X-ray CCD calibration system using fluorescent lines

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Abstract

We have developed a CCD calibration system using fluorescent X-ray lines with energies ranging from 1.49 keV (Al K\textsubscript{\alpha}) to 11.2 keV (Se K\textsubscript{\alpha}). The absolute X-ray flux is calibrated by a gas proportional counter, while the emerging spectra are monitored by solid-state silicon detectors. In order to suppress contaminating X-rays in the fluorescence spectra, mechanical collimators were set in the X-ray beam line, high-purity targets for fluorescent lines were used, and band-pass filters were put on the X-ray beam line. As for the purity of the fluorescent X-rays, the typical purity achieved was \sim 98\%. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The next Japanese X-ray satellite, Astro-E is scheduled to be launched in early 2000. One of the main instruments on Astro-E is four X-ray CCD cameras (X-ray Imaging Spectrometer, or XIS in short) placed on the focal planes of the X-ray telescopes. In order to extract reliable X-ray spectra from astronomical objects, building of an accurate response function through on-ground calibration is a key aspect of the XIS study in this mission. The X-ray response is being investigated in collaborative studies by researchers at Kyoto University [1], Osaka University [2], and ISAS (Institute of Space and Astronautical Science). In practice, the investigation is divided into two parts, the soft X-ray band (0.4–2 keV) and the hard X-ray band (2–12 keV), and we (Kyoto University) are responsible for the part concerning the hard X-ray band. Thus, we have developed an X-ray CCD calibration system for the XISs in the energy band above 2 keV\textsuperscript{2}. The relevant response function changes continuously versus the energy of incident X-rays because the main components of the CCD chip, silicon and oxygen, exhibit no absorption.
edge and no other anomaly in this energy band. Therefore, we have selected several monochromatic X-ray lines for evaluating the response function. An X-ray fluorescence method has been commonly applied not only for the calibration of detectors [3], but also for analysis of trace elements especially in biological studies [4], but, owing to the large size of apparatus in our system and the need for a strict detector response to incident X-rays, the effect of contamination within the fluorescent X-rays is of crucial concern.

2. Configuration

The system consists of two vacuum chambers (see Fig. 1); one is for generation of fluorescent X-rays (the X-ray generating chamber), and the other is for X-ray irradiation of the XIS (the XIS chamber). Since X-rays from the generator go through high-vacuum paths to the detectors, no absorption effect and no fluorescent line with the air is produced. The X-ray generator (Kevex: K5039S) is placed on a top-side flange of the X-ray generating chamber, which emits the primary X-rays from the tungsten (W) target, and the X-rays hit a secondary target laid on a rotating stage inside the chamber. We employed eight secondary targets consisting of Al (1.49), polyvinylidene chloride for Cl (2.62), Ti (4.51), Fe (6.40), Ni (7.47), Zn (8.63), Se (11.21), where numbers in parentheses are the K\textalpha line energies in the unit of keV [7]. The line energies of carbon and hydrogen from the polyvinylidene chloride target are extremely low compared to that of the Cl lines, and therefore do not interfere with the Cl line. The secondary X-rays (mainly the fluorescent lines) go into the XIS chamber and irradiate the XIS on a stage, which can move in the direction perpendicular to the X-ray beam. When the XIS is in an off-beam position, the X-ray spectra can be monitored by means of a solid-state silicon detector (SSD) placed at the end-point of the beam line (at the end-flange of the XIS chamber). The fluorescent X-ray spectra and flux are monitored in real-time by means of an SSD on a side-flange of the X-ray generating chamber (SSD for real-time monitor in Fig. 2), whereas the absolute flux is estimated by means of a proportional counter (PC), which is placed in the position of the XIS, before and/or after the calibration run. The secondary target is a thin plate, with the surface tilted on a 45° angle from both the primary and secondary X-ray beam lines and the line to the real-time monitor SSD (see also Fig. 2).
The operation temperature of the XIS is controlled to be \(-90^\circ\)C. In order to avoid water condensation on the CCD chips and X-ray absorption by the air, both of the chambers are placed under high vacuum by means of dry (oil free), turbo molecular and cryo pumps to about \(10^{-6}\) Torr, well below the water vapor pressure of \(\sim 10^{-5}\) Torr at \(-90^\circ\)C under which conditions X-ray absorption by the air is also negligible.

3. Performance

A calibration system using X-ray tubes has been reported by Jones et al. [3] and Manning et al. [6] for ACIS, the X-ray CCD camera onboard the Chandra satellite. However, X-rays in this system exhibit significant contamination below the energy of the main peaks as shown in Ref. [3]. This may make it necessary to estimate the low-energy tail and the constant component to evaluate the response. We thus focused particular efforts on investigation of the origin of the contamination and how to suppress the contamination.

3.1. Spectra of the primary X-rays

Contaminating X-rays included in the primary X-rays would cause a significant background component by scattering through the secondary target. Therefore, we first obtained the spectra of the primary X-rays at several generator voltages by installing the X-ray generator in a port and a SSD on the opposite side of the port of the XIS chamber. For stable operation, the X-ray generator has a certain lower flux limit, which still causes severe pile-up for the SSD. Thus, we installed a diaphragm made of Ni plate which decreased the aperture of the SSD. The X-ray spectrum at 20 keV generator voltage is shown in Fig. 3. Since we used tungsten (W) as the primary target, the characteristic X-rays of W L\(_x\), \(\beta_{1,2}, \gamma\) and M complex are clearly seen on the continuum of bremsstrahlung emission. A weak line at \(\sim 7.5\) keV is thought to be attributable to the Ni diaphragm, and is probably not a real component of the primary X-rays. No other emission line can be seen in the spectrum, and the contamination by impurities from the anode, the Be windows or the walls of the X-ray generator is negligible. These features hold at generator voltage levels below 20 keV which we use in the calibration operation.

3.2. Minimizing the contamination

Several contaminating lines were found in the fluorescent X-rays generated in our system (see Fig. 3 left). In the pre-calibration with an SSD, we found these lines and their possible origins, then eliminated most of them as follows. First, the spectra contain Cr, Fe and Ni K\(_x\) lines photo-ionized by primary or secondary X-rays at walls of the chambers or the supports of the secondary targets. Therefore, we put collimators before and after the secondary targets, and as a result these line fluxes decreased by about one half. Second, impurities in the secondary targets also produce fluorescent X-rays, hence we used high purity (99.99–99.999%) targets to reduce them. Third, we found several unidentified soft X-ray lines which are thought to be fluorescent lines derived from light elements in the secondary targets or Bragg reflection components of the primary X-rays. To suppress them, we used a foil filter. The flux ratio of the fluorescent line to the softer X-rays increases, but the absolute flux of the fluorescent line decreases as the thickness of the filter increases. Thus,
the optimum thickness of the filter is found when the optical depth of the filter is \( \sim 0.5 \) at the K\( \alpha \) line energy. Fourth, there may be contamination due to Thomson scattering including Rayleigh scattering of the primary X-rays by the secondary targets. Since the primary X-rays just above \( E_{\text{edge}} \) are efficiently converted to fluorescent X-rays, the optical depth of the secondary target at \( E_{\text{edge}} \) is tuned to be \( \sim 1 \) to minimize the ratio of the Thomson component to the fluorescent X-rays. Moreover, the absorption coefficient exhibits a large jump at the K-shell edge energy (\( E_{\text{edge}} \)) of the filter element. The Thomson component in the energy band between \( E_{\text{edge}} \) and \( \sim 2 \times E_{\text{edge}} \) is effectively suppressed if the element of the filter is the same as the target element [5]. Thus, we tuned the maximum energy of the primary X-rays to be \( 2 \times E_{\text{edge}} \). In fact, we set the voltage of the X-ray generator at 15 kV for the iron target with \( E_{\text{edge}} \) being 7.1 keV.

Fig. 4 shows the SSD spectra of Zn before (left) and after (right) suppression of the contamination using the above-mentioned technique. We found many emission lines in the left spectrum, most of which are contamination lines. The line at 1 keV is probably Na K\( \alpha \), a contaminating element on the Zn surface. The 3–5 keV bump has no candidate element, and may be due to the Bragg reflection. K\( \alpha \) lines of Cr (5.41), Fe (6.40) and Ni (7.47) come mainly from the chamber walls, whereas that of Cu (8.04) is due to impurities in the target. The right spectrum shows that these features are effectively suppressed, then a low-energy tail and constant component are apparent. In comparison with the \(^{55}\)Fe spectrum, we conclude that X-rays in the right panel spectrum are those of Zn origin, except for small residuals of Cr, Fe and Ni lines. The ratio of the fluorescent lines, 'K\( \alpha \) + K\( \beta \) counts' to the total counts is about 98.4%.

3.3. Estimating the Thomson scattering component

The component due to Thomson scattering of the primary X-rays still contaminates the secondary X-rays. We estimate the flux using characteristic X-rays (W L\( \alpha \), \( \beta_{1,2} \)). In this case, Se is a suitable element to see the Thomson scattering component because W L\( \alpha \), \( \beta_{1,2} \) lines can be Thomson scattered into the secondary X-rays without being largely absorbed by Se. We fit the spectrum of the primary X-rays with a model of absorbed simple bremsstrahlung and Gaussian lines. Assuming a single process of Thomson scattering of the primary X-rays in the secondary target, the X-rays are attenuated in a manner inversely proportional to the absorption coefficient. The Thomson scattering flux depends on the polarization angle, but we confirmed that the polarization of the relevant primary X-rays is \(< 10\%\), when the energy is lower than 60\% of the applied voltage of the X-ray tube (which is the case in our system). The left panel of

![Fig. 4. SSD spectra before (left panel) and after (right panel) suppression of the contamination. Vertical scales are normalized by the intensity of Zn K\( \alpha \). Events at 10–20 keV are the pile-up component.](image-url)
Fig. 5 shows the Se spectrum, and the right panel is the result of the single Thomson scattering normalized by the flux of W L\textsubscript{a}. This model well reproduces a hard continuum of the Thomson scattering component. However, the W L\textsubscript{b1,2} intensity of the model is \(\sim 60\%\) larger than the experimental spectrum (left). One possibility is that a small portion of the glue in the Se grain target may not be removed from the target surface, and we overestimate the X-rays around the W L\textsubscript{b} lines, some of which are scattered by the glue and hence are not absorbed by the Se grain, but this is still debatable, and the Thomson scattering component may be \(\sim 50\%\) of the tail of Se K\textsubscript{a}. Thus, our model still has \(\sim 60\%\) uncertainty in the tail energy band. However, the upper limits of Thomson scattering components of the other targets were found to be negligible compared with the tail components.

References