MAXI observation of X-rays reflected from the Moon

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The challenge of detecting reflected X-rays from the Moon dates to 1962.[1)] At that time, the only known X-ray source was the Sun. The study attempted to detect fluorescent X-rays produced on the lunar surface by solar X-rays. However, no X-rays from the Moon were observed. Instead, the first X-ray source (Sco X-1) was discovered and X-ray astronomy began.

Strong solar flares occurred on February 22 and September 14, 2024 (Table 1). X-rays from the flares were absorbed by the Moon, and the fluorescent X-rays were captured by MAXI (Fig. 1). Emission lines of three elements, Si (1.748 keV, averaged neutral Kalpha and Kbeta lines), Ca (3.719 keV) and Fe (6.459 keV) were observed. They are abundant elements on the Moon surface.

We calculate the physical processes in five steps. 1. X-ray spectrum of the solar flare is assumed. 2. The illuminated X-ray is photo-electrically absorbed. 3. Fluorescent K X-rays are emitted according to the K fluorescent yield. 4. Some fluorescent X-rays are absorbed during the escape. 5. They reach the MAXI detector. We calculated the full Moon case, because the incident X-ray and output X-ray trace the same path at the full Moon (180 deg. reflection), which simplified the calculation. We considered the area of the ocean and high land and their chemical composition. Subsequently, we averaged them to make an ideal regolith. Because the mean-free-paths of these X-ray energies are shorter than 1 mm, the physical processes complete in one regolith.[2)]

The first observations of the three elements were ∼0.7 of the calculated values and the second ones were ∼0.3. Next, we investigated the relation of the line intensities to the Moon age. We plotted the line fluxes relative to the calculations of the full Moon in Fig. 2. The bright area of the Moon is one reason for the discrepancy, but it is not sufficient (blue line in Fig. 2). More detailed calculations of a smooth sphere considering the incident angle from the Sun and output angle to the earth cannot explain it, either (yellow line in Fig. 2).

In optical light, the full Moon is extremely bright. The intensity is not proportional to the bright area. This is because the Moon surface is bumpy and the bumps cast shadows to the surface.[3)] The optical curve (green line in Fig. 2) agrees well with the observations. The X-ray observations would suffer the same effect of shadow of the bumps as the optical light.

MAXI detected the reflected X-ray from the Moon at the solar flares twice. The detected spectra consisted of Si, Ca and Fe fluorescent lines. The observed intensities were all weaker than the calculated values. The line intensities to the Moon age are on the optical light curve, indicating the shadow of the bumpy

Table 1. Two MAXI observations of reflected X-rays from the Moon of the X-class solar flares.

	First	Second
Time (UT) in 2024	Feb.22 22:34	Sep.14 15:26
Solar flare intensity	X6.3	X4.2 at obs.
Moon age (area)	13.0 (96.7%)	11.5 (88.5%)
Flux(2-10keV) [erg/cm^2/s]	9.15 × 10^{-9}	2.57 × 10^{-9}

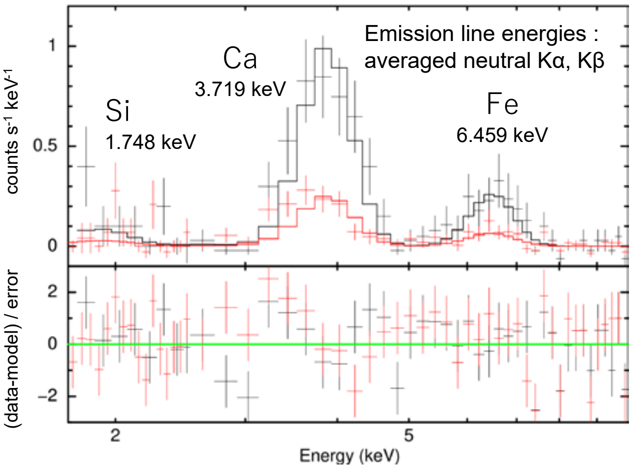

Fig. 1. Observed X-ray spectra with the best fit models. black: first observation, red: second one.

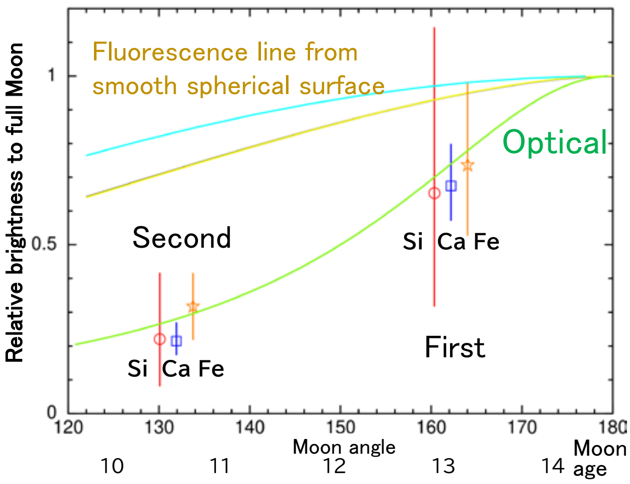

Fig. 2. Moon flux and anti sun-Moon-earth angle. blue: bright area, yellow: smooth sphere, green: optical light.

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Table 2. Observed and calculated values.

	First obs. [ph/cm^2/s]	Calc.	Second obs.	Calc.
Si	1.60 (0.78-2.80)	2.37	0.43 (0.16-0.81)	1.73
Ca	1.16 (0.97-1.39)	1.81	0.32 (0.26-0.40)	1.32
Fe	0.39 (0.28-0.52)	0.51	0.13 (0.09-0.17)	0.37

surface also affects in the X-ray.[4)]

References

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