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C1XS results - First measurement of enhanced Sodium on the Lunar surface

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Abstract

We describe the first unambiguous evidence of enhanced Sodium on the lunar surface revealed by the Chandrayaan-1 X-ray Spectrometer (C1XS). The C1XS onboard the Chandrayaan-1 spacecraft was designed to map the surface elemental chemistry of the Moon using the X-ray fluorescence (XRF) technique. During the nine months of remote sensing observations (Nov'2008 - Aug'2009), C1XS measured XRF emission from the Moon under several solar flare conditions. A summary of entire C1XS observations and data selection methods are presented. Surface elemental abundances of major rock-forming elements viz., Mg, Al, Si and Ca as well as Na derived from C1XS data corresponding to certain nearside regions of the Moon are reported here. We also present a detailed description of the analysis techniques including derivation of XRF line fluxes and conversion to elemental abundances. The derived abundances of Na (2-3 wt%) are significantly higher than what has been known from earlier studies. We compare the surface chemistry of C1XS observed regions with the highly silicic compositions (intermediate plagioclase) measured by the Diviner Radiometer instrument onboard Lunar Reconnaissance Orbiter(LRO) in those regions.

Keywords: X-ray Fluorescence(XRF), Chandrayaan-1, C1XS, lunar surface chemistry

1 1. Introduction

2 Study of lunar surface chemistry is essential in understanding the forma-
 3 tion and evolution of lunar crust and interior under different geochemical
 4 processes on the Moon. The lunar surface has been explored extensively
 5 through returned samples from the Apollo and Luna missions and through
 6 orbital remote sensing measurements in multi-wavelengths. Since different
 7 elements undergo different geochemical processes, the lunar surface chem-
 8 istry is generally studied from the observation of major types of minerals on
 9 the Moon. Surface mineralogy is inferred through visible and near-Infrared
 10 (IR) spectroscopy. High resolution global lunar mineral maps are available
 11 from various instruments such as the Ultraviolet-Visible (UV/VIS) multi-
 12 spectral camera and Near IR camera on Clementine (Nozette et al., 1994;
 13 McEwen & Robinson, 1997), the Spectral Profiler (SP) and Multiband Im-
 14 ager (MI) on Kaguya (Manabu Kato et al., 2010; Ohtake et al., 2008) and
 15 the HyperSpectral Imager (HySI) and Moon Mineralogical Mapper (M³) on
 16 Chandrayaan-1 (Bhandari, 2005). Elemental abundances can be inferred
 17 indirectly from Near IR spectroscopy which is primarily sensitive only to
 18 Fe-bearing minerals. Diversity in the chemical composition of the Moon
 19 is mostly addressed using these proxy lunar mineral maps. Recently, the
 20 Diviner Lunar Radiometer experiment onboard the Lunar Reconnaissance

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21 Orbiter (LRO) provided new insights to the iron-poor mineralogy of the
 22 Moon using thermal IR spectroscopy (0.3 to 400 μm) (Paige et al., 2010).
 23 Gamma-ray spectroscopy is also used to record gamma-ray spectra from
 24 rock-forming and radio-active elements (Lawrence et al., 1998).
 25 X-ray fluorescence (XRF) spectroscopy through remote sensing has a long
 26 history in studying the chemical composition of atmosphere-free solar sys-
 27 tem bodies (*for example, Apollo 15 (1971), Apollo 16 (1972) (Adler & Gerard,*
 28 *1972; Adler et al., 1973a,b), Smart-1 (2003) (Grande et al., 2003), Kaguya*
 29 *(2007) (Okada et al., 2008), Change-1 (2007) (Huixian et al., 2005) and*
 30 *Chandrayaan-1 (2008) (Grande et al., 2009) for the Moon, Near Earth As-*
 31 *teroid Rendezvous (NEAR) (1996) for the asteroid Eros (Trombka, 2000;*
 32 *Nittler et al., 2001), HAYABUSA (2003) for the asteroid 25143 Itokawa*
 33 *(Okada et al., 2006)).* Solar X-rays excite surface elements of these bodies
 34 to yield characteristic emission lines. X-ray remote sensing provides an un-
 35 ambiguous and unique identification of elements. The upper-most layer of
 36 the Moon (few 100 μm thick) is covered with lunar regolith - fine pulverized
 37 grains of bedrock due to meteoritic bombardment. Interaction of soft X-rays
 38 (1 - 10 keV) incident on the surface are limited to the top few microns on the
 39 lunar surface (e.g., 2 microns for Na) in contrast to depths of centimeters to
 40 tens of centimeters for gamma-rays. Thus X-ray remote sensing provides a
 41 clean, direct and independent measure of elemental abundances which can
 42 be compared with abundances derived from other spectral techniques. We
 43 present new results from the most comprehensive analysis of data from the
 44 Chandrayaan-1 X-ray Spectrometer (C1XS) experiment during many weak
 45 solar flares.

46 2. Status of lunar surface chemical mapping

47 The majority of our current knowledge on the chemical makeup of the
 48 Moon is obtained from geochemical studies of returned lunar samples, aug-
 49 mented by analyses of lunar meteorite samples collected from different
 50 places on the earth. Adding to this are the direct remote sensing measure-
 51 ments from different missions. Remote sensing in X-rays/or gamma-rays
 52 provides the capability for direct chemical mapping of the Moon, but is
 53 limited by the quantity and quality of the data. Since the Apollo era, sev-
 54 eral lunar missions carried X-ray and gamma-ray experiments to map the
 55 elemental abundances. However, a unified cross calibrated map does not
 56 yet exist.

57 2.1. Gamma ray mapping

58 Characteristic gamma-rays are produced when high energy cosmic rays
 59 interact with the nuclei of rock-forming elements. Abundances of light ma-
 60 jor elements viz., Ca, Si, Al, Mg, O are derived indirectly due to strong
 61 dependency on neutron production as well as changes in the lunar sub-
 62 surface neutron flux (Yamashita et al., 2008). Furthermore, gamma-ray
 63 data exhibit a complex and highly uncertain background arising from var-
 64 ious sources (Zhang et al., 2012). Global maps of various rock-forming
 65 and radio-active elements are available from the Gamma Ray Spectrometer
 66 (GRS) onboard Lunar Prospector (LP) (Lawrence et al., 1998). Recently,
 67 the global distribution of Ca abundance on the Moon has been obtained
 68 from the GRS data from Kaguya (Yamashita et al., 2012). However, the
 69 accuracy of abundances from GRS data is limited since the blending of the
 70 lines and the mix of physical processes make the analysis uncertain.

71 2.2. X-ray mapping

72 The surface chemistry of the Moon can be studied from the character-
 73 istic X-ray line intensities of different elements, emitted under solar X-ray
 74 bombardment. Simultaneous measure of the incident solar X-ray spectrum
 75 is essential for deriving elemental abundances. Major dependencies such as
 76 matrix effects, geometry and elastic scattering of solar X-rays also have
 77 to be considered for precise elemental analysis. Other factors affecting
 78 the line intensity such as sample inhomogeneity and particle size distri-
 79 bution are difficult to characterize. XRF experiments in Apollo 15 and
 80 16 (Adler & Gerard, 1972; Adler et al., 1973a,b) covered only 10% (Clark,
 81 1979) of the area on the equatorial region on the nearside of the Moon
 82 and estimated relative abundances with respect to Si. Other X-ray exper-
 83 iments such as D-CIXS (Grande et al., 2003) onboard SMART-1 and XRS
 84 onboard Kaguya (Okada et al., 2008, 2009) suffered from severe radiation
 85 damage which restricted its ability to yield meaningful quantitative anal-
 86 ysis. Hence there are no measures of absolute elemental abundances from
 87 any earlier X-ray experiments.

88 C1XS reached and observed the Moon flawlessly without losing much
 89 of its high spectral capability. Due to overall low solar activity in this
 90 period, it could not produce global elemental maps of the Moon during its
 91 short mission life of ≈ 9 months. Nevertheless, simultaneous observation
 92 of multiple elements were seen during a few relatively weak flares. Most
 93 interestingly, C1XS measured the direct detection of sodium from the lunar
 94 surface.

95 3. C1XS observations

96 3.1. Overview of C1XS

97 C1XS (Howe et al., 2009; Grande et al., 2009), onboard Chandrayaan-
 98 1, was designed to map the abundances of major rock-forming elements
 99 on the lunar surface using the XRF technique. The extended solar mini-
 100 mum that prevailed during the Chandrayaan-1 mission time-frame (Nov'08
 101 - Aug'09), left C1XS with only a handful of solar flares (a few C, B and A
 102 class flares) during which quantitative analysis could be carried out. C1XS
 103 used an array of 24 Swept Charge Devices (SCDs) (Lowe et al., 2001), with
 104 each of area 1 cm^2 , to record the X-ray emission with energies of 0.8 to
 105 10 keV. Spatial resolution for a single spectral observation varies from <50
 106 km to >1000 km depending on spacecraft altitude and integration time.
 107 Simultaneous observation of solar X-rays, in the energy range of 1.8 to 20
 108 keV, impinging on the Moon, was obtained from the Si-PIN based X-ray
 109 Solar Monitor (XSM) (Alha et al., 2009) also onboard Chandrayaan-1. A
 110 detailed description of C1XS instrument, its observations, steps involved
 111 in data reduction and spectral extraction are given in Narendranath et al.
 112 (2011)(here onwards Paper-I).

113 3.2. Data selection

114 The light curve of the C1XS experiment for the entire mission is shown
 115 in Fig. 1. The plot shows integrated C1XS counts in the energy range 1
 116 keV - 10 keV (red color points in Fig. 1) plotted along with GOES solar
 117 soft X-ray flux in the energy range 1.55 keV - 12.4 keV (blue color lines in
 118 Fig. 1). It is clearly seen that the solar X-ray activity was very minimal
 119 during the entire duration and was relatively active in X-rays only in the

month of July 2009, in contrast to other times. After careful examination of all data, we adopted the following criteria in choosing good data from C1XS observations:

C1. Identification of useful observations corresponding to solar flares

C2. Selection of good observation intervals where the observed data are not contaminated by any sudden increase in the flux of charged particles

Many flare observations were filtered out due to contamination from charged particles. Also flares below B3 (dashed lines in Fig. 1) are not considered for analysis as lines corresponding to Ca, Ti and Fe are absent, resulting in large errors in the derived abundance values. Analysis and results of the biggest flare seen by C1XS (a C3 flare), which occurred on the 5th July 2009 are published in Paper I. Results from flare observations during the early phase of the mission (12th December 2008 and 10th January 2009) are given by (Weider et al., 2012). Here we discuss results from flare observations made on the 4th, 6th and 8th July 2009 ($\leq$ C1 class flares), as shown in the inset of Fig. 1b, which satisfied the aforesaid criteria. Footprints of these observations covered a large area on the nearside of the Moon (Fig. 2). The majority of these observations span over lunar southern latitudes which include the relatively young impact crater Tycho and its rays. A summary of good observation intervals chosen for analysis along with the class of flares observed and their respective locations on the Moon are given in Table 1

Table 1: Selected good observation intervals of C1XS data

Date/Time (UTC)	Class of solar flare	Description of observed region
4 th Jul'09 01:18:00-01:21:59	$\approx$ B3.5	• Nearside highland region - covered some portions of Tycho rays
6 th Jul'09 17:04:29-17:19:44	$\approx$ C1.1	• Nearside highland region - covered the crater Tycho and majority of its rays
8 th Jul'09 05:27:31-05:30:20	$\approx$ B4.2	• Nearside mixed region - from crater Capuanus to crater Campanus.

142 4. C1XS data analysis

143 C1XS observations can be broadly grouped into three types viz., back-
144 ground observations, ie., when X-ray & particle events are not observed,
145 flare observations and observations during high fluxes of charged particles.
146 Light curves depicting these types of observations are shown in Fig. 3.
147 Spectral analysis of weak flare observations is severely constrained by low
148 signals, requiring that data from multiple ground pixels be summed. This
149 leads to coarser spatial mapping. Following are the major steps involved in
150 spectral analysis:

- 151 1. Build background spectrum appropriate for the observation
- 152 2. Derive scattered spectrum of solar flare, reflected off the lunar surface
- 153 3. Derive X-ray line fluxes corresponding to different elements through
154 spectral analysis
- 155 4. Convert line fluxes to elemental abundances using specially developed
156 inversion algorithms

157 4.1. Background estimates

158 Background emission in X-rays arises from various sources (Hall et al.,
159 2008). Apart from cosmic X-rays, interaction of high energy charged parti-
160 cles in lunar orbit with the instrument leads to production of X-rays which
161 also contributes to the overall observed continuum background. The Moon
162 encounters two major particle environments in a synodic month (29.6 days):

163 (a) Solar wind & high energy cosmic ray particles (≈ 24 days):

164 Continuous flux of protons and electrons with energies ranging from
165 eV to GeV around the Moon contribute mainly to the observed steady
166 X-ray background in C1XS.

167 (b) Charged particles in the Earth's geotail (≈ 6 days):

The geotail
168 extends up to several hundreds of Earth radii and it primarily com-
169 posed of energetic electrons with an average energy of 1 keV (increas-
170 ing to several keV occasionally; (Prakash, 1975)). Sporadic release
171 of accelerated charged particles during solar eruptive events can alter
172 the background spectrum significantly. The accelerated charged par-
173 ticles travel with different speeds and reach the Earth and the Moon
174 at different times. Spectral contamination due to bursts of charged
175 particles is clearly identified by enhanced counts observed in the C1XS
176 light curve (refer Fig. 3c).

177 The Moon was coincidentally inside the geotail when flares occurred
178 during the 1st week of July 2009. Data over a complete orbit, without
179 particle contamination and with solar activity less than A class flare level
180 (ie., $< 1 \times 10^{-8}$ W/m²) alone are considered for background estimation.

181 Some of the observations made on the 6th and 8th July 2009 satisfied this
 182 condition and the time-averaged background X-ray spectrum used for our
 183 current analysis is shown in Fig. 4. For comparison, spectral hardening due
 184 to a sudden burst of charged particles inside the geo-tail is also shown in
 185 Fig. 4.

186 *4.2. Scattering of solar X-rays*

187 Background subtracted C1XS spectra contain XRF lines along with elas-
 188 tically scattered solar X-rays. In order to model the scattering component,
 189 the incident solar spectra for the observed C1XS timings are obtained from
 190 XSM data which was constantly observing the Sun. XSM spectral anal-
 191 ysis is performed using the solar soft package (SSW) (Freeland & Handy,
 192 1998) which uses solar models based on the CHIANTI5.2 (Dere et al., 1997;
 193 Landi et al., 2006) atomic database and the best fit solar parameters (ie.,
 194 temperature, emission measure and coronal abundances) are obtained. The
 195 best spectral fit to one of the observed XSM spectra for a C1 class flare is
 196 shown in Fig. 5 with its spectral components. Using the best fit solar model
 197 we calculated the scattered solar component following the same approach
 198 given in Paper I (sec. 6).

199 *4.3. XRF analysis*

200 Detailed spectral analyses are carried out using the X-ray spectral anal-
 201 ysis package (XSPEC) (Arnaud, 1996), where the XRF lines are modeled
 202 as Gaussian functions along with an estimated spectrum of scattered solar
 203 emission corresponding to a location/time interval (included as table model

¹). It was noticed that the presence of a 0.4 μm thick Al filter in front of the detector could possibly contaminate and yield excess counts at 1.5 keV. Using C1XS ground calibration data (Narendranath et al., 2010), we applied a correction factor (≈ 0.15) to the detection efficiency at 1.5 keV and derived the XRF line flux of the elements. One of the best-fit C1XS spectra is shown in Fig. 7, with XRF lines indicated. Due to the relative weakness of the incident solar flares, XRF signatures of Ti & Fe are not visible in most of the observations.

Apart from lines of major rock-forming elements, C1XS has clearly observed the XRF signature of Na at ≈ 1.04 keV in many spectra. Earlier C1XS reports by (Narendranath et al., 2011) and (Weider et al., 2012) also discussed the detection of Na from the Moon. The former proposed the possibility of high Na content on the lunar surface, while the latter suggested that it could originate from the scattering of incident solar spectrum. XRF line fluxes of the elements, including Na (wherever observed), determined for different flare observations are compiled in Table 2.

4.4. Deriving elemental abundances

We developed an XRF inversion code *x2abundance* to convert the observed X-ray line flux to absolute elemental abundances, where a new approach is adopted using Fundamental Parameter (FP) (Criss & Birks, 1968; Rousseau & Boivin, 1998) method. A detailed description of the algorithm of *x2abundance* along with assumptions and limitations are given

¹Table Model - A model in XSPEC can also be defined as a two column table (energy versus photon intensity at some specified binning) as opposed to an analytical form. The final model spectrum is calculated by interpolation across the bins.

227 by (Athiray et al., 2013a). The algorithm was validated rigorously using
 228 laboratory-based XRF experiments on metal alloys and lunar analogous
 229 rocks (Athiray et al., 2013b). Dependencies which affect XRF intensities
 230 such as the incident spectrum (I_o), matrix effects and geometry effects are
 231 all incorporated. However, the code assumes a flat, homogeneous surface
 232 which is not the case in reality. Remote sensing XRF experiments mainly
 233 sense the lunar regolith which comprises distribution of particle sizes rang-
 234 ing from sub-micron-sized particles to cm-sized rocks (McKay et al., 1991).
 235 The observed XRF intensity get affected by the distribution of particle
 236 size, as the mean free path of soft X-rays is smaller than the mean particle
 237 size of lunar regolith. Laboratory experiments by (Maruyama et al., 2008;
 238 Näränen et al., 2008) shows that XRF intensity decreases with increasing
 239 phase angles (angle between source-surface-detector) and increases with de-
 240 creasing size of particles. However, this effect is expected to be small on
 241 C1XS results where the ground pixel dimensions are large (hundreds of km)
 242 and considers a large distribution of particle sizes (Weider et al., 2012). The
 243 effect is further minimized with the use of flux fractions (line flux/sum of
 244 the flux in all lines).
 245 Elemental abundances along with uncertainties are determined using *x2abundance*,
 246 where the uncertainties in line flux measurements are transformed to uncer-
 247 tainties in abundance values following statistical methods. The abundances
 248 of Ti & Fe are kept frozen to the weighted average values derived from the
 249 C1XS C3 flare observation (5.0 wt% & 0.13 wt%) (Paper I), since they are
 250 not seen in the present spectra due to weak flare excitation. The derived
 251 elemental abundances along with 1σ uncertainties are given in Table 3.

252 5. Results & Discussion

253 With good spectral resolution, C1XS observed XRF lines of the major
 254 rock-forming elements Mg, Al, Si and Ca from the Moon simultaneously,
 255 as well as sodium for the first time. Due to inadequate solar activity and
 256 reduced mission life C1XS could not achieve its objective of global lunar
 257 elemental mapping. However, with the best available data, we have de-
 258 termined the elemental abundances for the C1XS-sampled locations on the
 259 lunar surface. Through rigorous spectral analysis, we have confirmed the
 260 unambiguous detection of XRF emission of Na from the Moon. Abundances
 261 derived for the 4th and 6th July observations clearly exhibit lunar highland
 262 features with high Al and Ca abundances and low Mg abundances. Abun-
 263 dances derived for the 8th July observation show high Al & Mg abundances
 264 which confirms a mixed terrain of highlands and mare.

265 Elemental abundances derived from the LP GRS, for a large area encom-
 266 passing the C1XS-observed regions (see dashed box in Fig. 2), are compared
 267 with C1XS abundances for the same regions in Fig. 7(a). We have applied
 268 the correction factor for the Al filter to our earlier published C3 flare data
 269 and re-derived the elemental abundances, which are also included in the
 270 plot. Fig. 7(a) shows that C1XS compositions along with 1σ uncertainties
 271 match well with the distribution of abundances derived from remote sensing
 272 gamma-ray observations. For comparison, Table 3 also includes the aver-
 273 age composition of lunar soils from Apollo 16 mission (Haskin & Warren,
 274 1991) and the average feldspathic highland terrane composition from lunar
 275 meteorites (Korotev, 2003). It is clear that the derived abundances of Na
 276 ($> 1 \text{ wt}\%$) are larger than what has been known so far ($< 1 \text{ wt}\%$). Also, our
 277 results seem to suggest an inverse relation between Ca and Na abundances

Fig. 8. According to our present understanding of highland regions from the returned lunar samples and meteorite collections, there exists a strong positive correlation between Al and Ca abundances, as shown in Fig. 7(b)i (Demidova et al., 2007). The results from C1XS show a lower Ca abundance for the intervals where Na is observed and the correlation improves when Ca and Na abundances are added and compared against Al Fig. 7(b)ii.

Lunar observations & Magma Ocean Theory : Our current understanding of lunar evolution is based on the Lunar Magma Ocean (LMO) theory (Taylor, 1982; Warren, 1985, 1990) which states that the Moon was mostly/partially molten in its past. Subsequently, elemental fractionation occurred during the cooling phase of the magma. The LMO theory advocates the assumption of a global distribution of ferroan anorthosites. Ferroan anorthosites mostly consist of anorthosite rocks which are characterized by plagioclase feldspar minerals with high calcium content. It is thus assumed, that the lunar highland crust was formed from plagioclase feldspar, floating on a global magma ocean. This theory is completely based on the analysis of samples of ferroan anorthosites collected from a small area on the nearside highland region of the Moon. However, solid solutions of the plagioclase feldspar mineral group include calcic and sodic end members called anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and albite ($\text{NaAlSi}_3\text{O}_8$) (Perkins, 2006). Also, different plagioclase minerals can be formed by varying the sodium/calcium content. Such minerals are considered to have intermediate plagioclase compositions. Diversity in plagioclase composition is studied by a factor called Anorthite number (An#) which is defined as $\frac{\text{Ca}}{\text{Ca}+\text{Na}+\text{K}}$ in moles. Fig. 9 shows different intermediate plagioclase minerals starting from high calcic

304 end member to high sodic end member. Studying the diversity of pla-
 305 gioclase compositions in the lunar highlands is an outstanding question in
 306 lunar science eg. (Donaldson Hanna et al., 2012a). This can be addressed
 307 by mapping the distribution of anorthite content (An#) on the lunar high-
 308 lands.

309
 310 Global distribution of pure ferroan anorthosite (PAN) obtained from the
 311 MI and SP instruments onboard SELENE, indicated high calcic plagioclase
 312 feldspar ($> \text{An}_{95}$) (Ohtake et al., 2009) in the highland crust, in clear sup-
 313 port of the LMO theory. It should be noted that both instruments were
 314 operated in the NIR region where plagioclase with minor amounts of iron,
 315 exhibits a broad absorption band centered around $1.25 \mu\text{m}$ owing to the
 316 electronic transitions of Fe^{2+} . But NIR spectroscopy is less sensitive to
 317 An# and hence cannot address the presence of calcic and sodic content in
 318 plagioclase feldspar.

319
 320 Thermal Infrared (TIR) spectroscopy has been extensively used in the
 321 laboratory to study the variations in plagioclase minerals (Donaldson Hanna et al.,
 322 2012b) using the position of Christiansen Frequency (CF), an emissivity
 323 maximum that indicates the composition related to (An#). In silicate min-
 324 erals, the emissivity maximum occurs around $8 \mu\text{m}$ when the real part of
 325 refractive index approaches unity (Pieters, 1999). Ca-rich feldspathic anor-
 326 thite exhibit CF positions around $7.84 \mu\text{m}$ whereas plagioclase with Na com-
 327 ponent shift towards lower CF values $\leq 7.8 \mu\text{m}$ (Donaldson Hanna et al.,
 328 2014). Ultramafic minerals exhibit intermediate and long CF values which
 329 are indicated in the CF value map shown in Fig. 10. Using this diagnos-

330 tic feature, the Diviner instrument onboard the LRO identified intermedi-
 331 ate plagioclase compositions (Greenhagen et al., 2010; Kusuma et al., 2012)
 332 over numerous areas on the Moon which were shown to be pure plagioclase
 333 feldspar using the NIR measurements of the MI and SP instruments. Fig. 10
 334 shows the overplot of C1XS observed regions on the LRO diviner CF value
 335 map. Some of the C1XS observed regions are likely to be dominated by the
 336 impact ejecta and disturbed regolith due to the young impact crater Tycho.
 337 It is clear that some of the regions observed by C1XS show unusual mineral
 338 compositions. The An# values derived from C1XS abundances correspond
 339 to intermediate plagioclase compositions such as labradorite and bytownite.
 340 However the LMO theory predicts alkali depletion over the whole Moon as a
 341 consequence of the moon-forming giant impact. The C1XS results indicat-
 342 ing high Na content contradict the extreme loss of volatiles by vaporization.
 343 There exist physical processes which do not require alkali depletion of the
 344 bulk Moon (Nekvasil et al., 2013). These authors have also shown that the
 345 bulk Moon could still retain alkali-rich contents under different tempera-
 346 ture and pressure conditions. From our observations over the impact crater
 347 Tycho and its rays, we suggest that the ejecta has excavated alkali-rich
 348 material from deep layers of the bulk Moon. Suggestive evidences are also
 349 seen in Diviner images showing unusual compositions over relatively young
 350 impact craters. The first results from the Ultraviolet-Visible Spectrometer
 351 (UVS) onboard LADEE (The Lunar Atmosphere and Dust Environment
 352 Explorer) measured spatial and temporal variations of Na flux in the ex-
 353 osphere (Colaprete et al., 2014). Associations with surface compositions,
 354 meteorites etc., are being examined and could pave the way for further
 355 confirmation.

356 6. Conclusion

357 To summarize, the C1XS experiment performed extremely well and
 358 proved its capability by distinctly observing XRF lines of rock-forming ele-
 359 ments from the Moon. In this paper, we have presented a detailed descrip-
 360 tion of the entire C1XS observation data. Due to lack of confidence, earlier
 361 quantitative elemental estimates for certain selected flare observations (5th
 362 Jul'09, 12th Dec'08 & 10th Jan'09) made by (Narendranath et al., 2011;
 363 Weider et al., 2012) did not include Na. Based on the selection criteria and
 364 spectral analysis steps described here, we clearly showed the unambiguous
 365 direct detection of Na from the Moon. Further, we also determined the
 366 elemental abundances, including Na for the first time, for additional flare
 367 observations on the 4th, 6th & 8th Jul'09. The derived abundances of sodium
 368 are significantly larger than what has been known from earlier studies of
 369 lunar materials. The compositions determined from C1XS tend to support
 370 recent theories and findings of intermediate plagioclase on the Moon. How-
 371 ever, precise Ca and Na abundance measurements are required on a global
 372 scale to address the evolution of the lunar surface. In this regard, the qual-
 373 itative and quantitative study of Na abundance by X-rays will be one of
 374 the prime science objectives of the CLASS instrument on India's upcoming
 375 second mission to the Moon, Chandrayaan-2.

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Table 2: X-ray line flux (photons/cm²/s) from C1XS spectral analysis with 1σ errors.

Approximate central co-ordinates of each ground pixel are given in the first column

Lat , Lon	Date	Na K α	Mg K α	Al K α	Si K α	Ca K α
Time in UTC						
-45.2 , 25.0	04/07/09	-	0.54 $\pm$	1.03 $\pm$	0.83 $\pm$	0.08 $\pm$
	01:18:00 -01:21:59	-	0.06	0.08	0.06	0.01
-30.2 , 25.0	04/07/09	0.72 $\pm$	0.83 $\pm$	1.59 $\pm$	1.06 $\pm$	0.06 $\pm$
	01:22:00 - 01:27:09	0.15	0.07	0.09	0.06	0.01
-63.2 , -10.5	06/07/09	-	0.92 $\pm$	1.54 $\pm$	0.94 $\pm$	0.18 $\pm$
	17:04:29 - 17:06:26	-	0.07	0.07	0.05	0.02
-53.2 , -10.5	06/07/09	0.56 $\pm$	1.26 $\pm$	2.10 $\pm$	1.46 $\pm$	0.12 $\pm$
	17:06:27 - 17:10:17	0.13	0.17	0.11	0.07	0.01
-43.0 , -10.5	06/07/09	0.73 $\pm$	1.30 $\pm$	2.08 $\pm$	1.31 $\pm$	0.04 $\pm$
	17:10:47 - 17:13:59	0.16	0.10	0.13	0.09	0.01
-30.7 , -10.3	06/07/09	-	0.88 $\pm$	1.40 $\pm$	1.08 $\pm$	0.02 $\pm$
	17:14:11 - 17:19:44	-	0.15	0.06	0.05	0.01
-30.0 , -28.7	08/07/09	0.45 $\pm$	0.73 $\pm$	0.92 $\pm$	0.42 $\pm$	0.03 $\pm$
	05:27:31 - 05:30:20	0.22	0.05	0.04	0.02	0.01

Table 3: Elemental abundances (wt%) from C1XS analysis with 1 σ uncertainties

Lat , Lon	Na	Mg	Al	Si	Ca
-45.2 , 25.0	-	4 $^{+1}_{-1}$	16 $^{+1}_{-1}$	18 $^{+1}_{-1}$	13 $^{+1}_{-1}$
-30.2 , 25.0	3 $^{+1}_{-1}$	4 $^{+1}_{-1}$	17 $^{+1}_{-1}$	17 $^{+1}_{-1}$	10 $^{+1}_{-1}$
-63.2 , -10.5	-	6 $^{+1}_{-1}$	18 $^{+1}_{-1}$	13 $^{+1}_{-1}$	14 $^{+1}_{-1}$
-53.2 , -10.5	2 $^{+1}_{-1}$	6 $^{+1}_{-1}$	17 $^{+1}_{-1}$	16 $^{+1}_{-1}$	10 $^{+1}_{-1}$
-43.0 , -10.5	3 $^{+1}_{-1}$	5 $^{+1}_{-1}$	17 $^{+1}_{-1}$	18 $^{+1}_{-1}$	8 $^{+1}_{-1}$
-30.7 , -10.3	-	4 $^{+2}_{-1}$	16 $^{+2}_{-1}$	23 $^{+3}_{-2}$	8 $^{+2}_{-3}$
-30.0 , -28.7	5 $^{+0}_{-1}$	9 $^{+1}_{-2}$	15 $^{+2}_{-2}$	16 $^{+2}_{-1}$	6 $^{+1}_{-1}$
Average feldspathic meteorite compositions	0.26	3.26	14.92	20.89	11.65
AP16 (Soil & Regolith Breccia Average)	0.35	3.62	14.41	20.98	10.41
LP average (dashed box Fig. 2)	-	5.32	13.28	20.23	10.96

(a) Nov'2008 - Apr'2009

(b) May'2009 - Aug'2009

Figure 1: The entire mission light curve of C1XS experiment from 22nd Nov.2008 - 3rd Aug.2009. The solar soft X-ray flux from the GOES satellite indicates the X-ray activity of the Sun during the life time of the mission. Useful C1XS observations are during solar flares with intensity B3 ($3 \times 10^{-7} \text{ W}/\text{m}^2$) and above which is marked as dashed line. Red points indicate C1XS integrated counts with a time bin of 16s; Blue lines indicate solar X-ray flux with a time bin of 1min. Flare observations discussed in this paper are shown in the inset of Fig. 1b.

Figure 2: Ground-track of C1XS observations made on 4th, 6th and 8th July 2009 plotted over the Clementine lunar albedo map (750nm). Elemental abundances from the LP gamma-ray data used for comparison are taken from the region of interest shown as dashed line box which encompass C1XS observed locations

Figure 3: Light curves showing C1XS integrated counts (1 keV - 10 keV) (*Red line-points*) along with X-ray solar flux obtained from GOES (1.55 keV - 12.4 keV) (*blue lines*) (a) background observation - without solar flare and high particle flux (b) flare observation showing a rise in solar flux and C1XS counts (c) particle hit observation indicated by a sudden rise in the C1XS counts without any corresponding increase in the solar flux

Figure 4: C1XS average background spectrum inside the geotail measured from multiple orbits during the month of July 2009 used for data analysis along with a spectrum corresponding to high particle flux (red color points).

Figure 5: Best fit to one of the solar spectra observed by the XSM on 6th July 2009, using the CHIANTI database. The observed continuum spectrum along with the ionized solar coronal emission lines are well modeled using *vtherm_abund* in OSPEX (Object Spectral Executive - an interface tool for solar X-ray data analysis in SSW) (Green line). Further, a Gaussian component is fitted at ≈ 2.1 keV (Yellow line) for improved fit. Red line represents the combined spectral fit and data points are in Black.

Figure 6: Best fit for the observed XRF spectrum for an interval during C1 class flare, with all components. Data points (black) are shown with error bars; XRF lines of major elements are marked. Residuals of fit (difference between model and data) in terms of 1σ error bar size are shown in the bottom panel of each figure. (a) Spectral fit convolved with detectors' response (b) Deconvolved photon spectrum corresponding to the best fit.

(a) C1XS abundances vs LP abundances

(b) C1XS abundances vs Lunar Meteorite abundances

Figure 7: Comparison of C1XS abundance with (a) GRS data from Lunar Prospector (Prettyman et al., 2006). (b) Lunar Meteorite compositions (Demidova et al., 2007). C1XS predict low Ca abundance in comparison to the correlation established between Al & Ca in lunar meteorite collections (i). Sum of Na & Ca abundances agree well with the correlation (ii).

Figure 8: Relation between Ca and Na abundances from CIXS observations. The point with inverted arrow is the upper-limit of Na abundance for that observation

Figure 9: Plagioclase solutions from calcic end member to sodic end member which are called intermediate plagioclase minerals referred by An#.

Figure 10: Track of C1XS observed region on the Moon - 4th, 6th and 8th July 2009 plotted over the LRO Diviner radiometer Christiansen Feature (CF) value map (in μm). Ca-rich plagioclase have CF positions around 7.84 μm whereas plagioclase with Na component shift towards low CF values ($leq 7.8 \mu m$). Mafic minerals such as pyroxene, olivine show long CF values as indicated in the color map. Some of the saturate blue regions in the map with lower CF values represent unusual compositions (Greenhagen et al., 2010).