns can explain the fundamental line disappearance in high luminosity ranges. These beamed patterns depend on

**Figure 13.** The ratio of derived width ($W_i$) to energy $E_i$ of two cyclotron scattering lines of Vela X-1 versus their depth (Depth$_i$), respectively. A positive correlation between $W_2/E_2$ and Depth$_2$ is found and a positive correlation of $W_1/E_1$ versus Depth$_1$ also exists.
the polar-cap radius $R_p$, which is determined by the luminosity and the neutron star mass (see Becker 1998):

$$R_p \sim \frac{0.4 R_{NS} M_{NS}^2}{M_{NS}^{10^{37}} L_x^{1}},$$

(2)

where $M_{NS}$ is the mass of the neutron star and $R_{NS}$ is the radius of the neutron star. Then, in high X-ray luminosity ranges $> 5 \times 10^{36}$ erg s$^{-1}$ for Vela X-1 (the total accreting luminosity will be higher, $\sim 10^{37}$ erg s$^{-1}$; see Rutovinov & Tsygankov 2009), one can derive $R_p > 0.1 R_{NS}$, so that a fan-like beam pattern is expected in Vela X-1. According to the simulations by Nishimura (2011), in a fan-like beam pattern the fundamental line tends to be shallower (consistent with the observed feature in Vela X-1, see also Fig. 10) while the first harmonic line tends to be deeper (see also Fig. 6).

It should be noted that the present non-detection of the fundamental line in high X-ray luminosity ranges is only reported in two X-ray pulsar systems with relatively long spin periods, Vela X-1 (283 s) and A0535+26 (103 s). However, in some bright X-ray pulsars with short spin period, like 4U 0115+63 (3.6 s), the fundamental line around 10–15 keV is detected even in the giant outburst (X-ray luminosity $> 10^{37}$ erg s$^{-1}$; see Li et al. 2012) and shows very wide and deep features. Thus the beam pattern transition could only occur in long spin-period X-ray pulsar systems. What differences exist between short and long spin-period pulsars in producing cyclotron scattering line features and what mechanism is involved (physics or geometry)? This issue requires further study through observations and theory.

There are no correlations between X-ray luminosity and cyclotron energies for both lines in Vela X-1. This behaviour is different from that discovered in Her X-1 and some Be X-ray transient sources during outbursts, though both Vela X-1 and Be X-ray transients (like 4U 0115+63) have similar accretion geometry. In Be X-ray transients, X-ray luminosity plays a critical role in affecting the variations of the fundamental line energy (see also the discussions in Becker et al. 2012). In the case of Vela X-1, however, the variations of cyclotron scattering line energies of both the fundamental and the first harmonic would be caused not by the change of accretion luminosity but by other physical properties. This difference in Vela X-1 and Be X-ray transients and Her X-1 (with a low-mass companion star) may be due to the different types of companion star and different accreting processes. Of course, the range of variation of observed luminosities in Vela X-1 is still smaller than those of Be X-ray transients, so it is difficult that the present data are used to study the relation of cyclotron line energy versus very wide X-ray luminosity range in Vela X-1. Therefore, the variations and correlations of cyclotron resonance scattering features in Vela X-1 and other wind-fed supergiant X-ray pulsars need further study, through both observations and theoretical work.

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