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► To cite this version:

S.Z. Weider, B.J. Kellett, B.M. Swinyard, I.A. Crawford, K.H. Joy, et al.. The Chandrayaan-1 X-ray Spectrometer: First results. Planetary and Space Science, 2012, 60 (1), pp.217-228. 10.1016/j.pss.2011.08.014 . hal-02458578

HAL Id: hal-02458578

<https://hal.science/hal-02458578>

Submitted on 29 Mar 2021

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The Chandrayaan-1 X-ray Spectrometer: First Results

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Keywords: Lunar X-ray spectroscopy; Lunar regolith; Lunar chemistry; Lunar crust; Gamma-ray spectroscopy

Abstract

We present X-ray fluorescence observations of the lunar surface, made by the Chandrayaan-1 X-ray Spectrometer during two solar flare events early in the mission (12th December 2008 and 10th January 2009). Modelling of the X-ray spectra with an abundance algorithm allows quantitative estimates of the MgO/SiO₂ and Al₂O₃/SiO₂ ratios to be made for the two regions, which are in mainly basaltic areas of the lunar nearside. One of these ground tracks includes the Apollo 14 landing site on the Fra Mauro Formation. Within the 1 σ errors provided, the results are inside the range of basaltic samples from the Apollo and Luna collections. The Apollo 14 soil composition is in agreement with the results from the January flare at the 1 σ uncertainty level. Discrepancies are observed between our results and compositions derived for the same areas by the Lunar Prospector gamma-ray spectrometer; some possible reasons for this are discussed.

1. Introduction

Remote sensing of the Moon reveals on a global scale the compositional (Lucey et al., 1998; 2000; Lawrence et al., 2002; 2003; Lucey and Cahill, 2006; Prettyman et al., 2006; Wöhler et al., 2011) and mineralogical (Belton et al., 1994; Pieters and Tompkins, 1999; Lucey, 2004; Pieters et al., 2006; Glotch et al., 2010; Greenhagen et al., 2010) heterogeneities of its surface. Such missions have revealed that the Moon's surface is more diverse than originally thought, based on the studies of the geological samples returned by the Apollo and Luna missions (Taylor et al., 1991; Lucey et al., 2006; Shearer et al., 2006). These remotely sensed data led to the recognition that the Moon can be broadly divided into three compositional terranes (Jolliff et al., 2000) that reflect the surface expression of the Moon's (i) primary crust (the Feldspathic Highlands Terrane), (ii) secondary crust (magmatic and volcanic deposits associated with the nearside Procellarum KREEP Terrane), and (iii) possible lower crust exposed in the South Pole-Aitken Terrane.

The new perspectives provided by compositional remote sensing datasets are fundamental to the understanding of the Moon's geological diversity and history. However, the picture is not yet complete. In particular, some key rock-forming elements, such as Mg, Al, Si and Ca, have only been mapped globally at low spatial resolutions (~150 km per pixel) using gamma-ray spectroscopy (Prettyman et al., 2006), although a recently published method based on optical spectral data (Wöhler et al., 2011) proposes that mapping some of these elements may be possible with higher spatial resolution. X-ray fluorescence (XRF) instruments on Apollo 15 and Apollo 16 (Adler et al., 1972a; 1972b; Adler and Trombka, 1977; Andre et al., 1977) were able to map the distribution of Mg, Al and Si for features down to ~15 km, but for only about a tenth of the lunar surface (Andre et al., 1977), as depicted in Figure 1a. Furthermore, for other key elements (i.e., Ti and Fe) there are significant discrepancies between the Clementine and Lunar Prospector datasets (Lawrence et al., 2002; Gillis et al., 2004; Lucey et al., 2006; Prettyman et al., 2006). Additional XRF detections of Ti and Fe in the lunar surface were made using D-CIXS (Demonstration of a Compact Imaging X-ray Spectrometer) onboard ESA's SMART-1 (Grande et al., 2007; Swinyard et al., 2009), but these have very limited extent and spatial resolution. As such, the tasks of characterising the compositional heterogeneity of the lunar

surface, identifying surface expressions of key lithologies, and interpreting this information in terms of the Moon's evolution remain unfinished. Figure 1a summarises the extent of the lunar surface that has been mapped compositionally with XRF by the Apollo 15 and 16, D-CIXS and C1XS (Chandrayaan-1 X-ray Spectrometer) instruments. The new C1XS dataset (uncalibrated data is currently available to the public in the PDS; a calibrated dataset should be released later in 2011) covers approximately 5% of the lunar surface that has not been previously mapped by XRF. The majority of these data pertain to Mg, Al and Si, but in select cases (e.g., data presented by Narendranath et al., 2011) other elements (i.e., Ca and Fe) were also detected.

2. The C1XS instrument and X-ray fluorescence

C1XS was a compact X-ray spectrometer (Grande et al., 2009a; 2009b; Howe et al., 2009) that flew onboard Chandrayaan-1, India's first mission to the Moon (Bhandari, 2005; Goswami and Annadurai, 2009). The mission operated in a lunar mapping orbit from December 2008 until its premature end in August 2009. The experiment utilised planetary X-ray fluorescence spectroscopy to measure the abundances of major rock forming elements in the lunar surface. The technique is only possible for atmosphere-free bodies in the inner solar system, where the flux of incident solar X-rays is high enough to cause fluorescent X-ray emission from the uppermost hundred microns in the planetary surface (Yin et al., 1993). The emitted X-rays are characteristic of elements from which they originate and they can therefore be used to help constrain variations in local surface geology. Normal levels of solar intensity result in the excitation of low atomic number elements, including several common in rock-forming minerals such as Mg, Al and Si. During solar flares, intense levels of solar X-rays are emitted and the excitation of heavier atomic-number elements such as K, Ca, Ti and Fe can also occur. A detailed description of the scientific goals of the instrument has been given by Crawford et al. (2009) and a full explanation of the technique is given by Clark and Trombka (1997).

C1XS exploited technology inherited from the D-CIXS instrument on ESA's SMART-1 mission (Grande et al., 2003; 2007; Swinyard et al., 2009). The instrument consisted of 24 nadir pointing swept charge device (SCD) detectors (Holland et al., 2004; Smith et al., 2007; Smith and Gow, 2009) that provided high detection efficiency in the 1 – 7 keV energy range containing the X-ray

fluorescence lines of elements of interest. Micro-machined gold-coated collimators provided a 28° (full width) field of view (FOV), equivalent to a 50 km (1.65° arc length) surface footprint from Chandrayaan-1's initial 100 km altitude orbit, and 100 km from its later (i.e., after 19th May 2009) raised orbit of 200 km. A controllable, 5 mm-thick aluminium door provided radiation shielding for the instrument during the launch and cruise phases, and contained a ⁵⁵Fe calibration source for each SCD detector. Full details of the instrument design and onboard data processing methodology can be found in Howe et al. (2009). The instrument's detection efficiency was derived as 42% at 1.48 keV from pre-flight laboratory measurements (Narendranath et al., 2010a) and in-flight calibrations provided the FWHM of the SCDs: 163 eV at 5.9 keV and -8°C (Narendranath et al. 2011).

The XRF flux from a planetary surface is highly dependent on the intensity and shape of the incident solar X-ray spectrum, which is highly variable even on short timescales (e.g., Donnelly, 1976; Bouwer, 1983; Crosby et al., 1993). To make quantitative estimates of elemental abundances in planetary regoliths via XRF spectroscopy it is therefore necessary to obtain an accurate measure of the solar X-ray spectrum and the planetary XRF spectrum simultaneously. For this reason C1XS was accompanied on Chandrayaan-1 by an X-ray Solar Monitor (XSM) instrument (Alha et al., 2009), which was based on a similar design flown on the SMART-1 mission (Huovelin et al., 2002; Alha et al., 2008). The XSM device consisted of a separate detector unit on the spacecraft that monitored solar X-ray emission. This non-imaging high purity silicon PIN sensor had a collimated wide FOV of 52° radius (circular field), which enabled Sun visibility during a significant fraction of the mission lifetime. XSM had an energy range (1 – 20 keV), spectral resolution (~250 eV at 5.9 keV) and sensitivity (~8000 counts/s for an X1 flare; 10⁻⁴ Wm⁻² in the wavelength range 0.1 – 0.8 nm) and was designed to provide sufficient information on the solar X-ray flux reaching the lunar surface to enable accurate interpretation of the fluorescent lines measured by C1XS. The sensitivity estimate is based on a simulated observation of an X1 flare using an observed solar X-ray spectrum from the SMART-1 XSM, which is rescaled from M-class to X-class and convolved with the response function derived from the calibrations of the Chandrayaan-1 XSM. However, as discussed in Section 4 below, the data reported here were obtained for A-class flares, an order of magnitude weaker than those XSM was designed to characterise (i.e., B-class flares and above; Alha et al., 2008).

As a consequence, the fluxes from these flares were insufficient for XSM to determine reliably the input spectrum, and other methods therefore had to be adopted to estimate the intensity and shape of the exciting solar spectra.

3. First observations

Shortly after commissioning, C1XS observed XRF from the lunar surface during two A-class solar flares ($10^{-8} - 10^{-7} \text{ Wm}^{-2}$) on 12th December 2008 and 10th January 2009. The first of these flares has a ground track (~1150 km in length) that crosses the full latitudinal extent of Mare Serenitatis, and also samples the highland areas to the north and south (see Table 1 and Figure 1b). It passes through lava flows within Mare Serenitatis that likely erupted between ~3.8 Ga and ~2.8 Ga (according to the crater-count ages of Hiesinger et al., 2000). These lava flows appear (see Figure 2) to be low-Ti basalts (~3 – 4 wt. % TiO_2) with relatively high FeO contents (~16 – 20 wt. %). The feldspathic highland regions at the north and south of the ground track are characterised by lower FeO and TiO_2 concentrations.

The second flare observation, on 10th January 2009, follows a track through Mare Insularum, Mare Cognitum and Mare Nubium (see Table 1 and Figure 1b) which includes the Apollo 14 landing site (3°38'43" S; 17°28'17" W) located in the Fra Mauro Formation. The analysis of this flare therefore provides an opportunity to test the C1XS data reduction methodologies (Swinyard et al., 2009; 2010; Narendranath et al., 2010b; Weider et al., 2011) with ground truth information from the Apollo 14 sample collection. The Fra Mauro Formation is interpreted as continuous ejecta from the Imbrium basin (Wilhelms et al., 1987; Stöffler et al., 2006), although it is likely to be intermixed with more locally derived material during ballistic sedimentation (e.g., Morrison and Oberbeck, 1975; Haskin et al., 2002). As such, the Apollo 14 landing site cannot be considered to be representative of either maria or the ancient feldspathic highlands (Lucey et al., 2006). The samples collected tend to be impact breccias with generally basaltic or KREEP-rich compositions (Hiesinger and Head, 2006) and radiometric ages that range from ~3.95 Ga (Stadermann et al., 1991) to ~3.77 Ga (Stöffler et al., 1989; Stadermann et al., 1991). According to Hiesinger et al. (2003), the lava flows that comprise the remaining footprint of this flare range from ~3.1 Ga to ~3.7 Ga. They also tend to have greater TiO_2 concentrations (from ~2.5 up to

~8 wt. %) than those in the 12th December 2008 flare ground track, but with a similar FeO content (see Figure 3).

4. Data processing, abundance modelling and sources of error

During both the observations described in this paper, C1XS collected X-ray flux data in the time-tagged single pixel mode (see Howe et al., 2009) and were converted into 16 second binned spectra. Pre-flight and in-flight calibration information (Narendranath et al., 2010a), along with instrument housekeeping data were used to calibrate each spectrum. For these observations, data from all 24 detectors were co-added in time in order to obtain sufficient counting statistics. Lunar XRF spectrograms for both flares are shown in Figure 4. In each case an average detector background level was subtracted; these backgrounds were determined from long-integrations obtained during periods of quiet (i.e., undetectable) solar activity. We note that both observations reported here were obtained while the Moon was in the Earth's magnetotail, resulting in somewhat higher background levels than when the Moon is outside the magnetotail. The final background-subtracted, energy-calibrated spectra were then modelled in an abundance algorithm to obtain quantitative elemental abundance estimates for the parts of lunar surface observed.

The abundance algorithm employed (Swinyard et al., 2009; 2010) has been shown to successfully recover major element abundances within ± 1 element wt. % for geological specimens of known composition (Weider et al., 2011). It follows the methods of Clark and Trombka (1997) which modifies the fundamental parameters approach (e.g., He and Van Espen, 1991) for the analysis of unknown materials using a wide, polychromatic source of X-rays that is relevant for planetary XRF spectroscopy. In addition to the energy-calibrated, background-subtracted C1XS spectra, the algorithm requires as inputs: (i) a modelled solar spectrum containing both the bremsstrahlung continuum and solar emission lines, (ii) the efficiency of the C1XS instrument as a function of energy, (iii) an arbitrary initial rock composition, and (iv) the phase angle of the observation. Using this information the algorithm iterates around the initial rock composition until a best fit to the C1XS spectrum is found (determined by chi-squared minimisation). Each elemental fluorescence line is tested in isolation, starting with the highest

energy lines whose abundances are updated before the next line is modelled. When all the lines have been tested the new values are used as the fixed initial composition and the procedure is repeated until there is no variation between runs (normally two complete iterations).

The model assumes a fixed Si abundance, thus all the other modelled elemental abundances are relative to the Si abundance chosen. This normalisation is possible because the Si concentration within the lunar regolith only varies between about 18 – 23 elemental wt. % (e.g., Rhodes and Blanchard, 1981; Fruland, 1983, Morris et al., 1983; Simon et al., 1985; McKay et al., 1986; 1989; Jerde et al., 1987; 1990). This variation in Si abundance has only a minor effect on the Mg and Al results; much larger uncertainties are introduced to the methodology due to our lack of direct and high spectral resolution knowledge of the incident solar flare spectrum, which dominates over all other uncertainties in the methodology.

By always expressing results as ratios of two elements inaccuracies due to calibration uncertainties, and variations in XRF intensity caused by physical and compositional differences in the regolith, should mostly be negated (Clark and Trombka, 1997), at least for the three low-energy elements (Mg, Al and Si) considered in this paper (Weider et al., 2011). This issue has been the focus of recent analogue laboratory experiments (e.g., Maruyama et al., 2008; Näränen et al., 2008; Weider et al., 2011) that have investigated the role of viewing geometry and surface roughness on the XRF intensity measured from regolith-like samples. These experiments have demonstrated a phase angle-related increase in XRF from compositionally heterogeneous samples, which is energy dependent, and it may therefore be problematic to express abundances as ratios of two elements that differ significantly in energy (e.g., Si and Fe) for data obtained at phase angles above $\sim 60^\circ$ (Weider et al., 2011). The same studies (Maruyama et al., 2008; Näränen et al., 2008; Weider et al., 2011) also document a decrease in XRF with increasing grain-size from heterogeneous samples, but such an effect is unlikely to have an impact on the analysis of XRF data from well-mixed (gardened) planetary regoliths such as the Moon's, especially on the large spatial scales involved.

Although the XSM (see Section 2.1) was flown onboard Chandrayaan-1 in order to measure the solar X-ray spectrum during periods of C1XS data acquisition, the solar X-ray flux during the A-

class flare observations discussed in this paper was insufficient for XSM to reliably characterise the incident spectrum. For this reason an alternative source for an incident solar spectrum is required. We have used the *atomdb* (version 2.0.0) database and modelling software (Harvard Chandra X-ray Center: http://cxc.harvard.edu/atomdb/features_idl_html) for this purpose. This software generates a high-resolution modelled solar spectrum with both the bremsstrahlung continuum and superimposed emission lines at a number of different temperatures. Based on the work of Kay et al. (2003) we estimate that the temperatures of the A-class flares observed here were between about 2.5 MK and 3.1 MK. The flare temperatures cannot have been significantly higher without exciting the Ca K α line at 3.7 keV which is not observed (see Figure 4). To allow for errors introduced by the uncertainty in the flare temperatures, we have modelled the C1XS spectra using both the upper and lower temperature limits and factored this into our quoted errors on the derived abundances (Section 5).

As described by Swinyard et al. (2010), the C1XS instrument efficiency has been derived from a model based on the expected X-ray absorption properties of the SCD detectors, calibrated with laboratory efficiency measurements of monochromated X-rays conducted during the pre-flight calibration campaign (see also Narendranath et al., 2010a). These measurements were made with the same thresholds and event selection criteria as employed in lunar orbit. The resulting efficiencies were found to be consistent with the SCD efficiency measurements obtained from observations of the Crab Nebula by the D-CIXS instrument on SMART-1 (Grande et al., 2007; Swinyard et al., 2009). We note that our abundance modelling procedure, which ratios abundances relative to Si, is relatively insensitive to the absolute instrument efficiency values, especially for the closely spaced low-energy lines discussed here.

As the initial rock composition for the modelling we adopt the average lunar surface composition derived from Lunar Prospector gamma-ray data (Prettyman et al., 2006; i.e., Mg: 4.35 wt. %; Al: 12.35 wt. %; Ca: 11.29 wt. %; Ti: 0.56 wt. %; Fe: 5.93 wt. %; as noted above Si was fixed at 21.00 wt. %). However, it is important to realise that owing to the iterative nature of the method, the final results obtained for Mg and Al are independent of the assumed initial composition (Weider, 2011). The mean phase angle of each observation, also required by the model, is obtained from the instrument pointing (SPICE) data.

5. Results

5.1. 12th December 2008 flare

The fitted spectrum (between 0.7 keV and 2.5 keV) for the 12th December 2008 flare is shown in Figure 5a, and for a subsection of this flare (whose footprint is entirely within Mare Serenitatis) in Figure 5b. These spectra show the three easily resolved low-energy peaks of Mg K α (1.25 keV), Al K α , (1.49 keV) and Si K α (1.74 keV). Although not resolved in these spectra, we note that the modelling also includes the adjacent K β lines. These spectra also appear to exhibit weak emission at $\sim$ 1.00 keV, which may possibly be due to the Na K α line at 1.04 keV. However, as discussed below, this region in C1XS spectra is likely to be dominated by scattered solar X-rays making any such assignment uncertain. The modelled abundances for Mg and Al are given in Table 2. The mean MgO/SiO₂ and Al₂O₃/SiO₂ ratios (averaged from the modelling at the two flare temperatures) for both flare sections are given in Table 3, along with errors which combine the 1 σ fitting errors and the range that arises from the modelling at two flare temperatures. These values are also shown in Figure 6a, where the C1XS results are compared to various lunar samples and Lunar Prospector values.

5.2. 10th January 2009 flare

Figure 5c shows the fitted spectrum for the whole of the 10th January 2009 flare. Figure 5d shows the spectrum for a subsection corresponding to the Fra Mauro Formation which includes the Apollo 14 landing site. The modelled elemental abundances for these spectra are given in Table 2 and the resulting MgO/SiO₂ and Al₂O₃/SiO₂ ratios are given in Table 3. These are compared to lunar samples and Lunar Prospector values in Figure 6b.

Again, these spectra possibly exhibit a weak emission at $\sim$ 1.00 keV, which could be due to the Na K α line. Moreover, this emission appears stronger in the Fra Mauro section of the ground track (Figure 5d). The observed line strength would imply a Na abundance of between $\sim$ 1.10 $\pm$ 0.28 wt. % and 1.65 $\pm$ 0.48 wt. % ($\sim$ 1.5 to 2.2 wt. % Na₂O), depending on the flare

temperature. This would be consistent with the average Apollo 14 soil composition being considerably richer in Na₂O (0.70 wt. %) than for all the other landing sites, whose values are between 0.31 wt. % and 0.54 wt. % (McKay et al., 1991). If this interpretation is correct, then these observations would represent the first XRF observation of Na on the Moon. However, as noted above, the spectral region of the Na K_α line is expected to be dominated by scattered solar lines which, depending on the scattering efficiency, could mimic the emission of lunar Na XRF. We illustrate this in Figure 7, which clearly shows that for high scattering efficiency the entire Na ‘line’ could be due to scattered solar lines, whereas the neighbouring Mg, Al and Si lines are essentially unaffected. We therefore have to caution that any interpretation of this feature as being due to Na XRF alone can only be tentative as it is not possible with these data to unambiguously fit the level of the scattered solar spectrum.

6. Discussion

6.1. 12th December 2008 flare

The C1XS element ratios (with 1 σ errors) for the mare basalt region of Mare Serenitatis (Figure 2) are within the compositional range of mare basalts (Figure 6a). Data collected from the whole flare footprint (Figure 2) have higher Al₂O₃/SiO₂ ratios, consistent with its ground track including feldspathic highland areas at its two ends. Generally, the Lunar Prospector gamma-ray compositions for the flare region overlap with the C1XS results in terms of Al₂O₃/SiO₂ within the 1 σ errors, but the C1XS results are consistently lower in terms of MgO/SiO₂. There could be three possible reasons (or a combination of these) for this discrepancy: (i) the C1XS results presented here are inaccurate; (ii) the Lunar Prospector results presented by Prettyman et al. (2006) are inaccurate; or (iii) there is an intrinsic problem with comparing planetary XRF and gamma-ray spectroscopy data. The likelihood of these options is discussed further in Section 6.4.

6.2. 10th January 2009 flare

The MgO/SiO_2 and $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios derived from the 10th January 2009 flare observations are within the range exhibited by mare basalt samples (Figure 6b). The ground track of this flare includes the Apollo 14 landing site, and as such, the C1XS results should have a similar composition to the average soil composition for Apollo 14, which is labelled in Figure 6b. This is indeed the case, with the Apollo 14 soil composition lying within the 1σ errors of the whole flare ratio and close to the Fra Mauro C1XS data point (although these two points are essentially the same within the errors).

The discrepancies between the C1XS and Lunar Prospector values observed for the 12th December 2008 flare are also observed for the 10th January 2009 flare (Figure 6b), although perhaps to a lesser extent. This suggests that the validity of comparing these two datasets warrants further investigation and is discussed below in Section 6.4.

6.3. Variation in spatial scales

It is possible that the agreement between the Apollo 14 soil sample composition and the C1XS derived MgO/SiO_2 and $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios is merely coincidental, owing to the disparity in the spatial scales represented by the soil samples ($<0.8\text{ km}^2$) and the C1XS footprint ($\sim 20,000\text{ km}^2$). This is also true in the case of relating Lunar Prospector gamma-ray data and the soil samples. FeO and TiO_2 concentrations derived from Clementine multispectral reflectance data can be used to investigate this issue. The concentrations derived (using the algorithms of Gillis et al., 2003; 2004) for pixels containing only the immediate area around the Apollo 14 site and the Fra Mauro region sampled by C1XS (i.e., within the dashed lines in Figure 3) are similar (within 1 wt. %). The Apollo 14 site concentration and the actual soil data (reported by McKay et al., 1991 and references therein) are equal in terms of TiO_2 , but differ by ~ 3 wt. % in terms of FeO . The expected variation in compositions derived from remotely sensed data at different spatial scales is therefore apparent to some extent in the Clementine data. Fe and Ti were not observed in the C1XS data reported here, so a direct comparison is not possible. We merely note that compositional variations on the order of a few wt. % between the local (sample) scale and the orbital remote sensing measurements are not unexpected.

6.4. Planetary XRF vs. gamma-ray spectroscopy

As outlined in Section 6.1, the lack of agreement between the C1XS results presented in this paper and the corresponding Lunar Prospector gamma-ray compositions (especially in terms of MgO/SiO_2) could be due to a combination of factors. Given (i) that the abundance algorithm methodology used here has been proven using laboratory test data from a lunar regolith simulant (Weider et al., 2011); (ii) the agreement of the 10th January 2009 result and the ground truth Apollo 14 sample composition; and (iii) that the errors associated with the uncertain solar flare temperatures are much larger than the algorithm's fitting errors, it is thought that the lack of agreement between the C1XS and Lunar Prospector results is unlikely to be due to the inaccuracy of the C1XS abundances presented here.

The better agreement between the sample and C1XS data than between the C1XS and Lunar Prospector data, or indeed than between the sample and Lunar Prospector data, further suggest that the discrepancy is more likely to lie with the Lunar Prospector values for Mg (at least on such a local scale as this, rather than for the global dataset). It has been noted (e.g., Wöhler et al., 2011), that for the respective landing sites (based on sample compositions compiled by Elphic et al., 2000) and the Lunar Prospector gamma-ray data, the correlation is not always good. This is especially true for Mg and Al, and particularly the former, which is systematically overestimated (by up to ~5 element wt. %) by Lunar Prospector. Furthermore, Lunar Prospector SiO_2 values (as presented by Prettyman et al., 2006) tend to be lower than Apollo soil compositions. If the Lunar Prospector data points in Figure 6 are normalised not to the Prettyman et al., (2006) SiO_2 values for the particular pixel, but to a sample average or the mean global Lunar Prospector value (i.e., ~43 to 45 wt. %), the ratios in terms of both MgO and Al_2O_3 become smaller. The $\text{Al}_2\text{O}_3/\text{SiO}_2$ Lunar Prospector and C1XS values agree better in all cases, but the Lunar Prospector MgO/SiO_2 values remain higher than the C1XS results, within the errors given. These issues with the Lunar Prospector dataset could therefore, at least in part, explain the C1XS-Lunar Prospector discrepancies and also why they are greater for Mg than Al.

It is also important to discuss the third possibility; that the discrepancies arise due to intrinsic differences between the two techniques, rather than because of either dataset having inherent

inaccuracies. The difference in energy of the radiation measured by the two techniques means that XRF only samples the top 100 microns of the lunar regolith (Yin et al., 1993), whereas gamma-rays can penetrate to a depth of ~ 1 m (Prettyman et al., 2006); and also that XRF spectroscopy is subject to matrix effects (e.g., Mantler, 2006). XRF analysis involves attenuation corrections that are dependent on the composition of the target material (e.g., Clark and Trombka, 1997); such attenuation corrections are not required for gamma-rays above 1 MeV for the compositional range of lunar materials (Prettyman et al., 2006).

The different sampling depths of the techniques may mean that compositionally distinct parts of the regolith are measured, with XRF “seeing” only the finest fraction of the soil at the very surface (up to ~ 100 μm), and gamma-rays seeing a greater mixture, down to a depth of ~ 1 m. The study of lunar regolith cores that were obtained during the Apollo missions have revealed an uppermost reworked, layer that varies between ~ 10 cm and ~ 50 cm deep. Beneath this layer are more complex facies consisting of layers of ejecta material from both large and small craters (McKay et al., 1991). It is therefore possible that the geochemistry of the very top of the regolith measured by XRF is different from the bulk composition of the top 1 m. In addition, regolith grain sorting processes (e.g., seismic shaking; Ostrach and Robinson, 2010) may be able to stratify the regolith and produce compositional layering, at least at in the uppermost layers observed here. The possible importance of such effects on the interpretation of lunar XRF spectroscopy has also been noted by Narendranath et al. (2011). Similar effects have been proposed by Riner et al. (2008) to explain the significantly higher Fe/Si ratios determined from the XRS on NEAR for the asteroid Eros (Lim and Nittler, 2009) than those determined from the GRS. Such compositional layering may also help explain the discrepancies between FeO and TiO_2 concentrations derived from the Lunar Prospector gamma-ray and Clementine multispectral reflectance datasets that have previously been noted (e.g., Lucey et al., 2006).

An alternative explanation for possible compositional stratification may be the presence of impact-formed, amorphous and inclusion-rich rims (60 – 200 nm thick) on the surface of individual soil grains (e.g., Keller and McKay, 1997). These are thought to be one of the main causes of spectral darkening due to space weathering in reflectance spectroscopy (Pieters et al., 1993; Allen et al., 1996; Keller and McKay, 1997). However, any compositional anomalies in

these very thin rims (even in terms of the ten to hundred micron scale to which XRF spectroscopy is sensitive) are unlikely to play a significant role in affecting the C1XS results.

Clearly, the issue of comparing planetary XRF and gamma-ray spectroscopy results is an important one that warrants further investigation. This should soon be possible through comparisons of C1XS data with the new gamma-ray results from the Kaguya mission (e.g., Gasnault et al., 2009).

7. Conclusions

XRF data obtained by C1XS during two A-class solar flares early in the mission have been analysed in this paper. The ground tracks of the observations pass through: (i) Mare Serenitatis and (ii) Mare Insularum, Mare Cognitum and Mare Nubium, including the Apollo 14 landing site in the Fra Mauro Formation. The calibrated, gain-corrected and background subtracted X-ray spectra for these flares have been fitted using an abundance algorithm in order to provide estimates of the MgO/SiO_2 and $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios for the two separate regions. The results agree, within the 1σ errors, with existing lunar sample compositions and the Apollo 14 average soil composition has been replicated with the flare data that includes this landing site. This represents an independent measure of lunar elemental abundances that can be compared to, but not calibrated with, ground-truth sample data (unlike other lunar remote sensing datasets).

There is, however, some discrepancy between our results and compositions derived from Lunar Prospector gamma-ray data and we suggest that the validity of comparing planetary XRF and gamma-ray spectroscopy results be investigated in more detail. This is especially important for other planetary bodies where no ground truth sample data are available. Examples include Eros (which has already been studied using these techniques; Nittler et al., 2001), and Mercury (with the forthcoming XRS and GRS datasets from MESSENGER (Goldsten et al., 2007; Schlemm et al., 2007) and BepiColombo (Fraser et al., 2010; Rothery et al., 2010). The C1XS-Lunar Prospector discrepancies may be evidence of compositional layering in the uppermost metre of the lunar regolith, where the finest fraction of the soil is compositionally distinct from the bulk material at depth.

The C1XS spectra from the Fra Mauro Formation include a possible detection of Na. When modelled this peak provides a Na abundance estimate that is consistent with the Apollo 14 average soil composition (the most Na-rich of the lunar soils). However due to uncertainties in the solar spectrum at this energy and the inability to separate the contributions from scattered solar lines and XRF from the lunar surface, this result is not presented with confidence.

While this paper documents the first solar flare events observed by the C1XS instrument, the data yield for just Mg and Al, is relatively small. Other results (e.g., Narendranath et al., 2011) from higher energy events illustrate better the full power (including data for Ca and Fe) of the C1XS instrument and XRF spectroscopy for the Moon and other suitable solar system bodies.

8. Acknowledgements

The authors thank an anonymous reviewer and Tom Prettyman for their helpful and thoughtful comments that have served to significantly improve this manuscript. C1XS was an ESA-provided instrument on India's Chandrayaan-1 spacecraft. We thank ESA and ISRO for this collaborative opportunity, and for support in mission planning, spacecraft operations, and data processing and archiving. SZW, KHJ and IAC acknowledge STFC and the Leverhulme Trust for financial support. This is LPI contribution ****.

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Table 1. Boresight location and phase angle during the December 12th 2008 and 10th January 2009 A-class solar flare C1XS observations.

	12 th December 2008				10 th January 2009			
	Time (U.T.)	Boresight longitude (°)	Boresight latitude (°)	Phase angle (°)	Time (U.T.)	Boresight longitude (°)	Boresight latitude (°)	Phase angle (°)
Start	02:27:00	14.01	44.24	45.17	15:56:00	-17.34	6.92	25.83
End	02:39:00	12.89	8.14	9.63	16:08:00	-18.18	-29.70	37.73

Table 2. Modelled abundances (elemental wt. %) for the lines in the spectra of both flares, with 1 σ fitting errors provided. Values are given for the upper and lower limits adopted for the flare temperatures (here expressed in units of a million kelvin; MK). Oxygen and silicon values are fixed in the modelling at the Lunar Prospector (Prettyman et al., 2006) average lunar surface composition values of 44.00 and 21.00 element wt. % respectively.

	12 th December 2008				10 th January 2009			
	<i>All</i>		<i>Mare</i>		<i>All</i>		<i>Fra Mauro</i>	
	2.5 MK	3.1 MK	2.5 MK	3.1 MK	2.5 MK	3.1 MK	2.5 MK	3.1 MK
Mg	3.00 $\pm$ 0.13	4.50 $\pm$ 0.13	3.00 $\pm$ 0.13	4.50 $\pm$ 0.38	4.75 $\pm$ 0.13	7.00 $\pm$ 0.25	3.75 $\pm$ 0.38	5.75 $\pm$ 0.63
Al	7.75 $\pm$ 0.38	10.00 $\pm$ 0.38	5.25 $\pm$ 0.88	6.50 $\pm$ 1.13	8.00 $\pm$ 0.50	10.50 $\pm$ 0.63	7.25 $\pm$ 1.13	9.50 $\pm$ 1.50

Table 3. Mean MgO/SiO₂ and Al₂O₃/SiO₂ ratios for 12th December 2008 and 10th January 2009 flares, as well as their smaller subsections. These mean values are calculated from the individual modelling of the spectra at both 2.5 MK and 3.1 MK (see Table 2). The errors combine the fitting errors and the range in values incorporated due to the two temperature models. The C1XS values are compared with the Lunar Prospector (L.P.) gamma-ray results (Prettyman et al., 2006) for pixels that overlap with the C1XS regions (as shown in Figure 2 and Figure 3).

	MgO/SiO ₂			Al ₂ O ₃ /SiO ₂		
	C1XS	L.P. Mean	L.P. Values	C1XS	L.P. Mean	L.P. Values
12th Dec. 2008 Whole flare	0.14 $\pm$ 0.03	0.28	0.27 $\pm$ 0.03 0.25 $\pm$ 0.03 0.28 $\pm$ 0.03 0.34 $\pm$ 0.03	0.37 $\pm$ 0.06	0.40	0.45 $\pm$ 0.04 0.36 $\pm$ 0.04 0.43 $\pm$ 0.03 0.76 $\pm$ 0.03
12th Dec. 2008 Mare	0.14 $\pm$ 0.04	0.28	0.25 $\pm$ 0.03 0.29 $\pm$ 0.03 0.31 $\pm$ 0.03 0.27 $\pm$ 0.03	0.25 $\pm$ 0.07	0.29	0.29 $\pm$ 0.04 0.29 $\pm$ 0.04 0.25 $\pm$ 0.04 0.34 $\pm$ 0.03
10th Jan. 2009 Whole flare	0.20 $\pm$ 0.05	0.27	0.24 $\pm$ 0.02 0.22 $\pm$ 0.03 0.13 $\pm$ 0.03 0.25 $\pm$ 0.03 0.33 $\pm$ 0.03 0.31 $\pm$ 0.03	0.36 $\pm$ 0.07	0.44	0.44 $\pm$ 0.03 0.55 $\pm$ 0.03 0.32 $\pm$ 0.03 0.39 $\pm$ 0.03 0.37 $\pm$ 0.03 0.53 $\pm$ 0.03
10th Jan. 2009 Fra Mauro	0.16 $\pm$ 0.05	0.32	0.33 $\pm$ 0.03 0.34 $\pm$ 0.03 0.28 $\pm$ 0.03	0.33 $\pm$ 0.10	0.45	0.34 $\pm$ 0.03 0.47 $\pm$ 0.03 0.54 $\pm$ 0.04

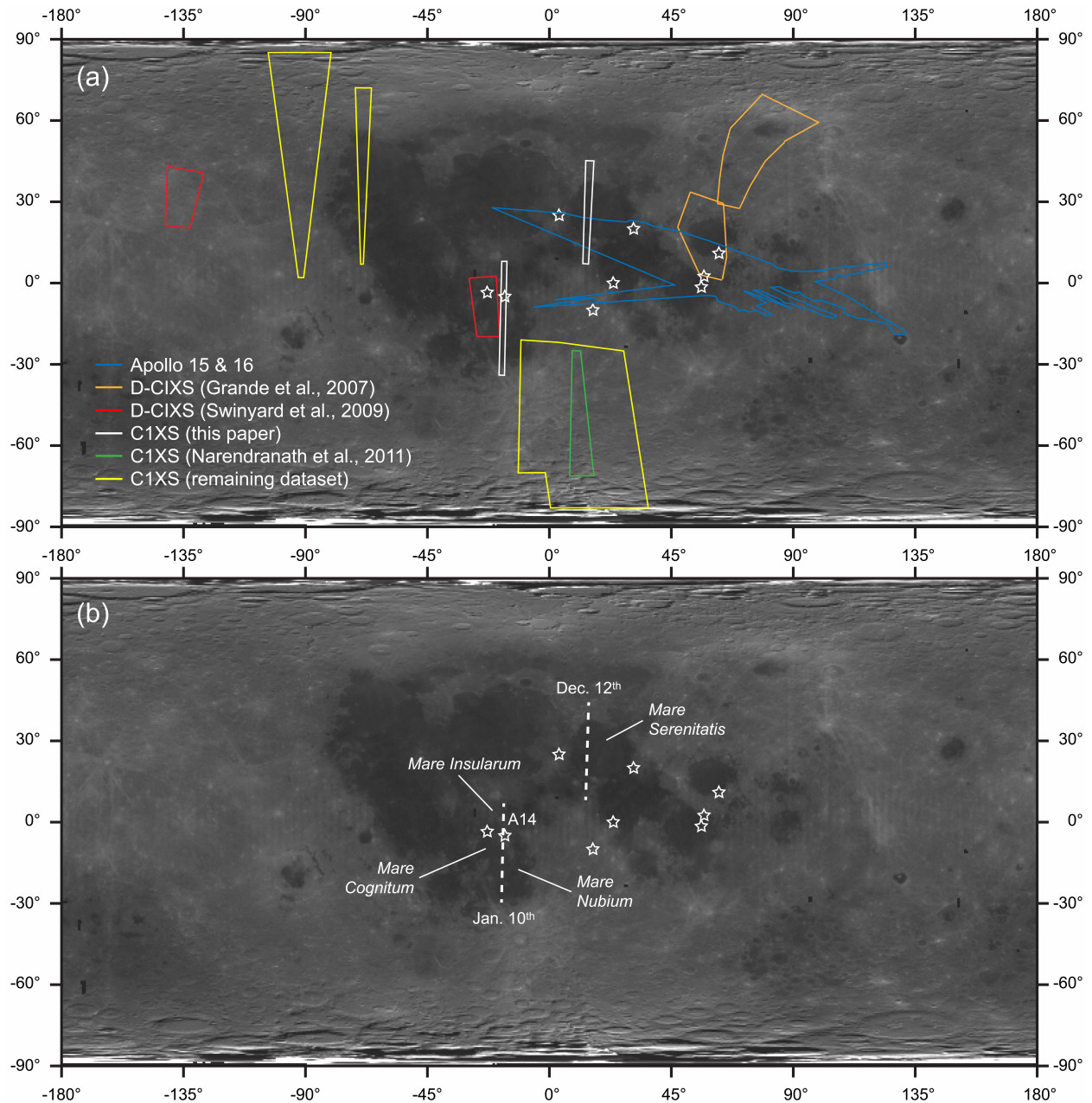


Figure 1. (a) Clementine albedo (750 nm) basemap of the Moon summarising XRF mapping of the lunar surface achieved by the Apollo 15 and 16, D-CIXS and C1XS instruments. All these data provide abundance information for Mg, Al, and Si; in some cases (Grande et al., 2007; Swinyard et al., 2009; Narendranath et al., 2011) other elements (i.e., Ca, Ti and Fe) are also detected. (b) Shows the boresight ground tracks (dashed lines) of the 12th December 2008 and 10th January 2009 C1XS observations, as well as the Apollo and Luna sample return mission landing sites (stars).

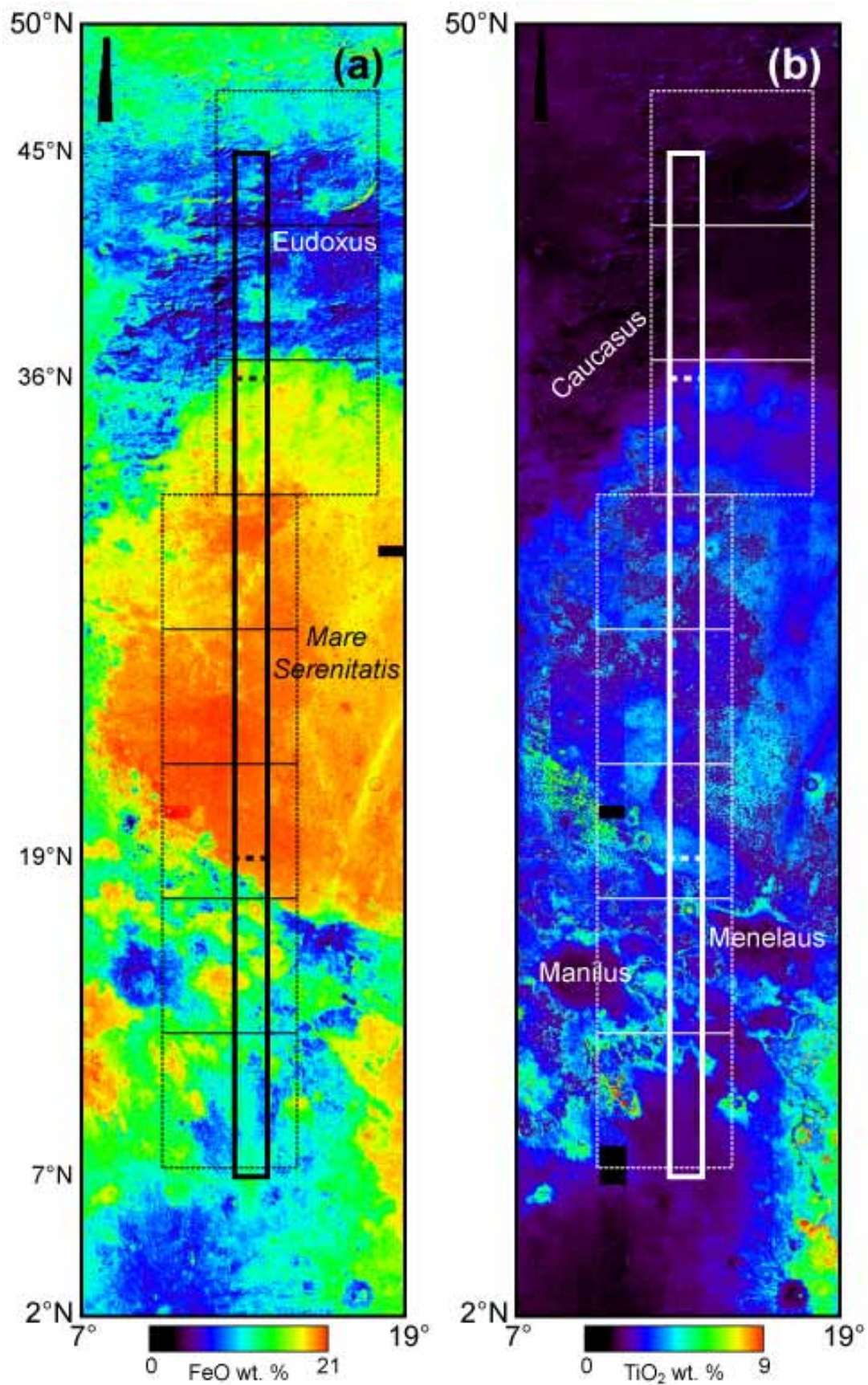


Figure 2. Maps of: (a) FeO wt. % and (b) TiO₂ wt. % content for the 12th December 2008 flare region, derived from Clementine multispectral reflectance data according to the algorithms of Gillis et al. (2004) and Gillis et al. (2003) respectively. The flare ground track (bold) and the mare subsection (bold dashed lines) are indicated; the width of the outlined boxes corresponds to the approximate FWHM (i.e., 25 km) of the detector footprint. Also shown are the boundaries (faint dotted lines) of the 5° Lunar Prospector gamma-ray dataset pixels for the region coinciding with the C1XS ground track.

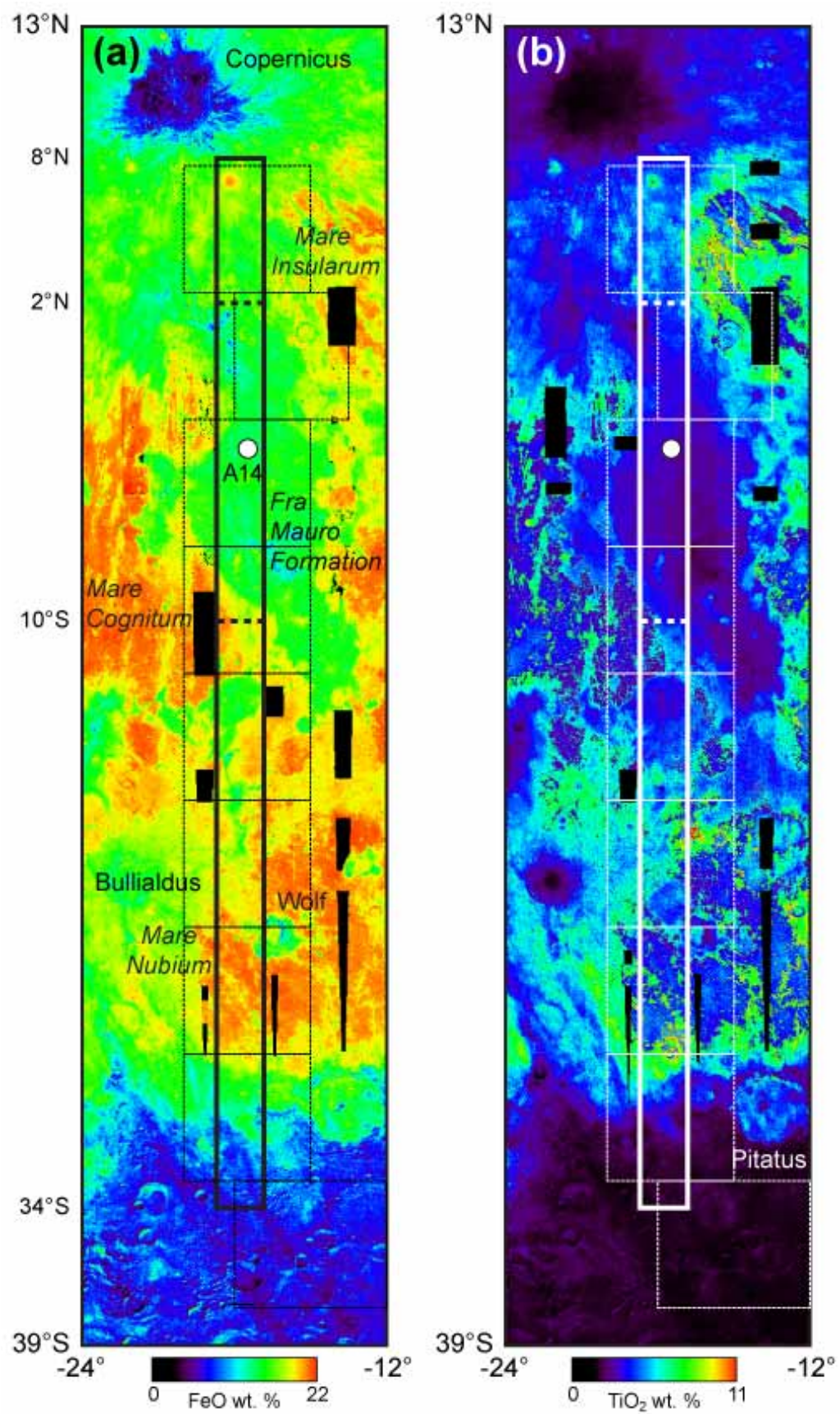


Figure 3. Maps of: (a) FeO wt. % and (b) TiO₂ wt. % content for the 10th January 2009 flare region, derived from Clementine multispectral reflectance data according to the algorithms of Gillis et al. (2004) and Gillis et al. (2003) respectively. The flare ground track (bold) and the Fra Mauro Formation subsection (bold dashed lines) are indicated; the width of the outlined boxes corresponds to the approximate FWHM (i.e., 25 km) of the detector footprint. Also shown are the boundaries (faint dotted lines) of the 5° Lunar Prospector gamma-ray dataset pixels for the region coinciding with the C1XS ground track.

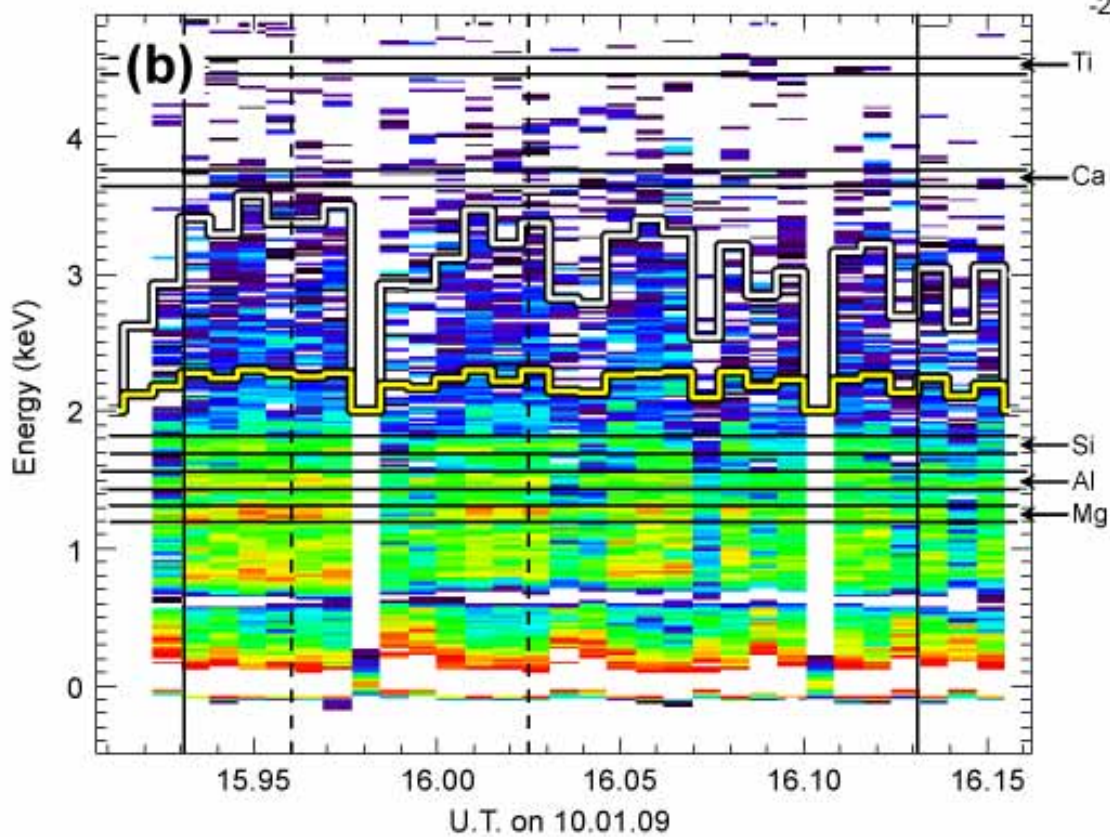
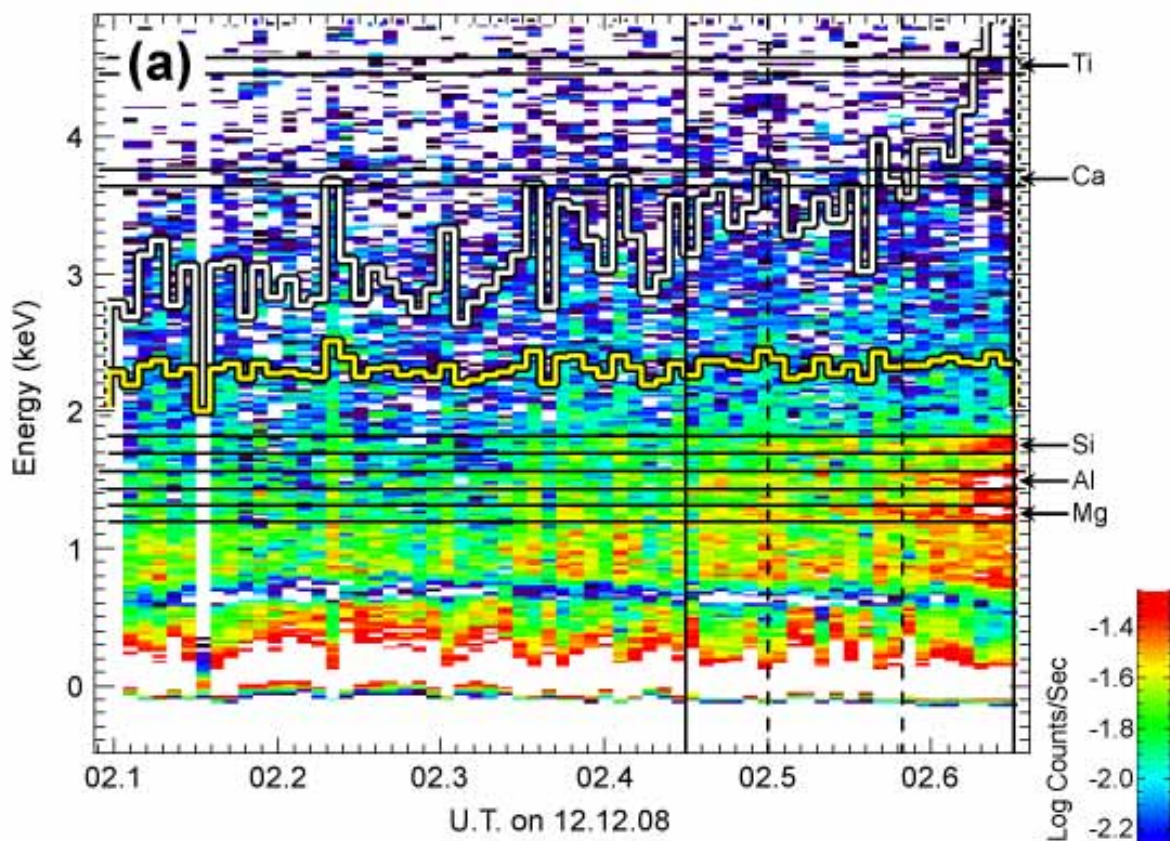


Figure 4. Spectrograms for the (a) 12th December 2008 and (b) 10th January 2009 flares, showing how the X-ray flux intensity varies with time and energy. The solid vertical lines indicate the start and end of each analysis; the dotted lines indicate the mare region in (a) and the Fra Mauro region in (b). The energies of the Mg, Al, Si, Ca and Ti K_α lines are indicated (note that no flux is detected for the latter two lines). The yellow and white histograms show the integrated counts in the energy ranges 1 – 2 keV and 4 – 17 keV respectively.

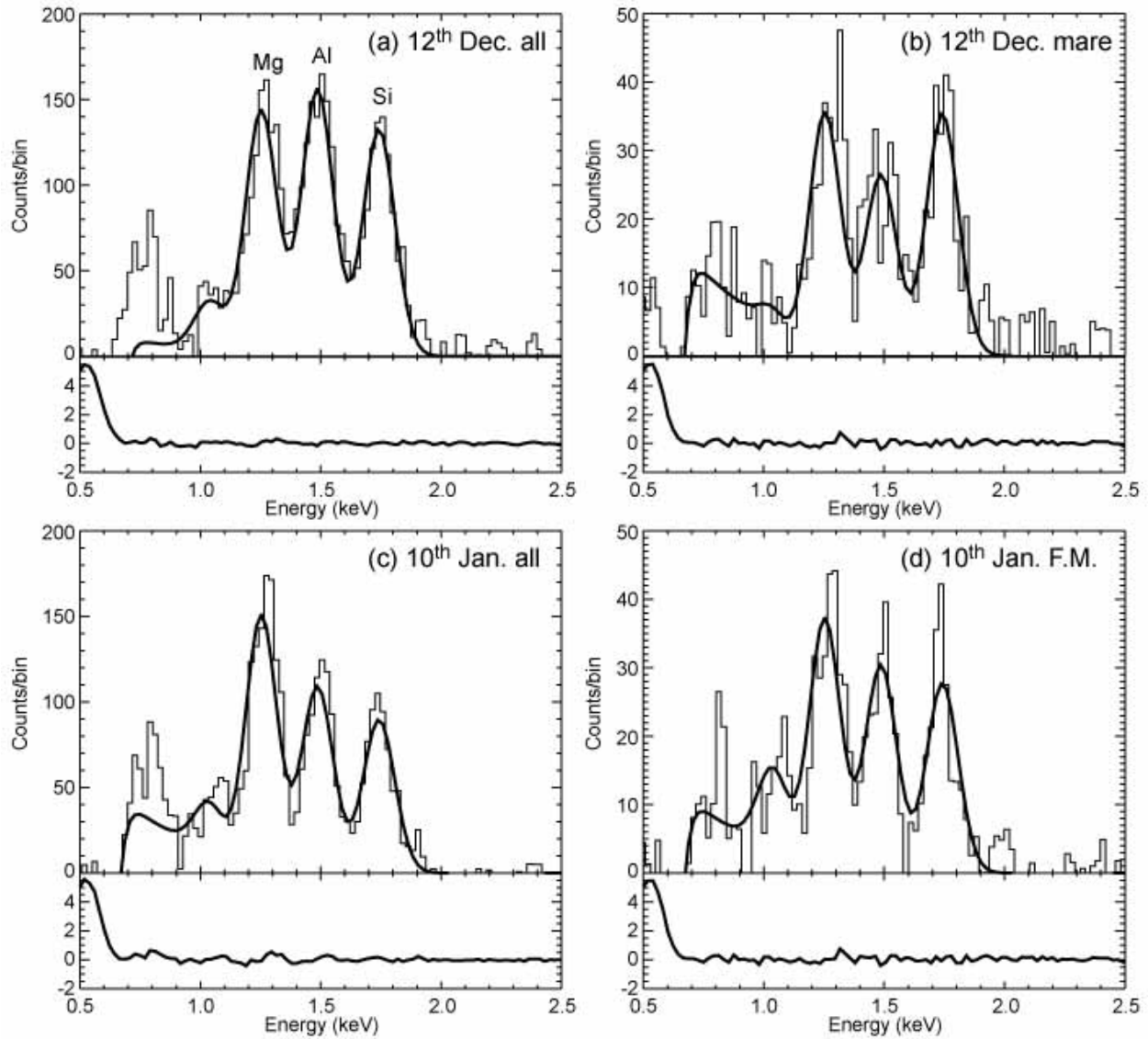


Figure 5. The background-subtracted C1XS spectra for: (a) the whole of the 12th December 2008 flare through Mare Serenitatis, (b) its mare subsection, (c) the entire 10th January 2009 flare through Mare Insularum, Mare Cognitum and Mare Nubium, and (d) the Fra Mauro Formation

subsection. The RAL abundance algorithm fitted model (generated using a 3.1 MK solar model) for each spectrum is also shown (smooth bold line), as well as the weighted residual in each case. The Mg K_{α} (1.25 keV), Al K_{α} (1.49 keV) and Si K_{α} (1.74 keV) peaks are clearly resolved in each case. The more indistinct peak at ~ 1 keV may be partly due to Na K_{α} (1.04 keV), but likely contains a contribution due to scattered solar lines (see Figure 7); the apparent ‘peak’ below 1 keV is a data processing artefact caused by instrument noise.

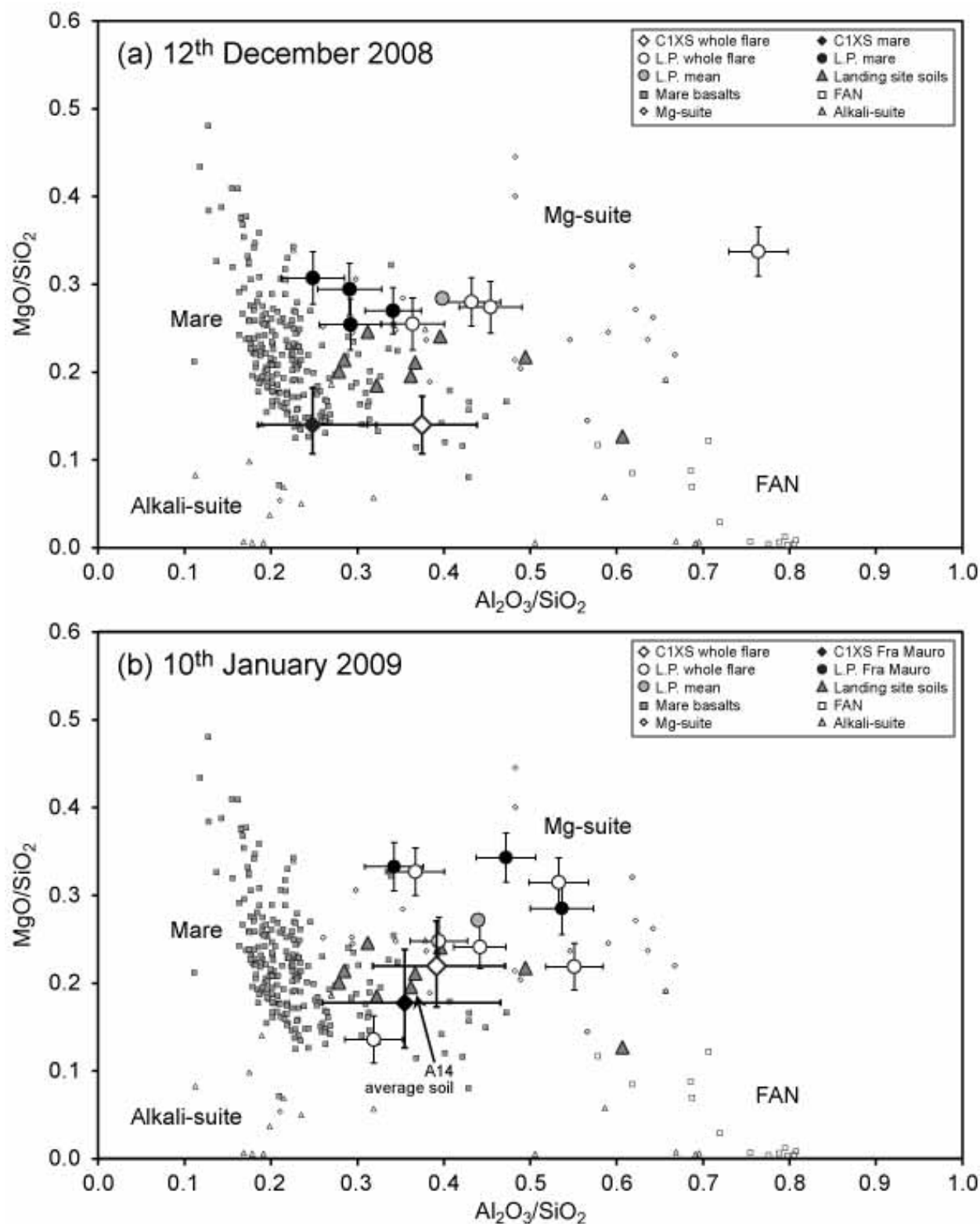


Figure 6. MgO/SiO₂ vs. Al₂O₃/SiO₂ plots showing the C1XS abundance ratios (given in Table 3) derived for the (a) 12th December 2008 and (b) 10th January 2009 flares. For both flares, the

ratio for the whole ground track is shown as well as for the subsection. The error bars on the C1XS values incorporate the 1σ fitting errors as well as the range in values provided by the two flare temperature models. Also shown are: (i) the Lunar Prospector (L.P.) gamma-ray data (Prettyman et al., 2006) for pixels that overlap with the flare ground tracks (as shown in Figures 2 and 3); (ii) the average returned soil compositions (from Table 7.15 of McKay et al., 1991) from each of the Apollo and Luna landing sites; and (iii) sample compositions of various lunar lithologies: the mare basalts, ferroan anorthosites (FAN), Mg-suite and alkali suite (data from Papike et al., 1998 and references therein), whose general fields are marked.

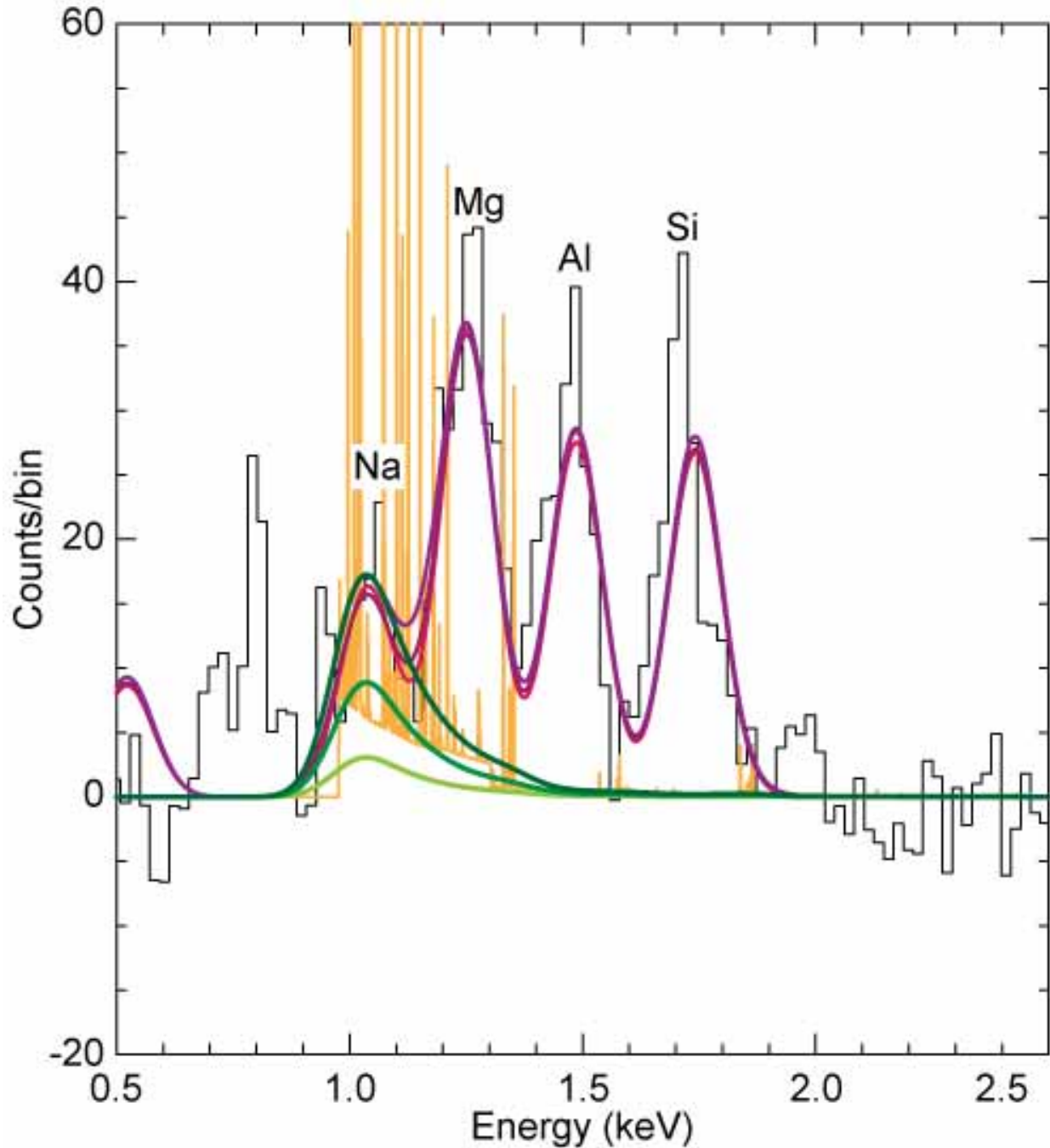


Figure 7. The possible consequences of scattered solar lines on the detection of Na K_{α} at 1.04 keV. The solid black line shows the data for the Fra Mauro region (as shown in Figure 5d). The orange line shows the expected energies and strengths of scattered solar lines, as predicted by the atomdb model (see Section 4); the green lines show these convolved to the C1XS resolution, allowing for a low-energy detector cut-off at 1 keV, with different levels of scattering efficiency from the lunar surface. Here we have used 0.05, 0.15 and 0.30 respectively for this

928 scattering efficiency factor. The red-purple lines are the equivalent fluorescence model
929 predictions for these background levels. Note how scattered solar lines may mimic the
930 appearance of lunar Na XRF when the scattering factor is high enough and yet the Mg, Al and Si
931 line strengths are largely unaffected. The apparent ‘peak’ below 1 keV in the actual data is a
932 processing artefact caused by instrument noise.
933