

OBSERVATIONS OF PAST LUNAR LANDING SITES BY THE D-CIXS X-RAY SPECTROMETER ON SMART-1

M. Grande¹, B.J. Kellett², C. Howe², C. H. Perry², B. Swinyard², S. Dunkin², J. Huovelin², L. Alha², L. C. D'Uston⁴, S. Maurice⁴, O. Gasnault⁴, S. Barabash⁵, K. H. Joy^{2,6}, I. A. Crawford⁶, D. Lawrence⁷, V. Fernandes⁸, I. Casanova⁹, M. Wiczorek¹⁰, N. Thomas¹⁶, U. Mall¹¹, B. Foing¹², D. Hughes¹³, H. Alleyne¹³, S. Russell⁵, M. Grady⁵, R. Lundin⁴, D. Baker¹⁴, C. D. Murray¹⁵, J. Guest⁶, A. Christou¹⁷

¹ Institute of Maths and Physics, University of Wales Aberystwyth, Penglais, Aberystwyth, Wales, SY23 3BZ UK e-mail: M.Grande@aber.ac.uk, Planets and Space Plasma Group, ² Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK, ³University of Helsinki Observatory, Finland, ⁴CESR, CNRS/UPS – France, ⁵IRF, Kiruna, Sweden, ⁶UCL-Birkbeck, London, UK, ⁷Los Alamos National Lab, USA, ⁸University of Coimbra, Portugal, ⁹UPC, Barcelona, Spain, ¹⁰Institut de Physique du Globe de Paris, France, ¹¹MPAE, Lindau, Germany, ¹²ESTEC, Netherlands, ¹³Sheffield University, UK, ¹⁴LASP, Colorado University, USA, ¹⁵QMUL, London, UK, ¹⁶University of Bern, Switzerland, ¹⁷Armagh University, UK.

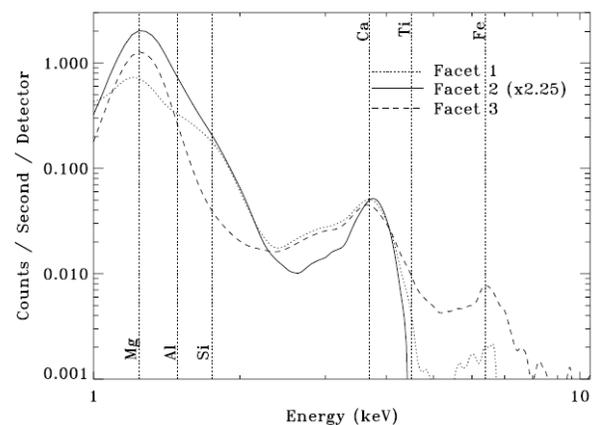
Introduction The SMART-1 mission has recently arrived at the Moon. Its payload includes D-CIXS, a compact X-ray spectrometer [1], [2] SMART-1 is a technology evaluation mission, and D-CIXS is the first of a new generation of planetary X-ray spectrometers. Novel technologies enable new capabilities for measuring the fluorescent yield of a planetary surface or atmosphere which is illuminated by solar X-rays. During the extended SMART-1 cruise phase, observations of the Earth showed strong argon emission, providing a good source for calibration and demonstrating the potential of the technique. At the Moon, our initial observations show a first unambiguous remote sensing of calcium in the lunar regolith. Data obtained are broadly consistent with current understanding of mare and highland composition. Ground truth is provided by the returned Apollo and Luna sample sets.

Observations: In March, 2005, the SMART-1 spacecraft reached its nominal lunar orbit, and we began full commissioning for lunar operations. During the pre-commissioning period in mid-January, 2005, observations of the lunar surface were made which coincided with the occurrence of several major M and X class flares. This opportunity provided an excellent chance to observe spatially localized fluorescence from the lunar surface. X-ray fluorescent elemental lines from the lunar surface are detected by all three facets of D-CIXS while the XSM instrument observes the input solar spectrum.

At the end of this interval, a long duration M-class solar flare began at 06:00 UTC on the 15th of January, 2005. The flare lasted for more than 1 hour but only ~30 minutes corresponded to D-CIXS observations. At this time SMART-1 was orbiting over the Moon's near-side eastern limb from about the equator, traveling northwards. As SMART-1 flew north, its altitude was also increasing from around 2100 km at 06:00 to ~3100 km at 06:35. Due to the nature of SMART-1's orbit and thermal dynamics, the spacecraft was performing a mid-orbit slew (rotation), and so D-CIXS's three facets had different surface ground tracks during

the observation of interest. However, this variability in footprints was very fortuitous as the instrument FOVs included areas of both mare basalt and highland lithologies, which have different and recognizable elemental signatures. Facet 1 (thin Al-filter, 12° FOV) was oriented throughout the observation toward highland areas to the north-east of Mare Crisium. Facet 3 (Mg-filter, 12° FOV) had a ground track that crossed Mare Crisium. Due to the 12° FOV and the 2100 km altitude, the facet 3 footprint always contains a mixture of mare and highland regions. The footprint of facet 2 (thin Al-filter, 8° FOV) encompassed the regions between the two facets shown and covered a mixture of mare and highland regions but with a smaller signal due to its narrower FOV.

Fig. 1 shows the particle background corrected spectra from summed data of the 3 D-CIXS facets for the interval 06:00 UTC to 06:35 UTC. Separate facet spectra have been derived by co-adding data from detectors. Essentially, elemental lines seen in the three different facet spectra represent an averaged geochemical signature from the areas covered by the D-CIXS ground tracks.



The spectra shown in figure 5 indicate that low-energy lines (Mg: 1.25 keV, Al: 1.49 keV and Si: 1.74 keV) are observed in detectors from Facet 1 and 2 (Al-filter). Detectors in Facet 3 are covered by a Magne-

sium filter which was designed to attenuate the signal from Al and Si X-rays, and so in the Facet 3 spectrum Mg is the only significant low-energy peak detected. Data taken from the Facet 3 spectrum also show a clear Fe peak at around 6.4 keV which is interpreted to be related to fluorescence from Mare Crisium (see below). All three facets clearly show the detection of a Ca emission peak at ~ 3.69 keV. Although inferences about the distribution of Ca in the lunar crust have been made indirectly from neutron and gamma ray measurements [3], this observation represents the first ever unambiguous remote sensing of Ca on the Moon.

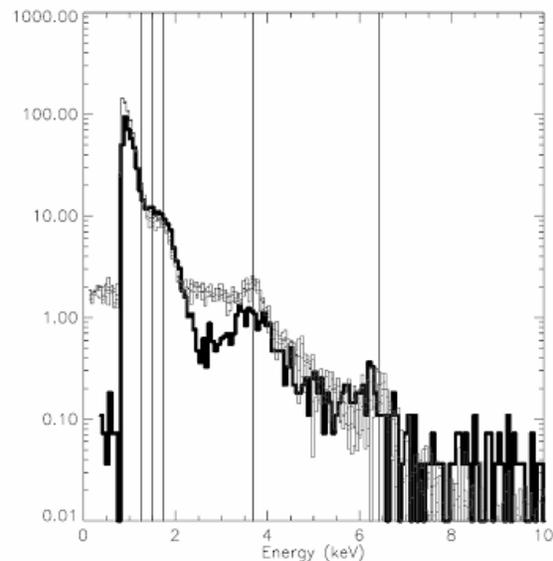
Discussion: The areas of the lunar surface observed during the flare of January 15 include Mare Crisium, and highlands to the north and east. The basaltic lavas of Mare Crisium, which appear dark in, are iron-rich owing to high modal abundances of mafic minerals (principally pyroxene). In contrast, the adjacent highlands are expected to be anorthositic (i.e., composed largely of the mineral plagioclase), and thus iron poor but relatively enriched in calcium and aluminium. Some 'ground truth' is provided by samples collected at the Luna 20 and 24 landing sites, both of which were located within the footprint of facet 3 during these observations.

Remote sensing by *Clementine* [4] and *Lunar Prospector* [5] suggests that the Soviet Luna 24 and Luna 20 iron abundances are reasonably representative of the Mare Crisium basalts, and the adjacent highlands, respectively. These remote sensing data also suggest that the highlands north and east of Crisium, are more anorthositic (i.e. poorer in Fe and richer in Ca) than those immediately adjacent to the Crisium basin and which were sampled by Luna 20.

These expectations are confirmed by the D-CIXS data shown in Figure 1, when facet 3 was over the centre of Crisium and facet 1 was observing the highlands approximately 900 km to the north (material apparently similar to that of the highlands of the Luna 20 landing site). As expected, the Fe flux is strongly enhanced over Crisium, while Ca is somewhat enhanced over the highlands. Moreover, although there is strictly no ground truth available for the facet 1 footprint, the greater variability of Fe relative to Ca between mare and highland regions apparent in Fig. 6 is explicable in terms of the Luna 20 and 24 results presented in Table 2: while Fe is almost three times as abundant in the Crisium basalts than in the adjacent highlands, the Ca abundance is only some 20% less. Essentially the same trend is obtained by comparing the Fe and Ca Lunar Prospector data [3], which imply a factor of 2 difference in Fe, but less than a 10% difference in Ca, between these two footprints.

Figure 2 shows a comparison of a spectrum obtained close to the Apollo 12 site, with a modelled spectrum,

derived from averaged Apollo 12 soil compositions [6]. The match between data (black line) and model (grey) is reasonable, with the exception of the low energy continuum, where the model clearly needs refinement.



Conclusions: The instrument demonstrates the capability of this method to perform X-ray fluorescence measurements of the Moon. A number of rock forming elements have been successfully detected from the Moon during solar flare events, and we have made the first unambiguous remote detection of Calcium from the lunar surface. For more detail see Grande et al 2007 [7]. All of this has been achieved during solar minimum and proves that the technique will be highly suitable for the upcoming Chandrayaan-1 mission [2]), when the mission will take place during the rising phase of the solar cycle, and for which it forms part of the core payload.

References

- [1] Grande, (2001) *Earth Moon And Planets*, Vol 85-6, pp 143-152).
- [2] Grande et al., (2003), *Planet. & Sp. Sci.*, **51** (6), 427.
- [3] Prettyman et al, *33rd LPS XXXIII* #2012.
- [4] Bussey & Spudis (2000), *JGR- Planets*, 105, 4235-4243.
- [5] Lawrence et al (2002) *JGRPlanets*, 107, (#E12), 5130, 10.1029/2001JE001530, 2002.
- [6] Haskin and Warren. 1991. *The Lunar Sourcebook*. Eds. Heiken [7] Grande et al (2007), in press *Planet. & Sp. Sci* 2006.