MAXI observation of reflected X-ray by the Moon

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The challenge of detecting reflected X-rays from the Moon dates back to 1962. At that time, the only known X-ray source was the Sun. They tried 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. The strong solar flares occurred on 22 February 2024 and 14 September 2024. X-rays from the flares were reflected by the Moon, and their fluorescent X-rays were captured by MAXI. Emission lines of three elements, Si, Ca and Fe, were observed, which are consistent with the elements that make up the Moon surface.

1. Moon

The Moon consists of an 'ocean' composed of basalt and a 'highland' composed of plagioclase rocks differentiated from magma. The surface is covered by sand-like 'regolith'.

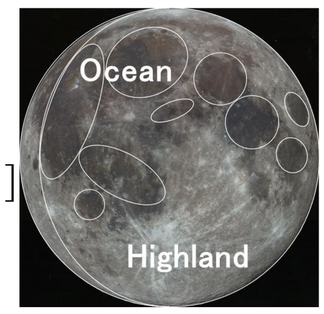
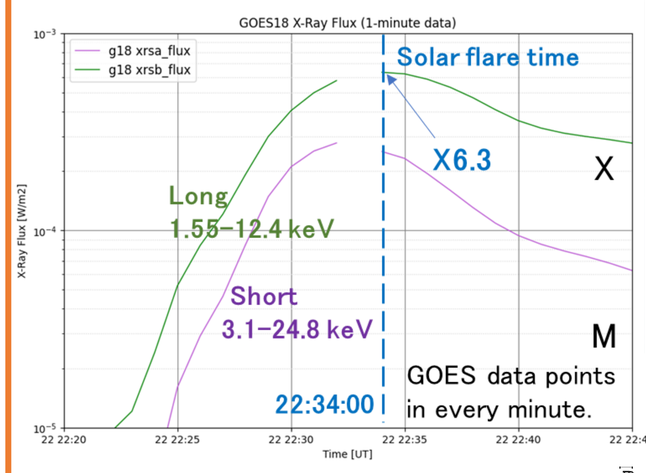


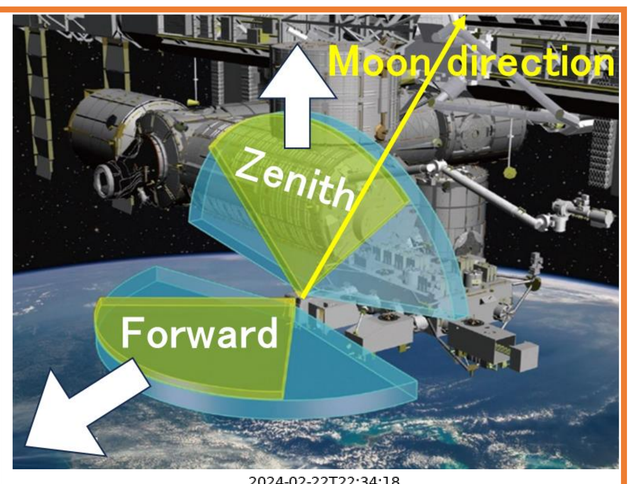
fig.1 Apparent Moon [1]
Ocean: 30.5%
Highland: 69.5%

table.1 Number ratio of elements of 'ocean' and 'highland'.[2][3]

	Ocean [%]	Highland [%]
O	59.29	59.52
Na	0.45	0.31
Mg	5.27	6.83
Al	3.11	6.18
Si	16.38	15.99
Ca	6.68	8.11
Ti	0.88	0.12
Fe	7.94	2.94
Total	100.00	100.00

2. Observations





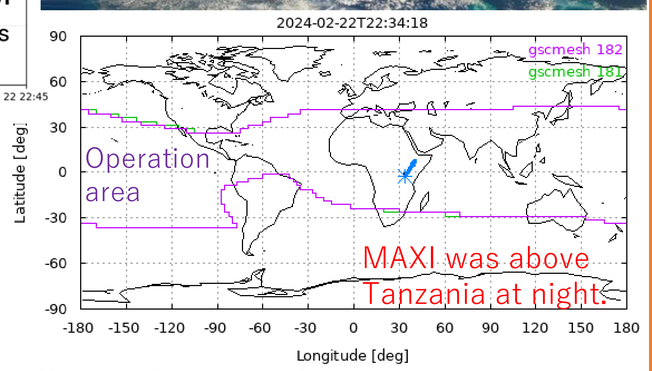


fig.2 GOES light curve, Moon direction and the ISS location at the flare on Feb. 22

table.2 Two observations of reflected X-ray from the Moon

	First	Second
Time(UT) in 2024	Feb. 22 22:34	Sep. 14 15:26
Solar flare intensity	X6.3 (at observation)	X4.2 (at observation)
Moon age (area)	13.0 (96.7% full moon)	11.5 (88.5% full moon)
flux(2-10 keV) [erg/cm²/s]	9.15×10^{-9}	2.57×10^{-9}

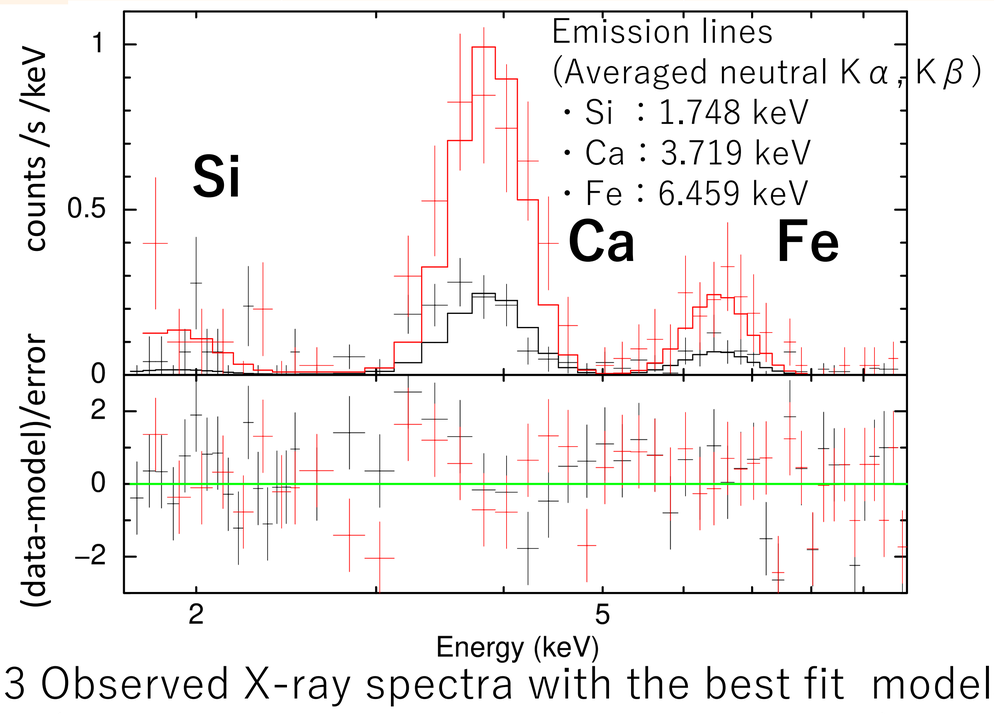


fig.3 Observed X-ray spectra with the best fit models (red: first and black: second observations)

3. Model Calculation

We consider a model from the solar flare to MAXI. Elemental ratios of the Moon surface are taken into account in the absorption cross-sections. The photoelectric absorption occurs within a single regolith grain.

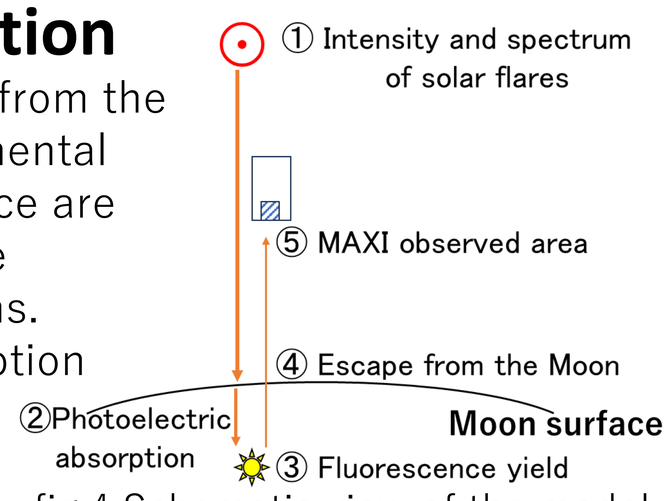


fig.4 Schematic view of the model

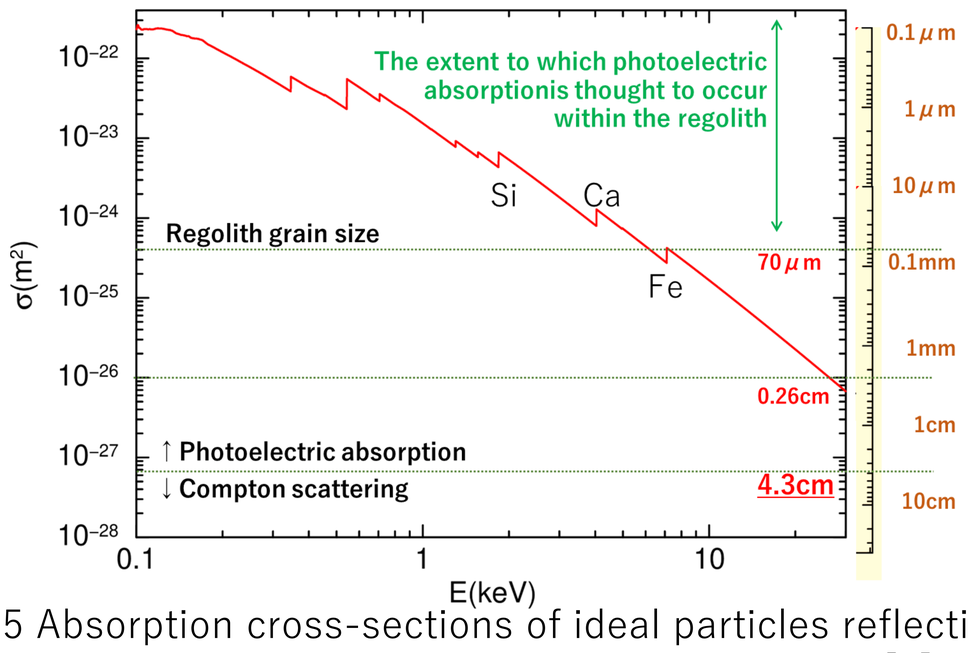


fig.5 Absorption cross-sections of ideal particles reflecting the element composition of the Moon surface. [4]

4. Comparison observation and model

table.3 Observed and calculated values [ph/cm²/s]

	First obs.	Calc.	Second obs.	Calc.
Si	1.60 (0.78-2.80)	2.30	0.43 (0.16-0.81)	1.54
Ca	1.16 (0.97-1.39)	1.82	0.32 (0.26-0.40)	1.18
Fe	0.39 (0.28-0.52)	0.51	0.13 (0.09-0.17)	0.33

Calculated values were ~1.5 times and 3 times larger than the first and the second observations. In fig.6, observations are shown as Si (red), Ca (blue) and Fe (orange). The data points are below the calculation of smooth surface. However, they are consistent with the curve of the optical light.

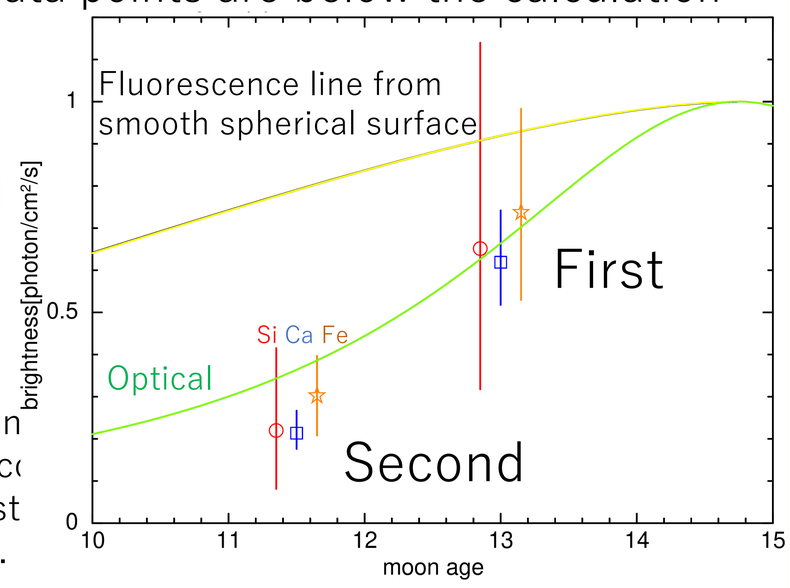


fig.6 Moon age and brightness. Moon distan and flare flux of the sec observation were adjust to the first observation.

5. Summary

The emission lines of three elements, Si, Ca and Fe, were observed, which are consistent with their ratios of the constituent elements of the Moon.

References

[1] LPI Resources The Clementine Mission (https://www.lpi.usra.edu/lunar/missions/clementine/images/)
[2] Science of the Moon Kushiro, Takeda, Mizutani
[3] Geology of the Moon Chosei Komori
[4] Glossary of astronomy (https://astro-dic.jp/regolith/)