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Properties of the Iron Line from Vela X-1

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Abstract

Properties of the iron emission line from Vela X-1 are studied with the gas scintillation proportional counters onboard Tenma. The energy and the width of the iron line are determined to be 6.43 ± 0.05 keV and less than 0.5 keV (FWHM), respectively. The fluorescence efficiency of the line is $\sim1.5\%$ even when the absorbing column is less than 5×10^{22} cm^{-2}. The iron line intensity during eclipse suggests the size of the line emitting region to be less than 5×10^{11} cm from the neutron star. A remarkable finding is that the iron line intensity is constant over the 283-s pulse period of Vela X-1 (no significant pulsation). This implies a special geometry of the matter near the neutron star.

Key words: Vela X-1; X-ray binaries; X-ray pulsars; X-ray sources; X-ray spectra.

1. Introduction

Past observations have revealed significant iron emission lines from most of the X-ray pulsars (Pravdo 1979; White et al. 1983; and references therein). Fluorescence is considered to be a plausible mechanism for the production of iron lines. The stellar wind from the companion star and the matter in the Alfvén shell of the neutron star have so far been considered as possible reprocessors. Undoubtedly, the iron emission line presents valuable information on both the structure of the binary system and the X-ray beam produced by the neutron star. However, detailed properties of the iron emission line from X-ray pulsars have yet to be explored. For this purpose, observations with better energy resolution are of crucial importance.

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Observations of the energy spectra of Vela X-1 by OSO-8 (Becker et al. 1978) and by HEAO-1 (White et al. 1983) have revealed an intense iron emission line with the equivalent width of 130–510 eV.

Tenma observed Vela X-1 for 11 d in March, 1983. With the superior energy resolution of gas scintillation proportional counters, we found for the first time the detailed properties of the iron emission line. In this paper we present the observed results of the iron line, and discuss the origin of the line emission.

2. Observation

Observation of Vela X-1 was performed in the period March 8–18, 1983, with the gas scintillation proportional counters of a total effective area 640 cm^2 on board Tenma (Tanaka et al. 1984; Koyama et al. 1984). This covers 1.1 times the binary period (8.96 d) of Vela X-1. Results on the pulse period of the source in this period are presented by Nagase et al. (1984). A sudden decrease of the X-ray intensity of Vela X-1 was observed on March 16. This is described by Inoue et al. (1984).

2.1. Energy Spectrum

An example of the observed pulse-height spectrum of Vela X-1 is shown in figure 1. The spectrum was accumulated for 1320 s starting on March 18.604 (ϕ=0.39). A prom-

$$E^{-\alpha}\exp[-(E-E_1)/E_2] \quad E\geq E_1\,,$$
$$E^{-\alpha} \quad E<E_1\,,$$

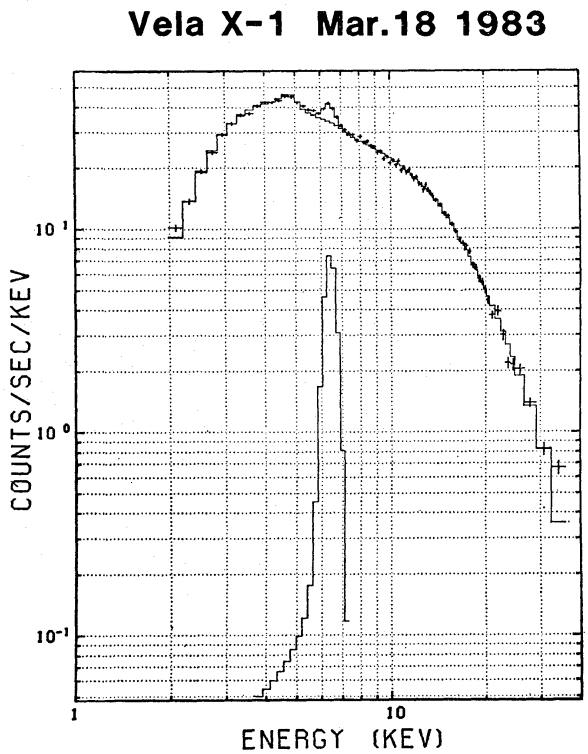

Fig. 1. The pulse-height spectrum of Vela X-1 observed on March 18.604, 1983 (ϕ=0.39). The data are fit with a power-law model spectrum and an emission line centered at 6.43 keV. The spectral parameters and their 90% confidence levels are α=1.13±0.02, E_1=14.7±0.9 keV, E_2=41.7±5.5 keV, and N_H=(4.5±0.2)$\times 10^{22}$ cm^{-2}, respectively.

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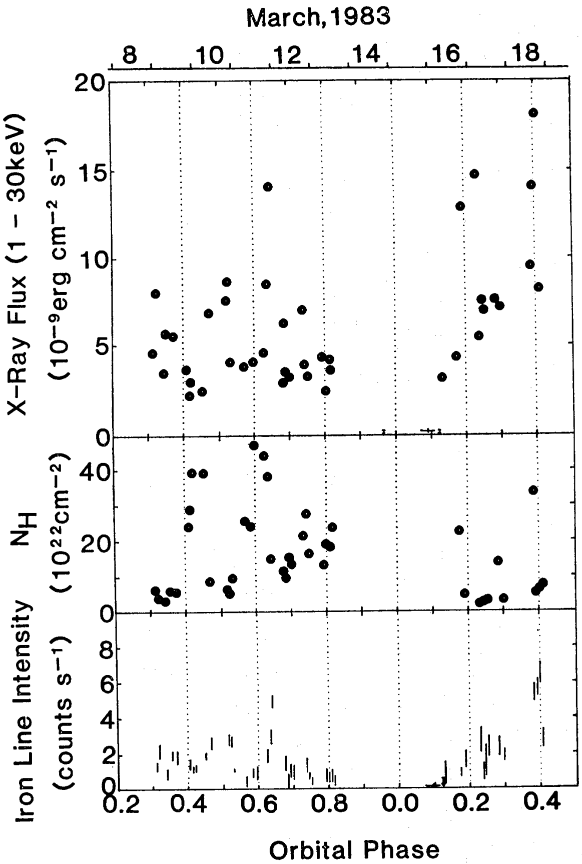

Fig. 2. The energy flux in the range 1–30 keV, the absorbing column N_H and the iron line intensity plotted as a function of time.

inent iron emission line with an equivalent width of about 150 eV is evident. The data are fit with a power-law model spectrum of the following form:

where E_1 is a high-energy cutoff energy characterized by an e-folding energy E_2. We also assumed an emission line around 6.4 keV, whose energy and intensity are varied as free parameters. Hereafter, errors denote 90% confidence levels.

Figure 2 shows the energy flux in 1–30 keV, hydrogen column density N_H, and iron line intensity, all plotted as a function of time. These values are obtained by performing spectral fittings for a continuous 10–30 min of data.

Vela X-1 sometimes exhibits flare-up on a time scale of $\sim$10 min. The size and the occurrence frequency of these flares are known to vary from orbit to orbit (Watson and Griffiths 1977; Charles et al. 1978; Nagase et al. 1983). If the effect of absorption due to the intervening matter is corrected for, the spectral shape of Vela X-1 does not change appreciably with its luminosity.

The column density of intervening gas N_H shows large variations ranging from 2×10^{22} cm^{-2} to 5×10^{23} cm^{-2} on a time scale of about an hour. An enhancement of N_H over 3×10^{23} cm^{-2} is observed on three occasions; March 9.89–10.17 (ϕ=0.43–0.46), 11.46–11.81 (ϕ=0.60–0.64), and 18.54–18.55 (ϕ=0.39). Besides such temporal enhancements of N_H, a gradual increase of N_H as a function of the orbital phase is also seen.

When N_H exceeds $\sim2\times10^{23}$ cm^{-2}, a significant absorption edge is seen near 7 keV. The energy of the edge is determined to be 7.3±0.2 keV for all the observed data, which indicates that the ionization state of iron is between Fe I and Fe IX. Spectral fitting for the

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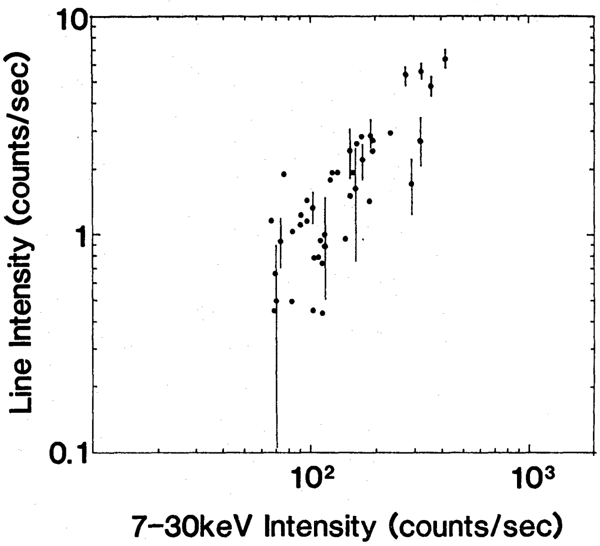

Fig. 3. The relation between the iron line intensity and the continuum intensity in the energy range 7.1–30 keV.

data which exhibit the most prominent absorption feature ($N_H = 5.0 \times 10^{23}$ cm^{-2}) on March 11.72 ($\phi = 0.625$) shows $\log(N_{Fe}/N_H) = -4.37 \pm 0.11$. This is consistent with a cosmical abundance of iron (e.g. Allen 1973). In two occasions around orbital phase 0.4, a significant low energy excess over the spectrum expected from the absorption by a neutral gas was observed below 5 keV. This feature is described in a separate paper.

2.2. *Iron Line*

Iron emission line is always present at a significant level in the pulse-height spectrum of Vela X-1. The energy of the line center is determined to be 6.43 ± 0.05 keV for all the data. This indicates that the ionization state of iron is between Fe I and Fe XIX if no energy shift in the source is present. Therefore, the ion temperature of the gas where iron line is produced is less than 1 keV. Upper limit to the line width intrinsic to the source is 0.49 keV (FWHM) for the spectrum shown in figure 1. Intensity of a possible second line at 6.7 keV (from Fe XXV) is less than 20% of that of the 6.4-keV line. These properties are common to the majority of data. Pulse-height spectrum on March 8 suggests a slightly broadened (FWHM$\lesssim$1 keV) enhancement centered at 6.4 keV.

Figure 3 shows the iron line intensity plotted against continuum intensity in 7.1–30 keV. The efficiency of the instrument is corrected for. For the continuum intensity, absorption due to the intervening gas is also corrected for. Although the fluctuations are quite large, a proportionality is seen between the iron line and the continuum intensities. This relation and the observed energy of the line indicates that the iron line from Vela X-1 is produced through the fluorescence of continuum X-rays by cold material. The fluorescence efficiency, defined as a ratio of the line intensity to the 7.1–30-keV continuum intensity, is about 1.5% for most of the data. However, figure 3 shows that this efficiency varies by a factor of >2. This implies that properties of the reprocessor (geometry, temperature, and abundance) sometimes change significantly.

To study the relation between the iron line intensity and the column density of the intervening gas, the fluorescence efficiencies are plotted as a function of N_H in figure 4. No clear correlation is present between the iron line intensity and N_H. The efficiency can be as large as 1.5% for any value of N_H ranging from 1.3×10^{22} cm^{-2} to 5×10^{23} cm^{-2}. There-

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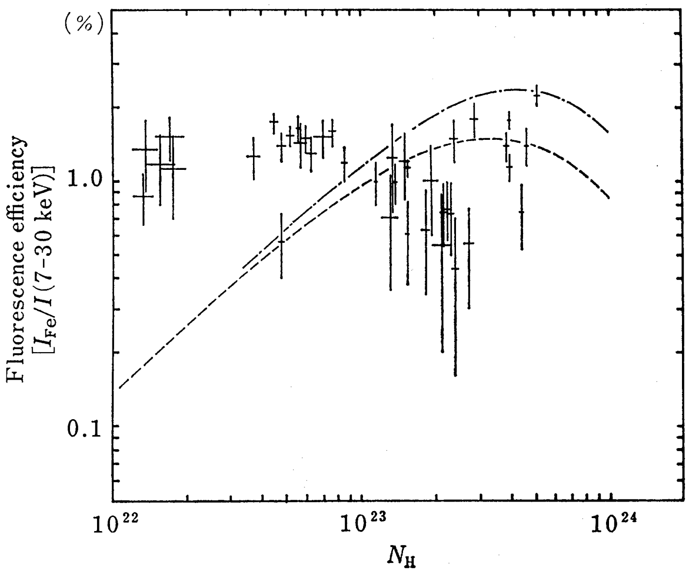

Fig. 4. The observed fluorescence efficiency of the iron line as a function of the absorbing column N_H. The curves show the calculated fluorescence efficiency of the iron line from neutral matter whose thickness corresponds to N_H, as obtained from a Monte Carlo simulation. The dashed and dash-dotted curves are for a 4π-shell and a sphere, respectively.

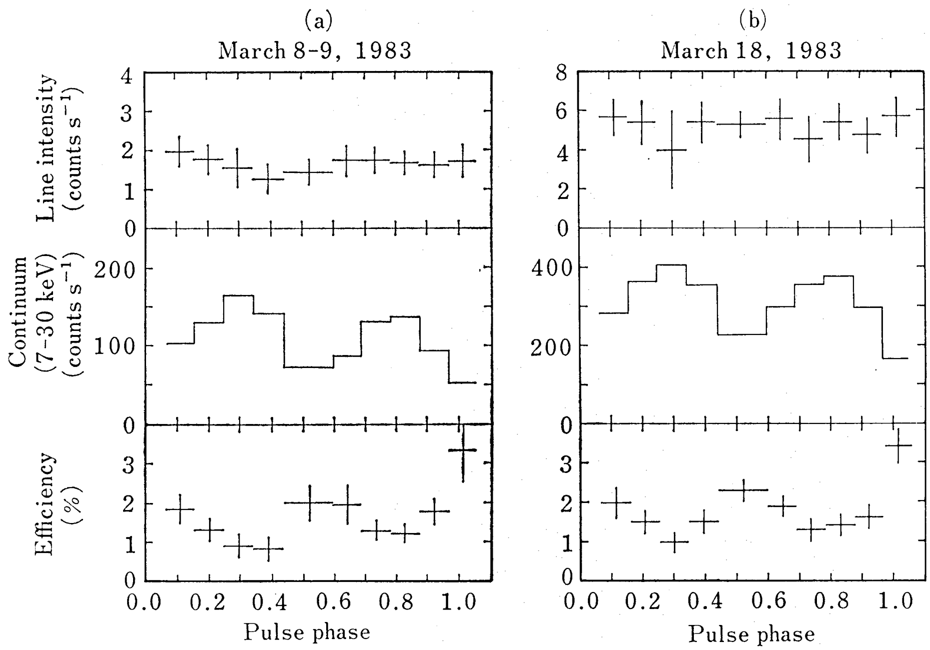

Fig. 5. The iron line intensity, the continuum intensity in the range 7.1–30 keV, and the fluorescence efficiency of the line as a function of the 283-s pulse phase of Vela X-1.

fore, the intensity of the iron line is independent of the thickness of matter between the neutron star and the observer.

The pulse-height spectrum is folded with the 283-s pulse period of Vela X-1 to study the properties of the iron line as a function of pulse phase. A remarkable finding is that the intensity of the iron line does not pulse. As shown in figures 5a and b, the line intensity is consistent with a constant value over the whole pulse phase, though continuum intensity

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levels vary by a factor of 3 for these two cases.

The constancy of the iron line intensity over the pulse phase is also confirmed for other orbital phases. We have investigated all the data for which N_H is less than 10^{23} cm^{-2}, since the iron line is clearly seen above the continuum for these data. For all of the data, the line intensity is found to be constant over the pulse phase. Therefore, this feature is most probably a common property to the Vela X-1 system. Note that the constancy of the line intensity over the pulse phase holds in spite of the variation of the continuum luminosity by a factor of three. During the 283-s pulse period, the continuum intensity above 7.1 keV varies by a factor of three. Accordingly, the fluorescence efficiency varies from $\sim 1\%$ at the pulse maximum to $\sim 3\%$ at the minimum.

2.3. *Eclipse*

A pulse-height spectrum of Vela X-1 at orbital phase 0.07 through 0.11 during eclipse was accumulated for 8700 s. The result is shown in figure 6. The average X-ray flux in 2–20 keV is 1.1×10^{-11} erg cm^{-2} s^{-1}, which is consistent with the previous result by OSO-8 (Becker et al. 1978). A significant hump is seen in the energy range 5.5–7.5 keV. In this energy range, no significant feature is present in the background spectrum. We, therefore, identified this hump as an iron emission line centered at 6.4 keV. The intensity of this iron line turns out to be 0.13 ± 0.06 count s^{-1}, which is about 6% of the average line intensity observed when the neutron star is out of eclipse.

3. Discussion

The present observations of Vela X-1 have presented for the first time the detailed

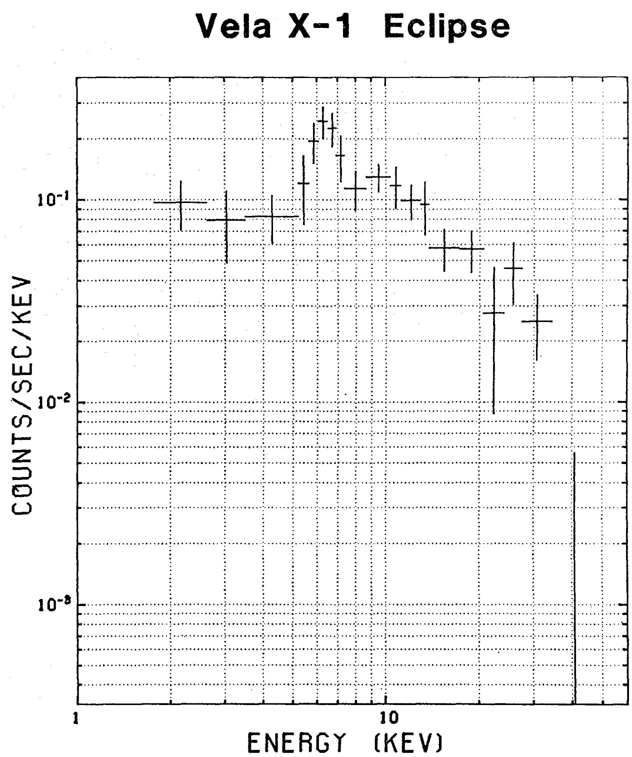

Fig. 6. The pulse-height spectrum of Vela X-1 accumulated for 8700 s at orbital phase ~0.1 during eclipse.

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properties of the iron emission line. The energy of the iron line is 6.43 ± 0.05 keV and the FWHM line width is less than 0.5 keV. It is now established that the iron line from Vela X-1 is produced by the fluorescence in cold ($kT < 1$ keV) material irradiated by the X-rays from the neutron star. Becker et al. (1978) observed a broad line at 6.8 ± 0.3 keV in the spectrum of Vela X-1. However, as these authors noted, the presence of the iron absorption edge causes an uncertainty in the line energy. When N_H is in excess of $\sim 1 \times 10^{23}$ cm^{-2}, an absorption edge of iron produces an apparent enhancement near 7 keV. This enhancement and the emission line at 6.4 keV may well be observed as a single broad feature with the energy resolution of proportional counters.

Becker et al. (1978) also discussed the possibility of the overabundance of iron based on the low-energy excess flux. They found on one occasion that the low-energy flux was relatively unabsorbed for a neutral gas of cosmical abundances whose thickness is derived from the depth of the absorption edge near 7 keV. As mentioned earlier, we observed a similar feature in two occasions from Vela X-1. It is found that the overabundance of iron cannot explain the observed spectrum. Apart from these exceptions, the absorption below 3 keV and the depth of the edge near 7 keV agree very well with the cosmical abundance of iron for N_H up to 5×10^{23} cm^{-2} as also found by Becker et al. (1978).

The surface of the companion star is considered to be a minor source of the observed iron line. Since the inclination angle of the binary orbit of Vela X-1 is larger than 73° (Joss and Rappaport 1984), the size of the irradiated stellar surface observed from the earth varies as a function of orbital phase. The apparent area at $\phi = 0.25$ is less than 30% of that at $\phi = 0.5$. However, the observed fluorescence efficiency of the iron line is 1.3 ± 0.3% at $\phi = 0.25$, which is almost equal to the efficiency of 1.5 ± 0.2% at $\phi = 0.5$.

The observation of Vela X-1 during eclipse at $\phi \cong 0.1$ has revealed a significant iron emission line, whose intensity is about 6% of that observed when the neutron star is out of eclipse. This gives important information on the size of the line-emission region. At $\phi = 0.1$, a few hours before the egress, the boundary of the region masked by the companion star is located at $\sim 5 \times 10^{11}$ cm from the neutron star. If iron line photons are produced in an extended region whose radius is much larger than 5×10^{11} cm centered at the neutron star, nearly half of the line photons should be observable at $\phi = 0.1$. However, only about 6% of the iron line photons are observed. Thus, most of the iron line photons from Vela X-1 are produced within 5×10^{11} cm from the neutron star. This also indicates that the stellar wind from the companion star which extends over $> 10^{12}$ cm is a minor source of the iron emission line.

We performed a Monte Carlo simulation of the fluorescence iron line emission from neutral matter surrounding an X-ray source. The result is plotted in figure 3 together with the observed results. In this plot, we express the line intensity in terms of the fluorescence efficiency. This is defined as the ratio of the output line photons to the incident continuum photons in 7.1–30 keV. Dashed and dash-dotted lines show expected fluorescence efficiencies of the iron line from neutral matter which surrounds the X-ray source in a shell and a sphere, respectively, as a function of the thickness of the matter. Cosmic abundances of elements are assumed. Energy spectrum of the incident continuum X-rays is assumed to be the same as the one fitted to the spectrum in figure 1, since this is the typical spectrum observed for Vela X-1. The fluorescence efficiency first increases with the thickness N_H of the gas. When N_H becomes larger than 3×10^{23} cm^{-2}, the efficiency starts to decrease. This is due to the absorption of the line photons within the gas. Hence, the fluorescence efficiency for a neutral gas has a maximum value of ~ 3% for $N_H \cong 2 \times 10^{23}$ cm^{-2}.

The observed fluorescence efficiency of the iron line from Vela X-1 is essentially independent of the observed N_H and mostly constant at ~ 1.5%. This corresponds to the equiv-

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alent width of about 150 eV. Moreover, the simulation curves indicate that this efficiency value is almost equal to the maximum expected for a cold gas shell. Especially, even for $N_{\mathrm{H}} \cong 10^{22}\ \mathrm{cm}^{-2}$, the observed fluorescence efficiencies are as large as 1.5%. The matter in a shell of this column density can account for only about 10% of the measured iron line.

This feature has important implications for the X-ray beam from the neutron star and the structure of the reprocessor. It is almost certain that the reprocessor does not spherically cover the neutron star. Rather, a thick matter with $N_{\mathrm{H}} \gtrsim 2 \times 10^{23}\ \mathrm{cm}^{-2}$ must be present out of the line of sight. Assuming that the neutron star emits a fan beam, i.e. the continuum flux averaged over the pulse period is isotropic, almost all of the X-ray photons have to hit the reprocessor of a thickness $N_{\mathrm{H}} \gtrsim 2 \times 10^{23}\ \mathrm{cm}^{-2}$ to account for the observed large fluorescence efficiencies. This contradicts the observed results because the observed efficiency is 1.5% even when the thickness of matter between the neutron star and the observer is less than $2 \times 10^{22}\ \mathrm{cm}^{-2}$. The other possibility is that the neutron star emits a pencil beam. In this case, one can consider the possibility that a much more intense X-ray flux is present than that observed, which would depend on the beam pattern and the orientation of the line of sight. If an unobservable intense X-ray flux is incident on the reprocessor, a reprocessor which subtends a significantly smaller solid angle may suffice to produce the observed iron line.

A remarkable and puzzling feature is that the iron line does not exhibit pulse modulations. This is true at all orbital phases and for various accretion rates in a range of a factor of three. We conclude that the constancy of the iron line over the pulse phase is an inherent property of Vela X-1.

Since most of the iron line photons are produced within 5×10^{11} cm from the neutron star as shown above, smearing due to the difference of photon travel times as large as a few hundred seconds in the reprocessor is unlikely. A reprocessor spherically surrounding the neutron star can explain the absence of the pulse modulation of the iron line intensity. However, this is excluded by the above discussion. The absence of the pulse modulation of the iron line intensity would rather suggest a special geometry of the reprocessor.

When matter is trapped in the magnetosphere of the neutron star, its relative orientation to the X-ray beam does not change with the rotation of the neutron star. The absence of the pulse modulation of the line intensity can be explained, if the iron line photons are emitted isotropically from such trapped matter. It is interesting to point out that the fluorescence iron line photons are emitted with roughly the same intensity in all directions when the thickness of the matter $N_{\mathrm{H}} < 1 \times 10^{23}\ \mathrm{cm}^{-2}$, i.e., when the matter is optically thin to the line photons. Absorption of the incident X-rays in the energy range >7.1 keV within the matter is less than 13% for such thickness of the matter. Therefore, the iron line photons are produced roughly homogeneously in the matter and escape in all directions without significant absorption.

The above scheme is one of the possibilities to explain both the observed large fluorescence efficiency of the iron line and the absence of its pulse modulation. It is certain that these properties of the iron emission line from Vela X-1 are tightly connected to the structure of the accreting matter onto the neutron star which has a strong magnetic field. Further study of the behavior of matter in the close region to the magnetized neutron star is desired to draw a realistic picture on the origin of the iron emission line.

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