X-ray Solar Monitor (XSM) -a stellar X-ray spectroscope of the Sun onboard SMART-1

Mikko Vaananen[1], Lauri Alha[1], Juhani Huovelin[1], Pasi Hakala[1], Keijo Hamalainen[2], Jarkko Laukkanen[2], Karri Muinonen[1], Osmi Vilhu[1]
[1]*Observatory, P.O. Box 14 FIN-00014 University of Helsinki, Finland,* [2]*Division of X-Ray Physics, P.O.B. 64, Dept of Physical Sciences, FIN-00014 University of Helsinki, Finland*

April 12, 2005

Abstract. SMART-1 was launched on 27 September 2003 from Kourou, French Guiana, and the instruments onboard are now scientifically operational. XSM provides a 52° field of view in the energy range of 1-20 keV with an energy resolution of 338 eV at 6 keV. We have cross calibrated XSM with GOES and RHESSI, and the fidelity of XSM data has been certified. XSM now offers data that may be used for independent spectral fitting science as well as complementary data to other solar instruments.

Keywords: abundances, corona, element, sun, photosphere, SMART-1, X-ray, XSM, RHESSI, GOES

1. Introduction

The Sun is characterised by high variability in its X-ray emission. This variability is attributed to flares that are defined as short duration X-ray bursts. The common belief is that the flares are caused by magnetic reconnection of plasma on the surface of the Sun and the corona. One of the principal explanations for the occurrence of flares is the existence of closed plasma loops on the Sun. When these loops short-circuit one another, the loops will explode, releasing its electromagnetic energy.

XSM provides X-ray measurements for independent solar and stellar science. The concurrent observations of XSM with other solar instruments can be used to make the solar-stellar connection in a variety of research problems. XSM coupled with a solar imaging instrument provides a test bed for developing stellar physics in our solar system, which can later be applied in space observatory missions such as Chandra and XMM-Newton. XSM may also be used independently in spectral fitting science of the Sun due to its high spectral resolution.

XSM has recorded half a million seconds of scientific data during its 15 months of operation. SMART-1 spacecraft was captured to a lunar orbit on 15th of November 2004 powered by an electric propulsion system (EPS). The lunar orbiting phase was scheduled to last until summer 2005, for details of SMART-1, please see (Foing, 2003). In addition to existing and scheduled data, a mission extension application has been approved in ESA for an additional year, starting at fall 2005. The outlook for using the existing data and the pending time of operation appears promising and we extend an open invitation to seize the opportunities provided by XSM.

2. Scientific Objectives & Design Considerations

Sun is especially active in the soft X-ray band and XSM is designed to record spectra in the 1-20 keV range with a resolution of 338 eV at 6 keV. The spectral range and resolution are suited to discovering new aspects of the Sun by spectral fitting science. Emission models may be fitted with the observed spectrum, and from these emission models it is possible to deduce physical characteristics of the Sun. For example, it is possible to track the temperature, elemental abundances and emission measure distributions of the plasma during a flare. As figure 1 shows, the XSM spectral range is well suited for complementary observations with RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) and GOES (Geostationary Operational Environmental Satellite). The energy ranges overlap considerably to enable cross-calibration and cross-checking between instruments, and also cover different complementary ranges. The binning period of 16s is sufficiently short for most spectral fitting science and complementary observations, as RHESSI rotates with a period of approximately four seconds.

Another ongoing current research problem concerns the spatial size of flares on stars. Various solar instruments, for example RHESSI (Lin, 2002), can be used to image the size of flares on the Sun. On the other hand, several methods for predicting the size of flares from spectroscopic observations exist. For example (Reale, 1997) uses a temperature-emission measure trajectories to predict the size of flaring plasma loops. XSM sees the Sun as a star, which gives rise to the opportunity to iterate this mathematical model of stellar physics with real 'stellar' observations of the Sun. The correctness of the model can be inspected with a solar imaging instrument, like RHESSI. The eventual outcome should be a general spectroscopic method of predicting flare sizes in other Sun-like stars. We have conducted an ESO (European Southern Observatory) campaign to identify such stars for future XMM-Newton or Chandra observations, aimed at testing stellar flare models developed with the solar instruments.

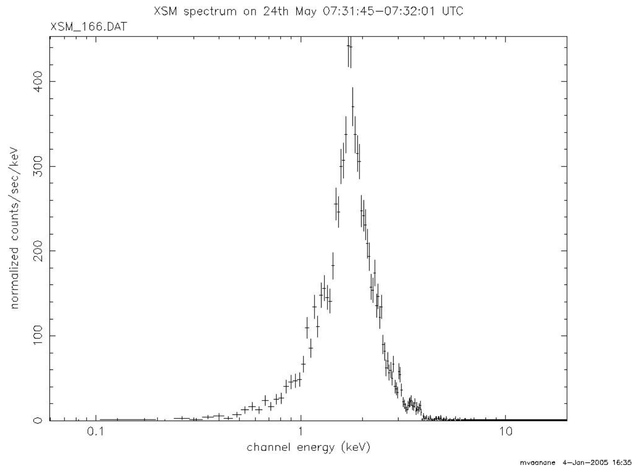

Figure 1. XSM records the solar spectrum between 1-20 keV, in contrast to GOES in the range of 1.55-24.8 keV and RHESSI 3keV-17MeV.

3. Instrument & Spacecraft

The XSM sensor box of aluminium contains a HPSi diode, a Peltier cooler, pre-amplifiers, shaping amplifiers, and a small shutter mechanism. The detector is based on a 500 μm HPSi PIN diode, mounted on a ceramic substrate. The detector system has a 1 cm circular Be-window of 25 μm thickness. For technical details, please see (Huovelin, 2002). Detectors of this type are known to be stable over time. XSM is also equipped with an inflight calibration source attached to the shutter door. The calibration source consists of a ^{55}Fe source that is coated with a 5 μm Ti foil.

4. Mission Operations & Ground Data Systems

In principle solar X-ray measurements can be made at all times when the Sun is in FOV of XSM. The measurements are calibrated in two ways. There is an inflight calibration source on board XSM, attached to the shutter door. Calibration can thus be performed when XSM is not observing the Sun, when the shutter door is closed. The data includes frequent calibration spectra. We can also cross calibrate XSM measurements with other instruments, such as GOES and RHESSI in the overlapping energy ranges, as shown in the results.

The data is processed to FITS (Flexible Image Transport System) files, and a separate response matrix and an ancillary response matrix

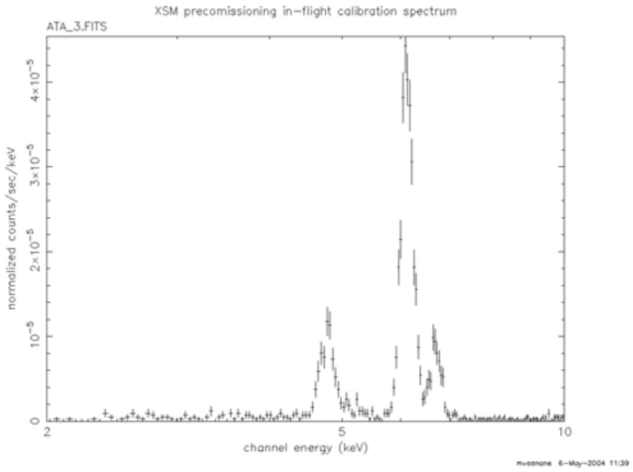

Figure 2. Inflight calibration spectrum of XSM, showing emission lines of 4.508 and 4.932 keV (Ti) and 5.895 and 6.492 keV (Mn).

are computed and provided for each data set. The data contains spectra binned at 16 seconds. The response matrix contains the response of the detector system. The ancillary response matrix takes into account the position of the Sun in the field of view of XSM. Details of the data reduction process will be made available in a future publication in Nuclear Instruments and Methods or Planetary & Space Science by Alha et al. Currently the data can be used with XSPEC, the default stellar spectroscopy package by LHEASOFT/GSFC/NASA (Goddard Space Flight Center). In addition, plans are underway to provide XSM data in an SSWIDL/OSPEX (Solar Software Interactive Data Language)/(Object Spectral Executive) readable format, the default solar spectroscopy package used by RHESSI and other solar instruments.

Data is publicly available starting from July 2005 from the planetary science data archive (PSA) of ESA, at http:/www.rssd.esa.int/PSA.

5. First Results

The obtained inflight calibration spectrum is shown in figure 2. We have fitted a model containing the terrestrially measured gaussian lines of the calibration source and can thus verify the in-flight energy scale of the detector to operate with satisfactory fidelity. The light curve of XSM on 24th of May 2004 in figure 3 is readily comparable with that of GOES in figure 4. The light curves display that both intruments seem to be working coherently in terms of relative fluxes.

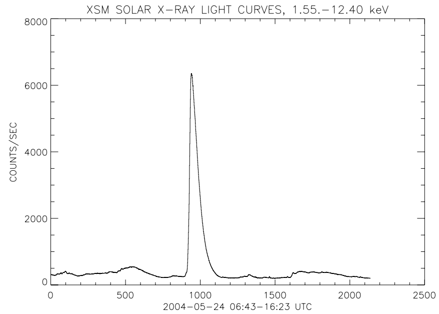

Figure 3. The XSM lightcurve to be compared with figure 4

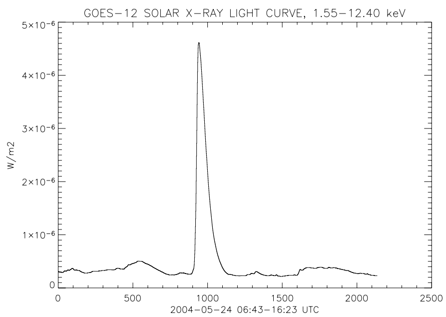

Figure 4. The GOES lightcurve to be compared with figure 3

Table I provides a comprehensive list of all XSM-GOES calibrations performed thus far in chronological order. The XSM flux calibrations were performed with XSPEC, using the vRaymond model occasionally complemented by a gaussian at 2.2 keV. GOES fluxes are available from the Space Environment Center (http://www.sel.noaa.gov/). We used 1-minute GOES data and 16 second XSM data to derive sample means and sample deviations for 5-minute intervals listed in Table I. XSM has recorded smaller absolute fluxes than GOES, which may be related to sensitivity issues of the two instruments. The insensitivity of XSM above 4keV could account for the 10-40% differences in flux levels, for the few points where errors do not overlap. Figure 5 displays that this difference seems time stable throughout the mission so far, the only exception being 29th of December, where XSM recorded higher fluxes than GOES that could not be explained by the error limits of measurement.

XSM did saturate during the 15th January 2005 M8.6 flare, and the flux level of $8.31{*}10^{-6}\ W/m^2$ was the highest we could measure reliably. The flux level of $3.11 * 10^{-8}\ W/m^2$ on the 5th of July 2004 is the lowest

Table I. Comprehensive calibration list of absolute fluxes of GOES and XSM measured in the 1.55-12.40 keV band during 5 minute periods in chronological order from April 2004 to January 2005. March and October of 2004 had no scientific data. Units are minutes and W/m^2.

Interval	time	GOES flux	GOES error	XSM flux	XSM error
1	03:01-06 26/4/2004	$7.75 * 10^{-7}$	$0.69 * 10^{-7}$	$6.97 * 10^{-7}$	$0.85 * 10^{-7}$
2	19:35-40 5/5/2004	$8.23 * 10^{-8}$	$0.14 * 10^{-8}$	$6.52 * 10^{-8}$	$0.19 * 10^{-8}$
3	7:29-34 24/5/2004	$3.22 * 10^{-7}$	$0.07 * 10^{-7}$	$2.38 * 10^{-7}$	$0.08 * 10^{-7}$
4	11:04-09 24/5/2004	$4.46 * 10^{-6}$	$0.15 * 10^{-6}$	$3.66 * 10^{-6}$	$0.52 * 10^{-6}$
5	05:42-47 16/6/2004	$5.94 * 10^{-7}$	$0.25 * 10^{-7}$	$2.78 * 10^{-7}$	$0.09 * 10^{-7}$
6	20:25-30 5/7/2004	$3.43 * 10^{-8}$	$0.01 * 10^{-8}$	$3.11 * 10^{-8}$	$0.11 * 10^{-8}$
7	05:31-36 31/7/2004	$4.63 * 10^{-7}$	$0.36 * 10^{-7}$	$4.22 * 10^{-7}$	$0.44 * 10^{-7}$
8	5:26-31 25/8/2004	$6.23 * 10^{-7}$	$1.15 * 10^{-7}$	$5.70 * 10^{-7}$	$1.29 * 10^{-7}$
9	20:51-56 13/9/2004	$7.07 * 10^{-7}$	$0.03 * 10^{-7}$	$6.07 * 10^{-7}$	$0.08 * 10^{-7}$
10	00:26-31 1/11/2004	$3.99 * 10^{-7}$	$0.08 * 10^{-7}$	$3.37 * 10^{-7}$	$0.10 * 10^{-7}$
11	22:01-06 29/12/2004	$5.11 * 10^{-7}$	$0.08 * 10^{-7}$	$6.36 * 10^{-7}$	$0.19 * 10^{-7}$
12	05:57-6:02 15/1/2005	$7.35 * 10^{-6}$	$1.19 * 10^{-6}$	$8.31 * 10^{-6}$	$1.47 * 10^{-6}$
13	6:21-26 20/3/2005	$1.18 * 10^{-7}$	$0.03 * 10^{-7}$	$1.30 * 10^{-7}$	$0.05 * 10^{-7}$
14	12:49-54 4/4/2005	$1.89 * 10^{-7}$	$0.60 * 10^{-7}$	$1.66 * 10^{-7}$	$0.67 * 10^{-7}$

flux we have been able to measure so far. Over the entire recorded dynamic range GOES has recorded slightly higher fluxes, apart from the highest flux measurement where the error margins overlap considerably. The insensitivity of XSM above 4keV is likely to account for this observed difference as well.

Table II displays the XSM/GOES flux ratios of Table I measurements and their errors. These ratios are plotted as a function of XSM flux in figure 6. The flux ratio seems to be between 1.21 and 0.52 which are the lower and upper limits of the highest and lowest ratio measurements, respectively. There appears to be no flux dependence with this ratio, and XSM seems flux stable over its dynamic range.

Absolute flux calibrations of XSM were done with both RHESSI and GOES, but in different energy bands due to the differences in sensitivities. Table III displays the two and only available clibrations of both instruments. The number of calibration targets is severely limited by the availability of data from both instruments, namely XSM. The dynamic range of calibrations is also limited, as XSM cannot detect small flux levels above 4keV.

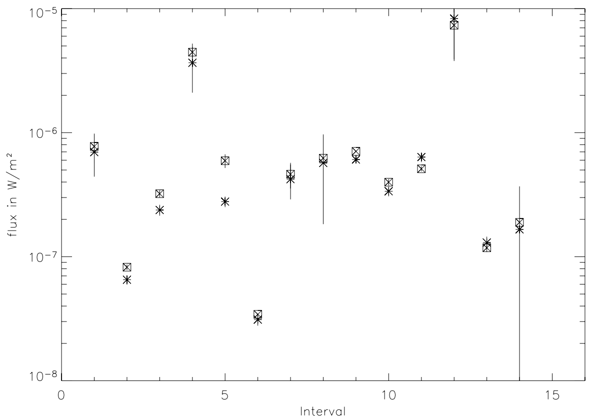

Figure 5. GOES and XSM calibrations Table I from April 2004 to April 2005. The error bars are 3 times the flux error (3-sigma rule). Crossed boxes are GOES fluxes, whereas crossed points are XSM fluxes.

Table II. Comprehensive calibration list of flux ratios of XSM and GOES measured in the 1.55-12.40 keV band during 5 minute periods in chronological order from April 2004 to January 2005. March and October of 2004 had no scientific data.

Time	XSM/GOES flux ratio	ratio error
03:01-06 26/4/2004	0.90	0.15
19:35-40 5/5/2004	0.79	0.03
7:29-34 24/5/2004	0.74	0.04
11:04-09 24/5/2004	0.82	0.15
05:42-47 16/6/2004	0.47	0.05
20:24-29 5/7/2004	0.90	0.04
05:30-35 31/7/2004	0.96	0.13
5:25-30 25/8/2004	0.82	0.29
20:50-55 13/9/2004	0.86	0.01
00:25-30 1/11/2004	0.83	0.04
22:00-05 29/12/2004	1.24	0.03
05:56-6:01 15/1/2005	1.27	0.25
6:20-25 20/3/2005	1.09	0.06
12:48-53 4/4/2005	0.90	0.66

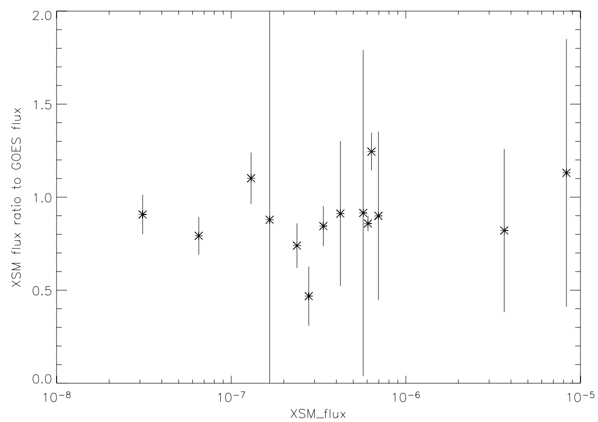

Figure 6. GOES and XSM flux ratios plotted as a function of XSM flux (Table II).The error bars are 3 times the flux error (3-sigma rule)

Table III. Absolute fluxes of RHESSI and XSM measured in the 5.0-8.0 keV band during a 5 minute flare period. Units are minutes and W/m^2.

Interval	time	RHESSI flux	RHESSI error	XSM flux	XSM error
1	26/4/2004 3:01:05-3:06:05	$8.20 * 10^{-9}$	$1.91 * 10^{-9}$	$4.82 * 10^{-9}$	$1.85 * 10^{-9}$
2	1/11/2004 0:26:00-0:31:00	$1.46 * 10^{-9}$	$0.26 * 10^{-9}$	$3.22 * 10^{-10}$	$1.61 * 10^{-10}$

XSM and RHESSI were cross calibrated for the two flares in the 5-8 keV band. This is the band where the sensitivites of the two instruments are most similar (Hugh Hudson, Richard Schwartz, private communication). We used 1-minute RHESSI data and 16 second XSM data to derive sample means and sample deviations for 5-minute intervals listed in Table III. The background was subtracted for RHESSI, whereas XSM background is negligible. Both fluxes were calculated with a thin target bremsstrahlung model, using 'bremss' in XSPEC for XSM and 'vth' in OSPEX for RHESSI. The errors are standard deviations, and thus in both calibrations the fluxes are within 3 standard deviations of each other.

6. Summary

XSM has been operating satisfactorily and 257 hours of scientific data has been collected from March 2004 to March 2005. The operation time of XSM is partly affected by the schedule and situation of its master instrument D-CIXS, to which it provides calibration data and from which it receives its power and control signals (Huovelin, 2002).

The cross calibrations of XSM with other instruments revealed that the light curves and relative fluxes match quite nicely with GOES. The absolute fluxes in the band 1.55-12.40 keV match also to within the boundaries of error for most calibrations. XSM and RHESSI fluxes in the 5-8 keV band are within the boundaries of error.

Due to its high spectral resolution, XSM is an excellent instrument for determining elemental abundances in the solar corona. We aim to utilise XSM data extensively in temperature and elemental abundance determinations of the solar corona, and make comparisons with abundances on other stars. A determination of coronal elemental abundance values is to be expected from XSM data within 2005. In addition we intend to utilise the data in monitoring said variables during the flare, and in investigations of size and spectral dependencies of flares. A particle physics experiment testing the generation of axions in the Sun is also being planned.

XSM data is publicly available starting from July 2005 from the planetary science data archive of ESA, at http:/www.rssd.esa.int/PSA.

Acknowledgements

This work was made possible by the continuing efforts of all ESA staff and other instrument teams involved in the mission. We are especially grateful to Bernard Foing at ESA and Manuel Grande at Rutherford Appleton Laboratory in the UK. Acknowledgements are in order also for the entire RHESSI -team for their important and enduring assistance. In particular we would like to extend our thanks to Brian Dennis, Richard Schwartz, Ken Phillips, Kim Tolbert GSFC/NASA and Hugh Hudson, Gordon Hurford, Robert Lin and Jim McTiernan of Space Sciences Lab at University of California at Berkeley. This work was funded by the following grants: Vaisala foundation 2003 PhD grant, research grants 74882 and 211061 of the Finnish Academy of Sciences.

References

Huovelin, J. et al. *The SMART-1 X-ray solar monitor (XSM): calibrations for D-CIXS and independent coronal science. Planetary and Space Science*, 50:1345-1353, 2002.

R.P. Lin et al. *The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). Solar Physics*, 210:3-32, 2002.

Reale et al. *Determination of the length of coronal loops from the decay of X-ray flares.* In *Astron.Astrophys.*, 325:782-790, 1997.

B.H. Foing et al. *SMART-1 mission to the moon: Technology and science goals. Advances in Space Research*, Volume 31, Issue 11, p. 2323-2333., 2003.