Optical loading study of X-ray imaging spectrometer for Jupiter exploration mission

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Thanks to the recent X-ray observatories orbiting the Earth, X-rays from Jupiter, its vicinity and satellites have been detected. These observations have revealed various aspects of Jovian environments, such as the aurora and magnetosphere. However, the low surface brightness and limited observation time has left many questions. Therefore, an X-ray remote sensing instrument is proposed for the Japanese orbiter in the international exploration mission to Jupiter planned in 2020’s. This instrument is named JUXTA (JUpiter X-ray Telescope Array). One of the major concerns about the observation at Jovian orbit is contamination on the data by optical photons from Jupiter. This effect, called optical loading, occurs since the semiconductor X-ray detector planned to be used in JUXTA is sensitive to optical lights. The optical loading degrades detector performance such as energy resolution and detection efficiency by mimicking signals. In this paper, the optical loading study for JUXTA is conducted by using the recent X-ray astronomy satellite data (Chandra, XMM-Newton and Suzaku). Our conclusion is that the optical loading can be mitigated under the current detector and telescope design in combination with a thick optical blocking filter.

Key words: X-ray, Jupiter, optical loading

1 Introduction
The Jupiter system consisting of Jupiter, satellites, the Io Plasma Torus, magnetosphere and so forth is an attractive science target for space plasma, astronomy, and astrobiology. ESA and NASA plan to launch two independent orbiter into the Jupiter system, in order to explore Galilean satellites, especially Ganymede and Europa. JAXA is proposing another orbiter to explore the Jovian magnetosphere, named
In recent years, our understanding on the X-ray emission from the Jupiter system, which includes not only Jupiter itself but also Jovian inner radiation belt (extends to \( \sim 6 R_J \); Jovian radius), the Io Plasma Torus, Io and Europa, has been greatly advanced with the current generation X-ray observatories, Chandra, XMM-Newton and Suzaku (Gladstone et al., 2002; Branduardi-Raymont et al., 2004; Branduardi-Raymont et al., 2007; Ezoe et al., 2010; Elsner et al., 2002). Since the X-ray emission relates to relativistic electrons and highly charged heavy ions in the Jovian magnetosphere, the X-ray imaging spectroscopy will greatly enhance the scientific fruits of JMO as a direct probe to study energetic particles as well as the ion distributions. Therefore, we propose an X-ray imaging spectroscopy instrument based on advanced telescope and detector technologies. Hereafter we call the X-ray instrument JUXTA (JUpiter X-ray Telescope Array) (Ezoe et al. in this proceedings). Figure 1 shows a design concept of JUXTA.

To realize the observation around Jupiter with X-rays, there are three major concerns. One is an optical loading. This is a contamination of the X-ray data by optical lights, because the semiconductor X-ray imaging detector planned to be used in JUXTA is sensitive to optical, IR and UV lights. Second is a radiation damage/noise due to the severe radiation environment in the Jovian magnetosphere. Third is the micrometeoroids and orbital debris, which can hit and damage the detector and telescope.
The technology candidate for the X-ray detector is DepFET (Depleted P-channel Field Effect Transistor) (Kemmer and Lutz, 1987). This has good image and spectral resolution, and is also radiation hard. DepFET combined detector-amplifier structure consists of a p-channel MOSFET integrated on the surface of an n-type silicon bulk. Since DepFET can be read out very fast at low noise, and no charge transfer is required, the device is intrinsically more radiation hard than X-ray CCDs.

In this paper, we focus on the optical loading and study how to mitigate this effect by using the experience of the X-ray CCD and the optical blocking filter onboard the Chandra, XMM-Newton and Suzaku satellites.

2 Requirements

2.1 Optical loading effects

Like an X-ray CCD (Lumb et al., 1991), the DepFET is sensitive to optical lights. Therefore if an astronomical object has a high optical-to-X-ray flux ratio, there is a possibility that X-ray signals become contaminated by optical photons. As a result, the data will be impeded in several ways. The first one is to degrade the system noise due to optically generated photoelectrons. This will also degrade the energy resolution. The second is to be registered the incorrectly energy scale, because a pixel has an offset noise. The third is that excess signal and noise fluctuations can affect the detection efficiency by disguising single pixel events as multiple pixel events. To prevent these effects, there are two ways. One is to utilize a tolerant detector for the optical loading. The other is to equip with an optical blocking filter consisting of a thin metal film on a plastic films. Since the optical blocking filter also causes X-ray absorption, the optimization of the thickness and material is crucial for the X-ray detector system design.

In the current generation X-ray CCDs onboard satellites, the optical loading have been observed. In particular, since planets in the solar system are bright at the optical wavelength, X-ray CCDs are likely to be affected by the optical loading. Indeed, the observations of Venus and Mars with Chandra suffered from the optical loading. The optical photons from Venus deposited charge in the CCD in addition to the X-ray photons, caused a systematic increase of the apparent energy (Dennerl et al., 2002). In case of Mars, the apparent energy in the spectrum of Mars was shifted due to the optical loading, a superposition of the charges released by X-ray photons and optical photons (Dennerl, 2002). Figure 2 shows the spectrum of Mars. In these satellites, the offset energy is monitored as a “dark image”. For instance, in the Chandra satellite the dark image is collected during the shutter closed. However, we cannot get rid of the energy offset generated by the optical loading with the dark image, because the optical photons can not reach the detector through the closed shutter and the event by optical photons are not included in the dark image. Of course, the optical blocking filter is assembled for each X-ray CCD. For instance, XMM-Newton utilize three types of optical blocking filter, which have different thickness and materials (thin, medium and thick). When Saturn was observed with XMM-Newton, the contamination by optical lights was found to be severe in the medium and thin filters. With the thick filter all optical lights could be sufficiently blocked (Ness et al., 2004).
Fig. 2. X-ray spectra of Mars (top) and its surrounding region (bottom), obtained with Chandra X-ray CCD (ACIS-I). Although the Martian spectrum appears to be dominated by a single narrow emission line at 0.65 keV, it is most likely the O-Kα fluorescence line at 0.53 keV. The apparent energy is shifted to higher due to optical loading. This picture is taken from Dennerl (2002).

JUXTA will be affected more than ever by the optical loading, because JUXTA will observe Jupiter in its vicinity, while the past observations with the X-ray CCD were conducted near Earth. Therefore, we need both the less sensitive detector for the optical loading, the DepFET, and the optical blocking filter.

2.2 Requirements for JUXTA

Table 1 is a summary of required specs of JUXTA taken from Ezoe et al. (in this proceedings). Especially, in terms of the performance of DepFET, unless charges due to optical loading do not saturate the potential wells of DEPFET, the true problem of optical loading is the fluctuations in number of charges created by optical lights, which affects the energy resolution and the minimum detectable X-ray photon energy.
The relation can be expressed as,

\[ N_{\text{opt}} = f \times A \times B \times \left( \frac{D}{C} \right)^2 \times E \times Z \ll N_{\text{minX}}, \]  

(1)

where the definitions of A to E are a geometric telescope area, a detector efficiency for optical lights, an angular extension of the optical emission, an angular pixel size, and a detector frame time, respectively. \( f \) is a total optical photon flux from the Jovian system. \( N_{\text{opt}} \) and \( N_{\text{minX}} \) are number of electrons created by an optical photon and an X-ray photon of required lowest energy 0.3 keV. \( Z \) is an optical blocking factor. The typical optical photon flux (term of \( f \)) is \( \sim 10^{10} \) photon cm\(^{-2}\) s\(^{-1}\) at 100 \( R_J \) from Jupiter. From the requirement in Table 1 and typical DepFET performance, \( A=10 \) cm\(^2\), \( C=1 \) deg, \( D=5' \), and \( E=1 \) msec. Here, the angular extension of 1 deg and the angular pixel size of 5' are assumed as the worst case for the optical loading in which the position of Jupiter is at 100 \( R_J \) planned apoapsis of the JMO and the angular pixel size is equal to the angular resolution (<5 arcmin). The detector efficiency (term of \( B \)) is assumed to be 50%. \( N_{\text{minX}} \) is \( \sim 80 \), based on an average pair creation energy of 3.65 eV in Si. Then, we substitute these values to Eq. (1), \( Z \) should be less than \( 2 \times 10^{-6} \) (in case of that the \( N_{\text{opt}} \) is two orders of magnitude smaller than the \( N_{\text{minX}} \)). We have to satisfy the \( Z \), and suppress the optical loading effects.

<table>
<thead>
<tr>
<th>Table 1. Scientific requirements for JUXTA.</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
</tr>
<tr>
<td>Energy band</td>
</tr>
<tr>
<td>Angular resolution</td>
</tr>
<tr>
<td>Energy resolution</td>
</tr>
<tr>
<td>Time resolution</td>
</tr>
<tr>
<td>Field of view</td>
</tr>
</tbody>
</table>

*The planned periapsis of the JMO.

3 Susceptibility to Optical Loading

A key parameter for the optical loading is the amount of light per pixel per frame time. Hereafter we call this F factor. The large F factor suggests that the detector is more susceptible to the optical loading effect. The F factor is proportional to

\[ F \propto A \times B \times \left( \frac{D}{C} \right)^2 \times E, \]  

(2)

where the definitions of A to E are the same in Eq. (1), and F is an optical loading susceptibility. The large telescope area, high detection efficiency to the optical light, small angular extension of the optical emission, large angular pixel size, and long frame time increase the number of optical photons accumulated during the frame.
Table 2. Optical loading susceptibility of the X-ray CCDs onboard the past missions and the DepFET.

<table>
<thead>
<tr>
<th>instrument</th>
<th>A. telescope name</th>
<th>L. telescope focal length</th>
<th>s. pixel size</th>
<th>E. frame time</th>
<th>F. factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chandra ACIS-I</td>
<td>1100 cm²</td>
<td>1000 cm</td>
<td>24 μm</td>
<td>3.2 sec (faint)</td>
<td>0.4</td>
</tr>
<tr>
<td>XMM EPIC MOS</td>
<td>2000 cm²</td>
<td>750 cm</td>
<td>40 μm</td>
<td>2.6 sec (full frame)</td>
<td>2.6</td>
</tr>
<tr>
<td>XMM EPIC pn</td>
<td>2000 cm²</td>
<td>750 cm</td>
<td>150 μm</td>
<td>73.4 msec (full frame)</td>
<td>1 (normalized)</td>
</tr>
<tr>
<td>Suzaku XIS</td>
<td>900 cm²</td>
<td>475 cm</td>
<td>24 μm</td>
<td>8 sec (normal)</td>
<td>3.3</td>
</tr>
<tr>
<td>JMO JUXTA DepFET</td>
<td>10 cm²</td>
<td>25 cm</td>
<td>360 μm</td>
<td>1 msec</td>
<td>0.000033</td>
</tr>
</tbody>
</table>

Based on this relation, we compare the optical loading susceptibility of DepFET designed for JUXTA (Ezoe et al. in this proceedings) to the X-ray CCDs, Chandra ACIS-I, XMM-Newton EPIC MOS (Turner et al., 2001) and pn (Strüder et al., 2001), and Suzaku XIS (Koyama et al., 2007). The results on the optical loading susceptibility are summarized in Table 2. In this table, the detector efficiency (term of B in Eq. (2)) is assumed to be the same (50%) for every detector and the distance to the Jupiter (d) is 5 AU except for JUXTA. In the JUXTA case, d is assumed to be 100R_J as the worst case in the same way as Section 2.2.

From Table 2, JUXTA is the best to be resistant to the optical loading.

4 Optical Blocking Filter

To mitigate the optical loading, the optical blocking filter is installed in front of the detector (see Fig. 1). However, the filter will also attenuate the X-ray transmission in the soft X-ray energy band, especially below 1 keV. In addition, optical brightness of the astronomical objects are very different. Hence, in XMM-Newton, the optical blocking filter is selectable. Figure 3 shows the transmission through the optical blocking filter of XMM-Newton, and indicates the decrease of the soft X-ray transmission by each of the optical blocking filter. Since JUXTA will observe only Jupiter, we should optimize filter materials and thickness, which can maximize the optical opacity and the X-ray transparency, to suit the optical brightness of Jupiter.

1http://cxc.harvard.edu/cdo/about_chandra/
When the thin layer is used as the absorber of the optical blocking filter, some mechanical support which does not affect the X-ray transmission are necessary. Plastic films are both mechanically resistant and transparent to X-rays. Polypropylene and polyimide are most used ones and the thin layer is deposited on the one or both side of them. Normally aluminum is used as the thin layer (∼100 nm or less), because of a higher X-ray transmission. However, aluminum also has a high transmission in the extreme ultraviolet. On the other hand, another material using for the optical blocking filter installed the current generation observatories is tin. The characteristic of tin is the sharp cutoff in its extreme ultraviolet transmission and lower X-ray transmission between 0.5 and 2 keV than aluminum (Palombara et al, 1996).

Since every X-ray CCD has a different optical loading susceptibility (F factor), the optical blocking filter is not the same. In Chandra\(^2\) and Suzaku\(^3\), aluminum coated polyimide is used for the optical blocking filter. In XMM-Newton\(^4\), two of the three optical blocking filters are made of the aluminum layer and another one is made of the both tin and aluminum. The detailed properties of the optical blocking filters used for the Chandra, XMM-Newton and Suzaku CCDs are summarized in Table 3. The

\(^2\)http://cxc.cfa.harvard.edu/proposer/POG/html/ACIS.html
\(^3\)http://www.astro.isas.ac.jp/suzaku/doc/suzakuTd/node10.html
\(^4\)http://xmm2.esac.esa.int/external/xmm_sw_cal/background/filter_closed/index.shtml

![Fig. 3. The X-ray transmissions through the optical blocking filter of XMM-Newton, obtained from http://henke.lbl.gov/optical_constants/filter2.html. The thick, medium and thin filters are shown in red, green and blue, respectively.](image-url)
Table 3. OBFs used for the X-ray CCDs in the current X-ray astronomy missions.

<table>
<thead>
<tr>
<th>instrument</th>
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<th>filter configuration</th>
<th>optical transmittance</th>
<th>X-ray transmittance</th>
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<tbody>
<tr>
<td>Chandra ACIS-I</td>
<td>Al 120 nm + polyimide 200 nm + Al 40 nm</td>
<td>$10^{-10}$ @ 600 nm $10^{-3}$ @ 900 nm</td>
<td>0.6 @ 0.6 keV</td>
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</tr>
<tr>
<td>XMM EPIC thick</td>
<td>Sn 45 nm + Al 55 nm + polypropylene 330 nm + Al 55 nm</td>
<td>$10^{-8}$ @ 900 nm</td>
<td>0.4 @ 0.6 keV</td>
<td></td>
</tr>
<tr>
<td>XMM EPIC medium</td>
<td>Al 80 nm + polyimide 160 nm @ 400~1000 nm</td>
<td>$10^{-5}$</td>
<td>0.7 @ 0.6 keV</td>
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<tr>
<td>Suzaku XIS</td>
<td>Al 40 nm + polyimide 100 nm @ 400~950 nm + Al 80 nm</td>
<td>$&lt; 3 \times 10^{-5}$</td>
<td>0.7 @ 0.6 keV</td>
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*Chandra data from [http://space.mit.edu/ACIS/cal_report/node126.html](http://space.mit.edu/ACIS/cal_report/node126.html). XMM-Newton thin filter data from [http://www.astropa.unipa.it/XACT/XMM.html](http://www.astropa.unipa.it/XACT/XMM.html), medium and thick filter is $10^{-2}$ and $10^{-5}$ times less transmittance, respectively. Suzaku data from Koyama et al. (2007) and Katayama et al. (1999). Data from [http://henke.lbl.gov/optical_constants/filter2.html](http://henke.lbl.gov/optical_constants/filter2.html). Although Suzaku telescope has a thermal shield with Al 30 nm + PET 220 nm, this effect is not included in the optical and X-ray transmission values.

thick filter of XMM-Newton EPIC can suppress efficiently the optical contamination for all point source targets up to $m_V = 1 \sim 4$ for MOS and $m_V = 0 \sim 3$ for pn (where $m_V$ is a optical magnitude). As with Chandra, XMM-Newton, and Suzaku, the optimization of the thickness and material of the optical blocking filter for JUXTA is necessary in order to satisfy the optical blocking factor (term of Z in Eq. (1)). Since the required Z factor is $< 2 \times 10^{-6}$, the thick filter of XMM-Newton and the Chandra filter can be appropriate based on the optical transmittance in Table 3.

5 Expected Brightness of Jupiter

The optical brightness of Jupiter will peak at 30 $R_J$ (the planned periapsis of the JMO). The expected visual magnitude of Jupiter and the maximum allowable magnitude can be estimated as follows.

The maximum apparent visual magnitude of Jupiter between 2020 and 2030 is $-2.9$ mag in 2023 November at the Earth–Jupiter distance of 4.0 AU, according to the NASA HORIZON ephemeris data base\(^5\). When Jupiter is seen at 30 $R_J$, this

\(^5\)http://ssd.jpl.nasa.gov/horizons.cgi
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magnitude converts to

$$-2.9 - 2.5 \log \left( \frac{4.0 \text{ AU}}{30 R_J} \right)^2 = -15 \text{ [mag].} \quad (4)$$

Because Jupiter is extended over $\sim 4 \text{ deg} \phi$ at $30 R_J$, assuming that the angular pixel size is $5'$, the average surface brightness per pixel becomes

$$m_{\text{pix}} = -15 - 2.5 \log \left( \frac{5 \text{ arcmin}}{4.0 \text{ deg}} \right)^2 = -6.6 \text{ [mag].} \quad (5)$$

As estimated in Table 2, the F factor (the optical photon flux per frame time per pixel) of the JUXTA system is 0.000033 times smaller than the XMM EPIC pn system. The maximum allowable brightness of the point source for XMM EPIC pn with the thick filter is $m_v = 0.08$ for G type star (see the table in section 4 in Lumb 2000). Assuming that the optical spectrum of Jupiter is similar to the G type star, i.e., the Sun, the maximum allowable brightness of the point source for the DepFET is estimated as

$$m_{\text{max}} = 0.08 + 2.5 \log(0.000033) = -11 \text{ [mag].} \quad (6)$$

In flux, $m_{\text{max}}$ is larger than $m_{\text{pix}}$ by a factor of

$$10^{[11-(-6.6)/2.5]} = 58.$$

Therefore, more than an order of magnitude margin is kept with this combination in exchange of the low energy efficiency.

6 Conclusion

The optical loading for JUXTA can be mitigated by combining the fast readout and small pixel DepFET detector with the thick optical blocking filter. The low energy efficiency is, however, sacrificed. The transmittance at 0.6 keV is reduced by a factor of $\sim 3$. The use of a lower optical transparent material, the higher speed readout, and/or the smaller pixel are desired to reduce the thickness of optical blocking filter and to increase the low energy quantum efficiency.

We should revisit this issue after the telescope and detector parameters are fixed. In addition, due to install the optical blocking filter the ice/outgas contamination on the optical blocking filter can become a problem. It can decreases the low energy effective area on the detector. Hence, we need to consider some countermeasures.

References


Ezoe, Y. et al., X-ray observations of Jupiter and beyond, in this proceedings.


