

First direct detection of Sodium on lunar surface from the Chandrayaan-1 X-ray Spectrometer (C1XS)

Introduction

The study of origin and evolution of the Moon has generated scientific curiosity for a long time. With improved technology, larger telescopes and better scientific instruments the lunar surface has revealed and created many more research interests. The surface exploration of the Moon gained momentum soon after samples were brought back by the Apollo and Luna missions. Since then, various remote-sensing experiments explored the lunar surface at multi-wavelengths. Chandrayaan-1, India's first lunar mission was launched on 22nd October 2008 and was in operation until August 2009.

Returned samples by Apollo and Luna missions have given us precise chemical and isotopic composition for samples of specific localities on lunar surface. Space-based remote sensing measurements can enrich our knowledge with a global view of lunar surface chemistry compared to localized findings from landing sites. Even after more than five decades of lunar space exploration, many scientific questions regarding the formation and evolution of the Moon remain unanswered. Diversity in the chemical composition of the Moon can be addressed through mineral mapping and elemental mapping. Surface mineralogy is performed using visible & near-IR (0.4 μm - 3 μm), mid-IR (7 μm - 25 μm) and UV (0.001 μm - 0.4 μm) wavelength bands which measure the spectral reflectance. X-ray and gamma-ray spectroscopy provide the capacity to do direct chemical mapping of the Moon. However, space instrumentation for X-rays and gamma-rays is very challenging and the study is limited by the amount and quality of data. Gamma-ray spectrometers in earlier missions have provided limited data on global maps of U, Th, K and Fe. Since the Apollo era, several lunar missions carried X-ray spectrometers (XRS) to map the surface elemental abundances. XRS on Apollo 15 & 16 covered only 10% of the area on the equatorial region on the nearside of the Moon; XRS on SMART-1

and Kaguya suffered from radiation damage which degraded the capability for precise quantification. Chandrayaan-1 X-ray Spectrometer (C1XS) on board Chandrayaan-1 was designed to map the abundances of major rock-forming elements viz., Mg, Al, Si, Ca, Ti and Fe on the lunar surface using the X-ray fluorescence (XRF) technique.

Working principle of C1XS instrument:

When an X-ray photon strikes an atom, it may either get absorbed or scattered. If the energy of the incident photon is greater than the binding energy of an atomic shell, an electron will be ejected by the photoelectric effect. The vacancy thus created is then filled by an electron from a higher shell resulting in the emission of an x-ray photon of energy characteristic of the atom, called X-ray Fluorescence (XRF). A schematic representation of XRF principle is shown in Fig. 1. Since the atomic energy levels of each element in the periodic table are distinct and quantized, the XRF emission from atoms can be used to directly identify the presence of elements. X-ray generators or radioactive sources are used in laboratory studies to illuminate the sample under study. For remote-sensing lunar studies, the Sun is the source of X-rays. The changes in solar magnetic configurations give rise to sporadic release of energy referred to as a solar flare where the X-ray emission suddenly increases, reaches a maximum and decays over a time scale of minutes to hours. Flares are often classified according to increasing intensity as belonging to A, B, C, M or X class (see table 1 for details), each class being ten times more intense than the previous. When solar X-ray photons impinge on the surface atoms of the Moon, XRF photons are emitted from the upper few microns (For example in the case of Moon, the upper 2-10 μm of regolith is sampled for Mg, Al and Si abundances) An X-ray detector in the orbiting spacecraft measures the energy spectrum which can be used to map surface chemistry of the Moon. The abundances of elements can be derived from the strength of XRF line intensities. However, the conversion of XRF line flux in to elemental abundances is not a straightforward process as the observed line intensities exhibit many dependencies some of which can be calibrated or modelled. Thus, X-ray remote sensing offers the best opportunity to study the composition of lunar regolith which can be different from the bulk lunar composition. It also provides an

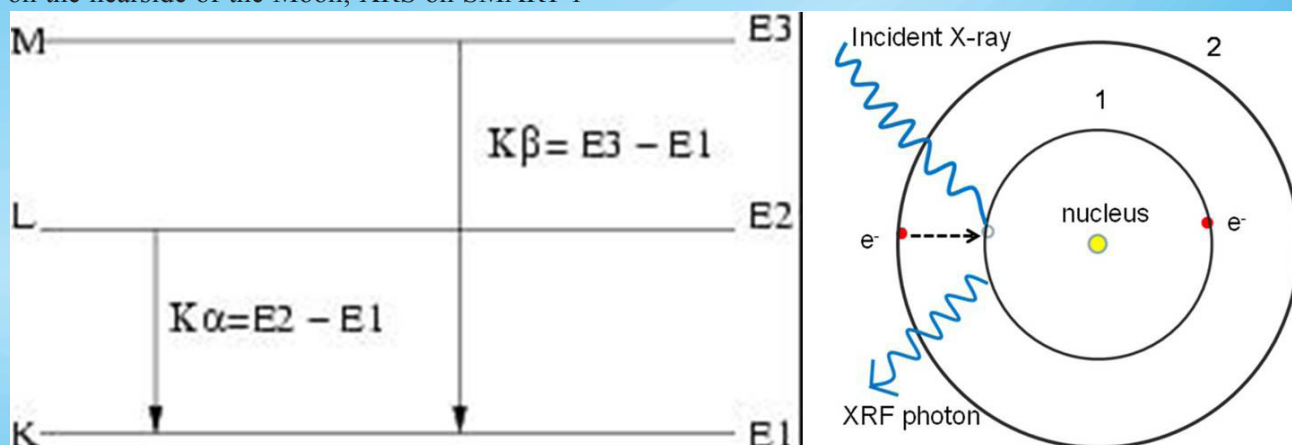


Figure 1: Representation of X-ray Fluorescence.

independent measure of elemental abundances which can be compared with abundances derived from other spectral techniques.

Table 1: GOES classification of solar flares

| Class | Flux (W/m^2) . (1.5-12.5 keV) |
|-------|--|
| A | $< 10^{-7}$ |
| B | 10^{-7} to 10^{-6} |
| C | 10^{-6} to 10^{-5} |
| M | 10^{-5} to 10^{-4} |
| X | $> 10^{-4}$ |

Summary of C1XS instrument :

C1XS was a joint collaboration between European Space Agency (ESA) and ISRO; the instrument was built at the Rutherford Appleton Laboratory (RAL), UK, with some design contributions (instrument and thermal) from ISRO and jointly calibrated and operated by RAL and ISRO. The instrument was designed with an array of 24 novel design X-ray detectors (Swept Charge Devices) to have an opening angle of 28.6° using collimators, made of copper coated with gold which define the ground pixel (area seen by C1XS on the lunar surface at a given instance) resolution of 25 km FWHM from 100 km altitude. However, spatial resolution for a single observation varies from 25 km to a few hundreds of kms, depending on spacecraft altitude and co-adding of adjacent pixel data for improved signal to noise ratio. Simultaneous observations of solar X-rays, in the energy range of

1.8 to 20 keV, impinging on the Moon, were obtained from the X-ray Solar Monitor (XSM) on board Chandrayaan-1, developed by the University of Helsinki in Finland.

C1XS observations – first spectral evidence of Na:

C1XS was the first well-calibrated X-ray instrument to reach and observe the Moon that could spectrally resolve the X-ray lines of all major rock-forming elements from the Moon simultaneously under different solar flare conditions. It was nominally operated only during the sunlit portion of the lunar orbit. Extended solar minimum that prevailed during the on-orbit time of Chandrayaan-1 (ie., Nov'08 - Aug'09), left C1XS with only a handful of solar flare (a few C-, B- and A-class flares) when simultaneous observations of the lunar surface were made.

A few A-class flare observations were made during December 2008 and January 2009, sampled around Mare Serenitatis, Mare Insularum, Mare Cognitum and Mare Nubium region [1]. The brightest flare observed by C1XS was a C3 flare which occurred on the 5th July 2009 measuring X-ray signatures of major rock-forming elements viz., Mg, Al, Si, Ca, Ti & Fe simultaneously. This observation covered regions on the lunar southern nearside highlands at detectors' maximum spatial resolution [2]. The Copernican-aged impact crater Tycho and its rays were observed during a C1-class flare that occurred on 6th July 2009. A few other B-class flare observations were also made on the 4th and 8th July 2009 covering

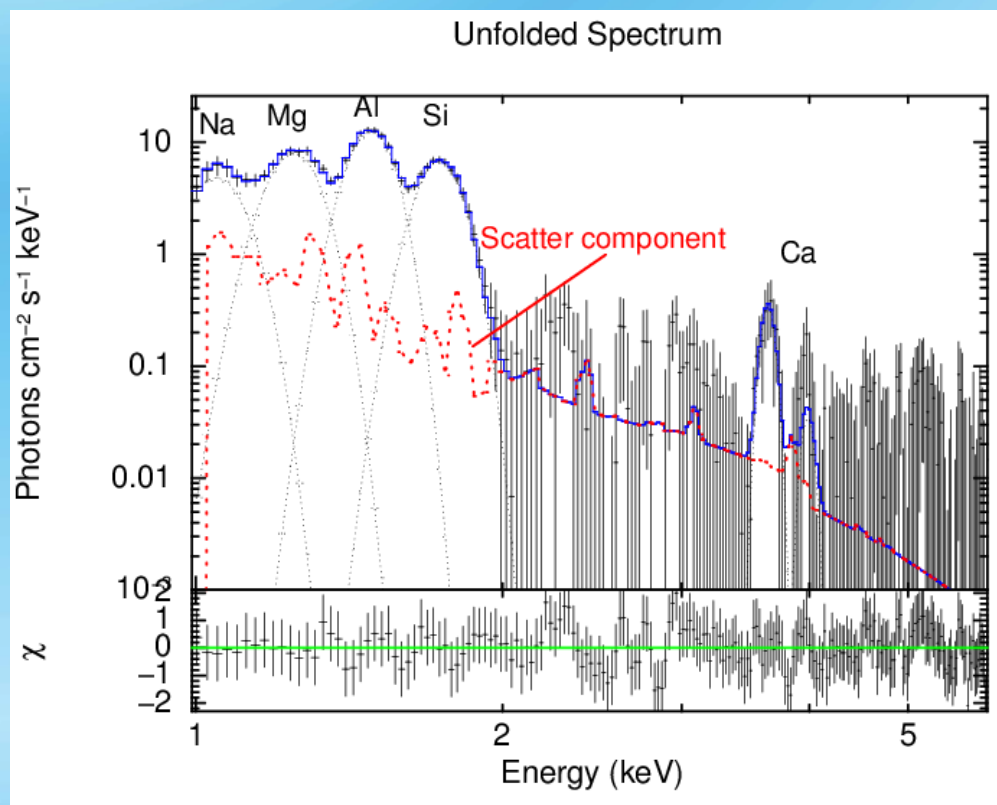


Figure 2: Best fit for the observed XRF spectrum for a C1 class flare on 6th Jul'09 - (17:10:47 - 17:13:59), with all spectral component. Data points are shown with error bars (black). Residuals of the fit (difference between data and model) in terms of σ are shown in the bottom panel of the figure. (Ref.: Athiray et al., 2014)

a portion of Tycho rays and around Palus Epidemiarum on the nearside of the Moon. Interestingly, some of the C1XS observations on the nearside highlands of the Moon showed the first direct spectral evidence of sodium on the lunar surface. One of the best fits to a C1XS spectrum observed on 6th July 2009, around the young crater Tycho, showing distinct XRF spectral line feature of Na at ≈ 1.04 keV, along with other rock-forming elements is shown in Fig.2. Due to excitation by a weak solar flare, XRF signatures of Ti & Fe were not visible in these observations. Using detailed spectral analyses, the unambiguous spectral evidence of Na from the lunar surface was firmly established [3,4].

Challenges in the measurement of Na

C1XS was operated in the energy range 1 -20 keV. The observed C1XS spectrum has three major spectral components (a) X-ray background (b) Scattering of solar X-ray spectrum and (c) XRF lines from the Moon. X-ray spectral detection of Na (~ 1.04 keV) from the Moon with high sensitivity is quite challenging. Extraction of XRF line intensity with less uncertainties require a detailed spectral modelling which demands precise ground calibration of X-ray detectors. Calibration of X-ray detectors at low energies ≤ 1 keV is very difficult. This constraint set a limit to our understanding of the spectral response of detectors which affect the sensitivity of measurements. Precise ground calibration was carried out for all C1XS detectors, using the RESIK X-ray beam-line at Rutherford Appleton Laboratory (RAL), UK. C1XS is the first well-calibrated X-ray instrument which measured the XRF line

of Na with a good sensitivity.

It is also very essential to understand scattering of solar X-ray spectrum which could potentially be the origin of measured Na line. The scattering component of solar X-ray spectrum is iteratively computed using measured XSM data. By following rigorous spectral modelling procedures, the first unambiguous detection of Na from the Moon is clearly demonstrated.

C1XS results – Discovery of enhanced Na and possible scientific explanation

Elemental abundances are determined using the XRF inversion algorithm ‘x2abundance’, where line intensities are converted to elemental abundances incorporating all major dependencies [5]. The derived elemental abundances along with $1-\sigma$ uncertainties for selected C1XS observations suggest enhanced Na abundances. C1XS is the first instrument which provided the unambiguous detection and quantification of moderately volatile Na on the lunar surface. The derived Na abundances (2 to 5 wt%) are larger than what has been known so far (< 1 wt%) from earlier geochemical studies of lunar samples. It was also found that the derived Ca abundances are lower for those intervals where Na is observed. Compositional analysis of lunar samples, meteorites and soil does not show any relation between Ca & Na abundances. For the first time, C1XS abundance results suggest an anti-correlation between Ca & Na. It is expected in lunar highlands that an increase in Na abundances should correspondingly decrease Ca and Al abundances. C1XS results show a trend of increasing

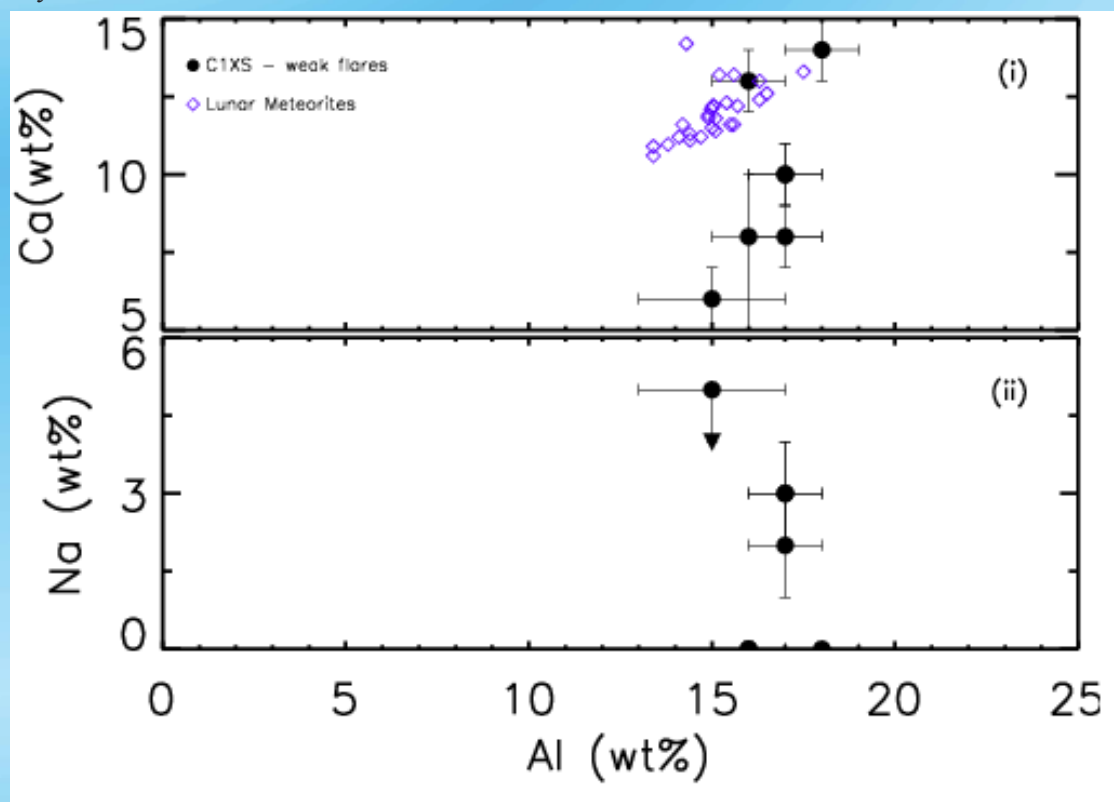


Figure 3: Comparison of C1XS abundance with Lunar Meteorite compositions [6]. Variation of Ca and Na abundances with respect to Al (i & ii) with abundance of Ca increasing with Al which do not agree with the established correlation in lunar meteorite collections (Ref: Athiray et al., 2014).

Na with decrease in Al abundances (Fig. 3). Sodium is a moderately volatile element and is considered to be lost during the early formation and evolution of the Moon via the giant impact event. C1XS results with high Na content contradict the extreme loss of volatiles by vaporization. The Moon can have intermediate plagioclase composition under different temperature and pressure conditions. The first direct detection of enhanced abundances of Na from certain regions on the Moon suggests a relatively cooler lunar surface evolution than expected. However, more precise elemental maps are required to understand the global evolution of the lunar surface.

If the presence of enhanced Na is considered to be widespread, then it could well be signature of serial magmatism, an alternative to global magma ocean where the temperatures could be relatively low. C1XS observed regions where enhanced Na abundances are found are likely to be dominated by the impact ejecta and disturbed regolith due to the young impact crater Tycho. Physical processes that could give rise to this enhancement eg., variable thermal cooling of magma or secondary processing of lunar surface remains equivocal. It is also to be mentioned that the measured XRF signal of Na cannot originate from deep layers of lunar regolith (within a few μm). If the observation of Na is localized only in certain regions on the Moon, then it can be well considered as an extra-lunar material present on the lunar surface. Volatile elements, such as sodium, are expected to be higher in unprocessed bodies such as comets and meteors which are formed in the outer regions of the protoplanetary disc. Now, it is well established that sodium lines are omnipresent in meteor spectra. Thus by mapping the abundance of moderately volatile elements on the lunar surface, one can identify and trace the extralunar material on the lunar regolith. In particular, a global map of Na can answer whether the bulk Moon is alkali depleted or not. This can also provide more clues on the diversity of plagioclase on the lunar highlands which is directly related to the thermal evolution of the Moon. Recent results from LADEE shows cyclic variation of Na abundances in the lunar exosphere illustrating the contribution of impacts and surface composition [7].

Summary

The first direct detection of enhanced abundances of Na from certain nearside highland regions on the Moon suggests a relatively cooler lunar surface evolution than expected. However, more precise elemental maps are required to understand the global evolution of the lunar surface. Our understanding of higher levels of sodium abundances on the lunar surface is still incomplete. Surface elemental abundances derived from limited C1XS observations raise the following questions:

- Can large amount of sodium be still present on the lunar surface?
- What causes the enrichment of volatile element Sodium on the lunar surface?
- Is the observed sodium enrichment on the lunar surface

a local effect or suggestive of wide-spread enhancements?

- How are the elements Ca and Na distributed on the lunar surface?
- Can loss in Ca abundance lead to enhanced Na?

To answer all these questions, good measurements of elemental abundances with finer spatial resolution for the entire lunar surface are required. Simultaneous measurements of Ca & Na abundances along with other rock-forming elements can provide more further insights to the formation and thermal evolution of the Moon. To complete the science goals left behind by the C1XS experiment, an improved spectrometer (Chandrayaan-2 Large Area Soft x-ray Spectrometer (CLASS)) is being developed for the next Indian Moon mission, Chandrayaan-2.

Further Reading:

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5. P. S. Athiray et al., Experimental validation of XRF inversion code for Chandrayaan-1, *Planetary & Space Science*, 89:183, 2013.
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