Chandrayaan-2
Solar X-ray Monitor (XSM)

Data Analysis Guide

Version 1.1
June 2021

Prepared by

Mithun N. P. S. & Santosh Vadawale

Email: xsmpoc@prl.res.in

Physical Research Laboratory
Ahmedabad

Document Revision History

Version	Date	Comments
0.1	15 Oct 2019	Initial version
0.5	20 Aug 2020	Updated based on changes in XSMDAS v1.0
1.0	10 Dec 2020	First release version; for XSMDAS v1.1; included walkthrough
1.1	28 Jun 2021	Updates with XSMDAS v1.2, included description of python tools

Contents

1 Introduction

Solar X-ray Monitor (abbreviated as XSM) on-board India's Chandrayaan-2 mission is designed to carry out broadband spectroscopy of the Sun from lunar orbit. It observes the Sun as a star and measures the spectrum every second in the soft X-ray band of 1 – 15 keV with an energy resolution better than 180 eV at 5.9 keV. Although the primary objective of XSM is to provide the incident solar spectrum for X-ray fluorescence spectroscopy experiment on Chandrayaan-2 orbiter that aims to generate global elemental abundance maps of the Moon, observations with XSM can independently be used to study the Sun.

This document serves as guide for the analysis of data obtained with XSM. Readers are reffered to the following references for description of XSM instrument, ground and in-flight calibration, data processing, and on-board performance.

1. M. Shanmugam *et al.*, "Solar X-ray Monitor Onboard Chandrayaan-2 Orbiter", Current Science, 118(1):45 2020.
   DOI: 10.18520/cs/v118/i1/45-52 arXiv:1910.09231

2. N. P. S. Mithun *et al.*, "Solar X-ray Monitor On Board the Chandrayaan-2 Orbiter: In-flight Performance and Science Prospects", Solar Physics, 295 (139), 2020.
   DOI: 10.1007/s11207-020-01712-1 arXiv:2009.09759.

3. N. P. S. Mithun *et al.*, "Ground Calibration of Solar X-ray Monitor On Board the Chandrayaan-2 Orbiter", Experimental Astronomy, 51:1, 2021.
   DOI: 10.1007/s10686-020-09686-5 arXiv:2007.07326.

4. N. P. S. Mithun *et al.*,"Data Processing Software for Chandrayaan-2 Solar X-ray Monitor", Astronomy and Computing, 34:100449, 2021.
   DOI: 10.1016/j.ascom.2021.100449 arXiv:2007.11371.

This guide gives an overview of the XSM data products, description of the XSM Data Analysis Software (XSMDAS) for generation of calibrated products from the raw data, overview of higher level analysis tools for XSM data products, specific analysis cases, and specific notes on XSM analysis in the subequent sections. More details on the data archive and file formats are available in the Chandrayaan-2 XSM Data Products and Archive Software Interface Specification Document available here.

2 XSM Data Files

Users can view the XSM light curve plots in the XSM POC website at:

`https://www.prl.res.in/ch2xsm/`

File type	Data level	`extn`	Content
Science data file	raw	`fits`	Raw data frames
HK parameter file	raw	`hk`	HK parameter
Sun angle file	raw	`sa`	Observation geometry parameters
GTI file	calibrated	`gti`	Good Time Intervals
Spectrum file	calibrated	`pha`	Time series spectrum (1s)
Light curve file	calibrated	`lc`	Light curve for full energy range (1s)

Table 2.1: XSM archive file content summary.

This website is updated with the flux light curves as and when the data becomes available and provides users with the facility to generate and examine plots of required duration. It also hosts other useful information for the users.

The XSM data is archived at ISRO Science Data Archive (ISDA) hosted at ISSDC. XSM public data can be downloaded from ISDA using PRADAN web portal at the following link:

`https://pradan.issdc.gov.in/pradan/`

XSM data is organized as files correponding to each day of observation (UTC). Zip files with data for any available day of observation can be downloaded from this website.

These zip files, having name of the format `ch2_xsm_yyyymmdd_vx.zip`, contain the raw (level-1) and calibrated (level-2) data sets of XSM for the given day of observation. When uzipped, this file generates the following directory structure with root directory being xsm. There will be XML label file associated with each product file which are not shown here.

```
xsm/
  data/
    yyyy/
      mm/
        dd/
          raw/
              ch2_xsm_yyyymmdd_vx_level1.fits
              ch2_xsm_yyyymmdd_vx_level1.hk
              ch2_xsm_yyyymmdd_vx_level1.sa
          calibrated/
              ch2_xsm_yyyymmdd_vx_level2.gti
              ch2_xsm_yyyymmdd_vx_level2.pha
              ch2_xsm_yyyymmdd_vx_level2.lc
```

It is advised that the users unzip multiple data files at the same location on their computer, so that it will be easier to navigate to data for multiple days of observation using the directory structure. The contents of the files are summarized in table 2.1. All files are in FITS format and the spectrum and light curve files follow OGIP standards and are compatible with spectral and timing analysis tools which are part of HEASOFT. Refer Data Products and Archive Interface Specification Document for further details on the file structure.

Calibrated products provided are for a standard set of parameters in the XSM Data Analysis Software (XSMDAS). The standard GTI include all times when the unocculted Sun is within the full FOV (±38°) of XSM and also with the instrument health parameters within recommended ranges. Spectrum file provided includes a time series of spectra with one second cadence where the counts are corrected for effective area variation with incidence angle such that they correpond to on-axis observations with XSM. Response file name (.rsp which include on-axis effective area) to be used along with this is recorded in the header and the response file is available in the CALDB distribution. It is recommended that OSPEX users take this calibrated spectrum to load following the instructions in a subsequent section. XSPEC users are advised to generate spectrum in raw counts along with ARF using *xsmgenspec* module of XSMDAS for the desired duration. The standard light curve is for the full energy range of 1 – 15 keV with a binsize of one second.

The XSM Data Analysis Software (XSMDAS) and the associated Calibration Database (CALDB) are made available so that users can generate level-2 products from level-1 data according to their requirements.

3 XSM Data Analysis Software

XSM Data Analysis Software (XSMDAS) carries out processing of level-0 data to level-1 and level-2 data products. XSM data archive includes raw level-1 data and calibrated level-2 products for standard set of parameters as described above.

The distribution of XSMDAS provided to the users in meant for generation of calibrated level-2 data products such as spectrum and light curves of desired binning parameters (different from that of standard level-2 products provided) from the XSM raw level-1 data sets. XSMDAS consists of different modules to carry out each task to generate each of the level-2 files. It also includes IDL script meant for loading XSM level-2 data into OSPEX. Installation instructions for XSMDAS are given below.

3.1 Installation

Download the installation package of XSMDAS and CALDB from `https://pradan.issdc.gov.in/pradan/` and follow the below instructions (available in README file within the package) to install.

Pre-requisites

- OS: Linux/Unix (CentOS 7.0+, Ubuntu 14.04+, RHEL 6.5+, Fedora 20.0+, SLED 11.0+, OS X 10.13+)
- Compiler: gcc 4.4+

Installation instructions

- Unzip the installation package `ch2_xsmdas_yyyymmdd_vn.mm.zip` to desired directory:

```
unzip ch2_xsmdas_yyyymmdd_vn.mm.zip
```

The top level directory is named xsmdas

- Setting Environment variables:

  Add following lines to ~/.bashrc

```
export xsmdas= <path to xsmdas directory>/xsmdas
export PATH="$xsmdas/bin:$xsmdas/scripts:$PATH"
export LD_LIBRARY_PATH="$xsmdas/lib/":$LD_LIBRARY_PATH
export PFILES="$PFILES:$xsmdas/pfiles"
```

  where <path to xsmdas directory> to be replaced with the absolute path under which xsmdas directory resides.

  source ~/.bashrc file as:

  . ~/.bashrc

  If the user has installed any other package that uses PIL with PFILES environment defined in /.bashrc, make sure that the other declaration are appending the pfile paths to the environment variable.

  If the user has HEASOFT installation, it is recommended that the command to source the initialization script of HEASOFT, commonly aliased as heainit, if included in .bashrc shall be after the above commands. This will create a local copy of Parameter files under $HOME/pfiles.

- Installation of libraries:

```
cd $xsmdas
./InstallLibs
```

  This will compile cfitsio and pil libraries from source.

- Installation of CALDB:

  Download the caldb zip file provided along with XSMDAS. Unzip the package ch2_xsm_caldb_yyyymmdd.zip to $xsmdas directory as:

```
unzip ch2_xsm_caldb_yyyymmdd.zip -d $xsmdas
```

  The caldb files will be extracted to $xsmdas/caldb directory.

- Compilation:

  Once the libraries are installed compile XSMDAS with

```
cd $xsmdas
make
```

This will generate executables under `$xsmdas/bin` and completes installation. IDL scripts required for OSPEX are present under `$xsmdas/idl`, a README file in the same directory explains its usage. Some additional scripts are provided under `$xsmdas/scripts` and their usage is explained in the next section.

Section 4 provides a complete user guide to the XSMDAS modules and specific use cases of XSMDAS is given in Section 5. Usage of higher level analysis tools like XSPEC and OSPEX with level-2 data products of XSM are given in Section 6. Section 7 provides a walkthrough of XSM data analysis and some important notes an caveats are listed in Section 8.

4 XSMDAS modules and Usage

Figure 4.1 gives the flow chart depicting the sequence of operations of XSMDAS modules or tasks. It shows the input level-1 files in orange boxes and the XSMDAS modules in green boxes which are operated on these level-1 files to obtain standard level-2 products shown in cyan boxes. Apart from the three modules shown in the figure an additional module for adding multiple spectra together is also provided. List of XSMDAS modules and their purpose is given below:

- *xsmgtigen* : Creates Good Time Intervals based on parameters ranges from a filterfile
- *xsmgenspec* : Generates spectrum from Level-1 science data with required parameters
- *xsmgenlc* : Generates light curve with required parameters
- *xsmaddspec* : Addes multiple spectrum files together

To execute a given module interactively, invoke the module in terminal and provide the prompted input parameters. For eg.

```
$ xsmgenspec
```

and then provide the inputs as shown in figure 4.2.

Instead of providing the input parameters interactively, user can provide them as arguments of the for parameterName = parameterValue. For eg.

```
xsmgenspec l1file=xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_level1.fits
specfile=xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_fulldayspec.pha
spectype=time-integrated tstart=0 tstop=0
hkfile=xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_level1.hk
safile=xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_level1.sa
gtifile=xsm/data/2019/09/17/calibrated/ch2_xsm_20190917_v0_level2.gti
```

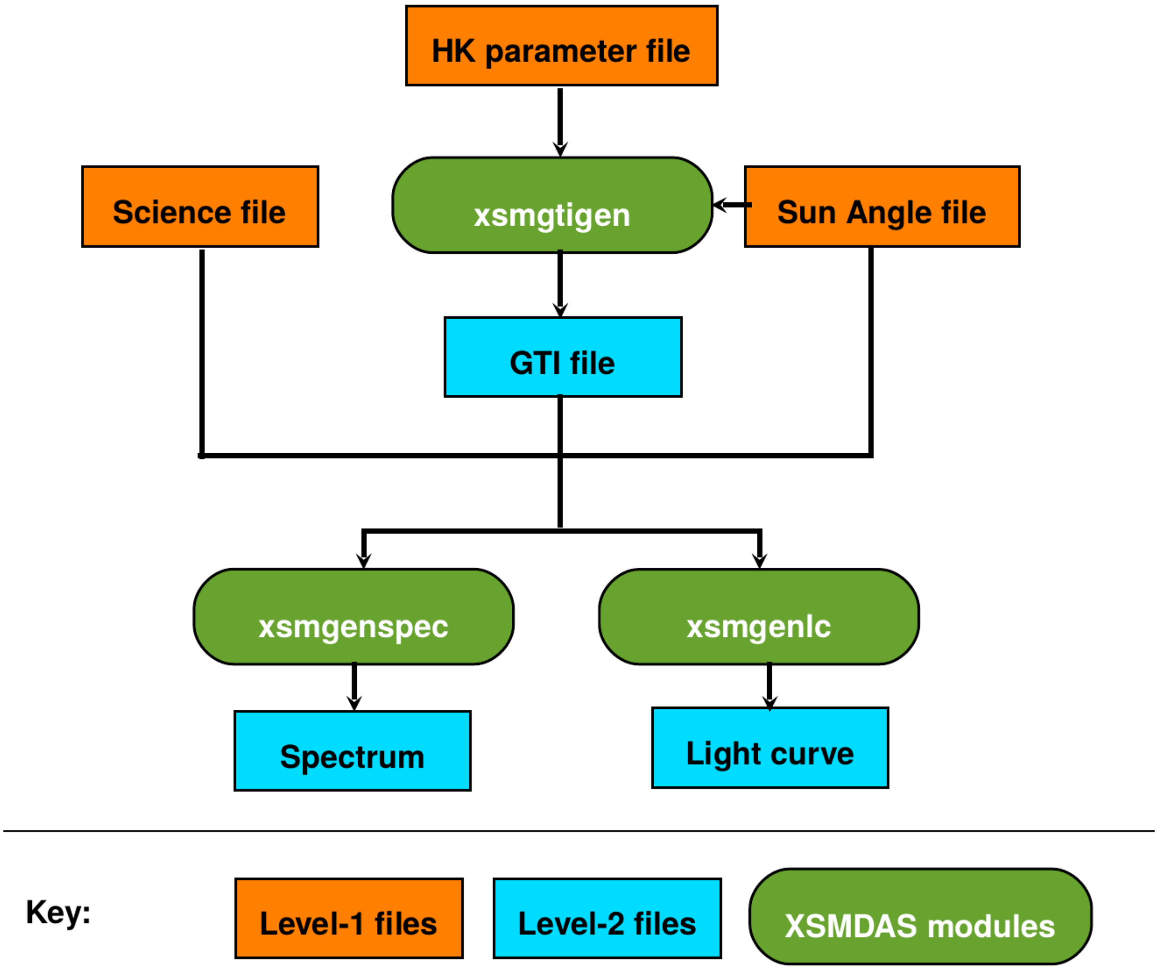

Figure 4.1: Overview of XSM Data Analysis Software work flow

Complete list of parameters for each module are listed in the respective help pages. Note that each module has a set of required parameters which the user will be prompted to provide in interactive mode and a set of optional hidden parameters. Hidden parameters are shown in square brackets [ ] in the help files and will assume default values if not set. These parameters can be set by the user only as command line arguments. It may be noted that inputs to XSMDAS modules does not recognize `~/` for home directory. Environment variables are recognized provided they are given within curly braces like `${HOME}` and `${xsmdas}`.

Help files of XSMDAS can be accessed by the command

```
xsmhelp
```

which will display the complete user manual. To view help for a specific module type

```
xsmhelp moduleName
```

Subsequent sections provide complete usage of each module listing all the available parameters.

```
-----------------------------------------------------------------------
  XSMDAS: Data Analysis Software for Chandrayaan-II Solar X-ray Monitor
                     XSMDAS Version: 1.06
                     Module : XSMGENSPEC
-----------------------------------------------------------------------
Enter Input Level-1 file [] : xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_level1.fits
Enter Output Spectrum file [] : xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_fulldayspec.pha
Enter output spectrum type <time-resolved or time-integrated> [time-resolved] : time-integrated
Enter start time for extracting spectrum [0] :
Enter stop time for extracting spectrum [0] :
Enter HK file [] : xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_level1.hk
Enter Sun angle file [] : xsm/data/2019/09/17/raw/ch2_xsm_20190917_v0_level1.sa
Enter GTI file [] : xsm/data/2019/09/17/calibrated/ch2_xsm_20190917_v0_level2.gti
----------------------------------------------------------------------
```

Figure 4.2: Interactive use of *xsmgenspec*

4.1 xsmgtigen

Purpose

This task finds out intervals of time (GTI) when the HK parameters and Sun angle related parameters are within the ranges specified by a user provided filter file

Parameters

- hkfile : Name of input HK file
- gtifile : Name of output GTI file
- safile : Name of input Sun Angle file
- filterfile : Name of input filterfile specifying ranges of any of the available parameters. See below for format of filter file and available list of parameters. With usesunang=no, any Sun angle related parameter in the filter file will be ignored. Standard filter file is available at `$xsmdas/pfiles/std_filterfile.dat`. This is set as the default input and it should be used in case of no specific requirement. If required to use different range of parameters, create another filterfile as per the format below and provide that as input. Do not edit the standard filterfile.
- usergtifile : Name of optional text file with a user defined GTI. File should contain one time interval per line, providing start and end time. Time should be in MET which is UTC seconds from 2017 Jan 01 0 UTC. Set to - if no user gti selection is needed. Start and stop times of observation in terms of MET are given in level-1 science data header as keywords TSTART and TSTOP.
- [usesunang] : Whether to use Sun Angle file parameters in selection of GTI(Y/N) Need to provide sun angle file as input if usesunang=yes. Default is yes.
- [clobber] : Whether to overwrite existing output files (Y/N). Default is yes

Filterfile format

Filterfile is a plain text file with one entry per line for each parameter. Each line starts with name of the parameter, then number of ranges of this parameter the user wishes to select for GTI followed by minimum and maximum for each of the range. Note that, the time durations when a given parameter is within ANY of the specified ranges will be included in GTI of that parameter and the overall GTI will be intersection of Good intervals for each of the specified parameters.

In case one wishes to keep a minimum value for a parameter and not a maximum, the second entry of the range should be '-'. Similar rule applies for setting maximum threshold for a parameter. In case an entry is made for a parameter in the filterfile, at least one range needs to be specified, this could be '- -' as well, which will result in no selection based on that parameter and result would be identical to case when the parameter is not listed in the filterfile.

See example below:

```
DetTemperature      1   1.7  2.0
MotorIRPos          2   0   0   2   2
HVMonitor           1   1.5   -
```

The above entries in a filterfile will select time ranges when (DetTemperature is between 1.7 and 2.0) and (MotorIRPos eq 0 or MotorIRPos eq 2) and (HVMonitor gt 1.5).

Recommended filterfile (`std_filterfile.dat`) parameters:

```
HVMonitor           1   1.0   -
DetTemperature      1   1.8   -
LV1Monitor          1   3.1   3.4
LV2Monitor          1   1.4   1.6
MotorIRPos          2   0   0   2   2
FrameDiscardFlag    1   0   0
SunTheta            1   -   38
SunFovFlag          1   1   1
SunOccultFlag       1   0   0
```

For most of the standard analysis requirements, there is no need to use a different filter file than this standard filter file. In case of specific reasons to filter the times for analysis based on parameter ranges other than this, users shall create a local copy of filter file with the parameters and ranges defined and this shall be provided as input. Even in that case, the ranges of the following parameters shall be kept as it is.

```
HVMonitor           1   1.0   -
DetTemperature      1   1.8   -
LV1Monitor          1   3.1   3.4
LV2Monitor          1   1.4   1.6
FrameDiscardFlag    1   0   0
```

The usual requirements for using a different filterfile are for generation of background as discussed in Section 4.6 or for generating calibration source spectrum. For selection of background, ranges of the parameters `SunTheta`, `SunFovFlag` will need changes and to select duration of calibration, range of `MotorIRPos` shall be set as 1 to 1 (see below list). Other parameters in the filterfile shall be used only if the user has familiarised with the instrument very well (refer to the publications) and understands the consequences of the selection. It will be useful to see plot the ranges of the parameters from HK or sun angle file before providing their selection ranges in filterfile.

List of all available parameters for filterfile

The expected range of values of bounded parameters are given in brackets. In case of only discrete values taken by a parameter, they are all listed. It may be noted that these are all possible values of the parameters and not the recommended ranges for selection of GTI for science analysis.

- EventCounter : Number of event triggers per second
- EventDetected : Number of detected events per second
- RampCounter : Ramp reset counter
- HVMonitor : High voltage Monitor (0 - 2.5 V)
- DetTemperature : SDD Temperature monitor (0 - 2.5 V)
- TECCurrent : TEC Current monitor (0 - 2.5 V)
- LV1Monitor : +3.3 V monitor (3.2 - 3.4 V)
- LV2Monitor : +1.5 V monitor (1.4 - 1.6 V)
- LLDRefVoltage : LLD reference voltage (0 - 1300 mV)
- TECRefVoltage : TEC reference voltage (0 - 1300 mV)
- MotorControlMode : 0-Auto 1-Manual 2-Forcestep
- MotorOperationMode : 0-IR 1-Counter 2-Step
- MotorSetPos : 0-Open 1-Cal 2-Bewind
- MotorIRPos : 0-Open 1-Cal 2-Bewind

- IRPowerStatus : 0-On 1-Off
- FrameDiscardFlag : 1-Mechanism moving 0-Stationary
- MotorAutoTime : Mechanims auto-movement decision time
- StepModeDir : Direction 0-clock;1-anticlock
- WindowLowerThresh : Event trigger threshold for Be to open movement
- WindowUpperThresh : Event trigger threshold for Open to Be movement
- PileupRejMode : 0-off; 1-on (default)
- PileupRejTime : Pileup rejection dead time (5 or 10 us)
- Ch1Start : Start channel for coarse range 1 for 100 ms data
- Ch1Stop : End channel for coarse range 1 for 100 ms data
- Ch2Start : Start channel for coarse range 2 for 100 ms data
- Ch2Stop : End channel for coarse range 2 for 100 ms data
- Ch3Start : Start channel for coarse range 3 for 100 ms data
- Ch3Stop : End channel for coarse range 3 for 100 ms data
- ULDEvents : Number of events in last channel (saturation)
- SunTheta : Polar angle subtended by Sun wrt XSM
- SunPhi : Azimuth angle of Sun wrt XSM
- SunFovFlag : 1-Sun within XSM FOV 0-Not in FOV
- SunOccultFlag : 1-Sun occulted for XSM 0-Sun not occulted
- RamAngle : Angle between S/C velocity and XSM boresight
- RA : Right Ascension of XSM boresight
- DEC : Declination of XSM boresight
- SunAngRate : Rate of change of Sun angle

4.2 xsmgenspec

Purpose

This task generates time-resolved or time-integrated spectrum from XSM level-1 science data for the desired GTI with the required set of parameters. Output spectrum file is compatible with standard X-ray analysis softwares XSPEC and ISIS. Please refer to the publications mentioned in the references in Section 1 to learn about calibration of XSM, if you wish to use any of the hidden parameters.

Parameters

- l1file : Name of input Level-1 science FITS file
- specfile : Name of output spectrum file
- hkfile : Name of input HK file
- safile : Name of input Sun angle file
- gtifile : Name of input GTI file
- spectype : Type of output spectrum file. Options are time-integrated or time-resolved. In case of time-integrated, integrated spectrum for the observation within specified tstart and tstop will be generated as type-I PHA file. In case of time-resolved, spectrum with time binsize as specified by tbinsize will be generated as type-II PHA file
- tstart : Start time for the output spectrum (should be in Mission Elaspe Time). Default [0] for tstart and tstop will generate spectrum for entire observation data filtered with GTI.
- tstop : Stop time for the output spectrum (should be in Mission Elaspe Time). Default [0] for tstart and tstop will generate spectrum for entire observation data filtered with GTI.
- tbinsize : Time binsize in seconds for generating time-resolved spectrum. Only integer seconds are accepted.
- [genarf] : Whether to generate the ARF file corresponding to the spectrum. This parameter is considered only when chantype=PI and areascal=no. Default is yes.
- [arffile] : Name of output ARF file corresponding to the spectrum. If set to 'default', arf file will have same base name as the output spectrum file
- [areascal] : Whether to apply area scaling to spectrum (Y/N). If set to yes, the spectrum generated will be corrected for relative area differences with Sun angle, it would be spectrum as observed by XSM on-axis. Default is yes. Note that for spectral fitting with XSPEC, it is recommended that the spectrum is generated with areascal=no and genarf=yes.
- [chantype] : Output spectrum channel type - PHA or PI. PHA is instrument channel spectrum and PI (Pulse Invariant) is gain corrected. Default value is PI.
- [gaincorfactor] : Additional gain correction factor to be applied for conversion from PHA to PI. Default value is 1.0. This gain factor would be multiplied with the gain value in CALDB file. If you need to increase the gain by 0.5%, set this parameter to 1.005. To decrease by 0.5%, set to 0.995 and so on. Be careful with the use of this parameter, if you do not know what you are doing, do not use this.
- [offsetcorfactor]: Additional offset correction factor to be applied for conversion from PHA to PI. Default value is 0. This offset in keV will be added to the offset from the CALDB.

- [sourcetype] : In case of chantype=PI, whether the gain correction should be done with source as Sun (illuminating at different positions on the SDD) or and cal (illuminating at center of detector always). Default is Sun.
- [addsyserror] : Whether to add channel-wise systematic errors in the output spectrum (Y/N). If set to yes, SYS_ERR column will have fractional systematic errors for each channel, otherwise it will be set to zero. Note that this is available only in case of PI spectrum. Default is yes.
- [gainfile] : Name of input Gain file. Required only in case of chantype=PI. Default [CALDB] will use gain file from the calibration database
- [eboundsfile] : Name of input ebounds file. Required only in case of chantype=PI. Default [CALDB] will use eboundsfile from the calibration database
- [effareaparfile] : Name of input effective area parameter file. Required only in case of genarf=yes or areascal=yes. Default [CALDB] will use area par file from the calibration database
- [abscoeffile] : Name of input absorption coefficient file. Required only in case of genarf=yes or areascal=yes. Default [CALDB] will use the file from the calibration database
- [syserrfile] : Name of input systematic error file. Required only in case of chantype=PI. Default [CALDB] will use the file from the calibration database.
- [clobber] : Whether to overwrite existing output files (Y/N). Default is yes

4.3 xsmgenlc

Purpose

This task generates light curve from XSM level-1 science data for the desired GTI with the required set of parameters. Light curve with minimum time resolution of 1 second can be generated for any channel range and light curve upto 100ms time resolution can be generated for three pre-defined channel ranges.

Parameters

- l1file : Name of input Level-1 science FITS file
- lcfile : Name of output light curve file
- hkfile : Name of input HK file
- safile : Name of input Sun angle file
- gtifile : Name of input GTI file

- lctype : Type of output light curve - standard or high-res. In case of standard light curve in any channel range with integer second time resolution is available and in case of high-res, the time resolution available in mutiples of 100ms for three pre-defined channel ranges.
- tbinsizesec : Time binsize in seconds for generating standard light curve Used when lctype=standard
- tbinsizems : Time binsize in milliseconds (only multiple of 100ms) for generating high-res lightcurve. Used when lctype=high-res
- enelow : Lower energy (0-17.5, default 0.5) for generating light curve when enesel=yes
- enehigh : Higher energy (0-17.5, default 15.0) for generating light curve when enesel=yes
- [areascal] : Whether to apply area scaling to lightcurve (Y/N). If set to yes, the lightcurve generated will be corrected for relative area differences with Sun angle, and output would be as observed by XSM on-axis. Default is yes.
- [enesel] : Whether to generate light curve for input energy range instead of input PHA range. Default is yes
- [chstart] : Start PHA channel for the output light curve (0-1023) when enesel=no
- [chstop] : Stop PHA channel for the output light curve (0-1023) when enesel=no
- [effareaparfile] : Name of input effective area parameter file. Required only in case of areascal=yes. Default [CALDB] will use area par file from the calibration database
- [abscoeffile] : Name of input absorption coefficient file. Required only in case of areascal=yes. Default [CALDB] will use the file from the calibration database
- [gainfile] : Name of input Gain file. Required only in case of enesel=yes. Default [CALDB] will use gain file from the calibration database
- [eboundsfile] : Name of input ebounds file. Required only in case of enesel=yes. Default [CALDB] will use eboundsfile from the calibration database
- [clobber] : Whether to overwrite existing output files (Y/N). Default is yes.

4.4 xsmaddspec

Purpose

This task adds together multiple XSM type-I PHA files to a single spectrum file, much like the ftool addspec. It takes care of proper addition of channel-wise systematic errors and also adds together the respective ARFs to generate a single ARF file to be used with the added spectrum. This tool is useful if one wishes to add spectra from multiple days together.

Parameters

- listfile : Name of the input file with the list of spectrum files that are to be added together. The list file should be a plain ASCII file with one PHA file name in each line
- specfile : Name of output added spectrum file
- [arffile] : Name of output added ARF file corresponding to the spectrum. If set to default, arf file will have same base name as the output spectrum file.
- [addarf] : Whether to add ARF files corresponding to the input spectra to generate an output ARF file. Default is yes.
- [clobber] : Whether to overwrite existing output files (Y/N). Default is yes.

4.5 Additional python tools

In addition to the above modules of XSMDAS, three useful python tools are provided along with the software. These tools require python3 and python packages datetime, numpy and astropy. For help on these tools, type moduleName -h

4.5.1 xsmmet2utc

This tool converts XSM Mission Elapse Time (MET) to UTC String. The time columns in XSM data files are in MET (seconds from 2017 Jan 01, 00 UTC) and this tool is to assist users to quickly get the UTC string corresponding to MET.
Usage: `xsmmet2utc [-h] MET`
This will print the UTC string corresponding to the MET

4.5.2 xsmutc2met

This tool coverts input UTC string to XSM MET. This may be useful to provide inputs to XSMDAS tasks in MET units such as the start and stop times in *xsmgenspec*. Usage: `xsmutc2met [-h] utc`
Here the UTC string should be in 'yyyy-mm-dd hh:mm:ss.f' format. If any of the time arguments are not provided, they will be considered zero

4.5.3 xsmcomputeflux

This tool computes broadband X-ray flux in the required energy range from time-resolved XSM spectra. This generates output text file with flux in Wm^{-2} units, assuming a diagonal redistribution matrix.
Usage: `xsmcomputeflux [-h] spec2file outfile Elow Ehigh`
Here the type-2 spectrum file should be generated with areascal=yes option in *xsmgenspec* and the time binsize should be same as that required for the flux data. The standard spectrum file provided under calibrated directory in the data archive can be used to generate flux with one

minute cadence. The output file always have timebins spanning the entire day and for bins where no data is available 'NaN' value is given for flux.

5 Specific Analysis Cases

In this section, some specific analysis cases are presented where the procedure to generated products with required options for XSMDAS modules are given.

5.1 Standard spectrum generation

To generate time-integrated spectrum for the entire day of observation (adding spectrum for all available duration), execute *xsmgenspec* as:

```
xsmgenspec l1file=l1fileName specfile=specfileName spectype=time-integrated
tstart=0 tstop=0 hkfile=hkfileName safile=safileName gtifile=gtifileName
```

where the file names of input files should be with path in case they are not in the present working directory. In case of no additional requirement, GTI files from level-2 data set can be used as input here. Tstart and tstop set to zero means the entire duation of data is selected. This will generate a type-I PHA file and corresponding ARF.

To generate time-resolved spectrum for the full observation, change the parameter value for spectype from above example and specify timebinsize as:

```
xsmgenspec spectype=time-resolved tbinsize=100
```

In this case, a type-II PHA file and respective type-II ARF file will be generated.

5.2 Spectrum for a flare duration

If a user wants to generate spectrum for a single duration t1 to t2, maybe for a flare, it can be done by setting tstart and tstop parameters in *xsmgenspec* as:

```
xsmgenspec tstart=t1 tstop=t2
```

It may be noted that t1 and t2 shall be in Mission Elapse Time (MET) which is number of UTC seconds since 2017 Jan 01. The time columns in all XSM data files are in MET. The start and stop times should also be within the data duration.

5.3 Light curve for user defined energy range

To generate light curve for a specified energy range, say 1 – 2 keV with a specified time bin size like 10 s, invoke *xsmgenlc* with options:

```
xsmgenlc enelow=1 enehigh=2 tbinsizesec=10
```

It may be noted that the timebinsize has to be integer seconds. This will generate a standard light curve file. If the energy range exceeds above 15 keV, the light curve generated would include ULD events recorded in the last ADC channel of the instrument. Thus, to get the light curves of solar X-ray emission, the light curve generation shall be restricted to below 15 keV.

5.4 Light curve with 100 ms binsize

XSM records light curves in three pre-defined energy bands with a cadence of 100 ms. To generate light curves with this cadence, use *xsmgenlc* as:

```
xsmgenlc lctype=high-res tbinsizems=100 areascal=no
```

The present version does not include effective area scaling for the high time resolution light curves, thus the option areascal=no. This will generate light curve file with three extensions having the light curves for three channel ranges. It may be noted that if the channel ranges for the 100 ms light curves have been changed during a given day, *xsmgenlc* will exit with error. In such cases, users have to create separate GTIs for different channel ranges by specifying in filterfile and executing *xsmgtigen* and use those GTIs for light curve generation.

5.5 Spectrum for user defined time intervals

In some cases users may want to apply time filtering of the data before generating spectrum. For example, the user wants to get quiet Sun spectrum for a day ignoring the durations of flares. In such cases, execute *xsmgtigen* with a usergti file option as:

```
xsmgtigen usergtifile=userfileName
```

The usergti file is a plain text file with start and stop times of required intervals. Note that additional time filtering for Sun visibility etc will be done by the module, so these intervals can be just what the user wants. The user gti file would be like:

```
int1_tstart int1_tstop
int2_tstart int2_tstop
int3_tstart int3_tstop
```

All times should be MET and within the duration of the data being analyzed. After generating the GTI with usergti option, the same shall be used in generation of spectrum.

5.6 Background spectrum

The standard filterfile options for GTI selection is for selection of observation of the Sun. In case a user wishes to generate background spectrum with Sun out of the field of view, the following entries shall be made in the filterfile which is input to *xsmgtigen*

```
HVMonitor           1   1.0   -
DetTemperature      1   1.8   -
LV1Monitor          1   3.1   3.4
LV2Monitor          1   1.4   1.6
MotorIRPos          2   0   0   2   2
FrameDiscardFlag    1   0   0
SunTheta            1   50  -
SunFovFlag          1   0   0
```

In case no duration are available in the present data set where these conditions are met, *xsmgtigen* will display that message. GTI generated with this filterfile shall be used in *xsmgenspec* to generate background spectrum.

6 Higher-level Analysis of XSM Spectrum and Light curve

XSM spectrum and light curve files are in standard FITS formats and thus can be used with widely used spectral or timing analysis tools as mentioned below. The files can also be read with FITSIO routines available in any of the programming langauges like Python and IDL if users wish to do any analysis or visualization.

6.1 Spectral analysis with XSPEC

XSM spectra generated by *xsmgenspec* are directly readable in XSPEC. It is recommended that users generate time-integrated (type-I) or time-resolved (type-II) spectra along with respective Ancillary Response File (ARF) using *xsmgenspec* without any area scaling for analysis in XSPEC.

To load a type-I XSM spectrum file in XSPEC:

```
data spectrumFile.pha
```

This will load the spectrum and the respective ARF and RMF files as recorded in the spectrum file header. ARF file is generated by *xsmgenspec* along with the spectrum and the RMF file is provided in the CALDB distribution. Two representative background spectra are provided under `$xsmdas/caldb/bkgspec`, which are generated from XSM observations when the Sun is out of its FOV. It is recommended that the users restrict the analysis to energy ranges where the source spectrum is dominant over the background, with the highest energy limited to 15 keV. As the background is slightly variable, it is possible that the provided background spectra are higher than that during an observation, this would not have any impact as long as the spectral fits are restricted to source dominated energy range. See the notes for advanced users in Section 6 about generating custom background for a given observation.

Refer XSPEC user manual at `https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XspecManual.html` for more details on XSPEC spectral analysis.

6.2 Spectral analysis with OSPEX

Pre-requisites for analysis with OSPEX:

- IDL Version 8+ on 64-bit platform
- SSW installation with at least SPEX and CHIANTI packages
- IDLastro package

To load the XSM spectral data (level-2 time-series PHA file) and response in OSPEX, two IDL routines are provided along with the XSMDAS distribution (see the directory `$xsmdas/idl`). Add this location to IDL PATH or copy the two IDL rouines named `ch2xsm_read_data.pro` and `ch2xsm_read_drm.pro` to any of the pre-defined IDL PATH locations, so that they are accessible by SolarSoft. It may be noted that these routines are not meant to be used independant of OSPEX.

For XSM analysis with OSPEX, start SSW IDL session and invoke OSPEX as:

```
o=ospex()
```

This will open up a window of OSPEX GUI. Then, set the spex file reader to the XSM data read routines as:

```
o->set, spex_file_reader='ch2xsm_read'
```

Then, use File –> Select Input option in the GUI to load the spectrum files. It is recommended that the standard level-2 PHA file with one second effective area scaled spectra provided in XSM data archive are used as input files for analysis in OSPEX. In case a user wishes to generate spectrum with a higher time bin size to load in OSPEX, use xsmgenspec with the options specified below:

```
xsmgenspec spectype=time-resolved areascal=yes genarf=no
```

After loading the file (s), further options in OSPEX can be used to generate light curves for any energy range or spectrum for any duration for further analysis. Multiple spectra files can be imported together if such a requirement arises. No separate background files are provided for use with OSPEX (background files meant for XSPEC mentioned in the previous section are not suitable for OSPEX), users shall select appropriate background duration within the data using the functionality in OSPEX, for eg. select pre-flare duration as background for flare spectroscopy.

It may also be noted that such pre-flare subtraction involves an approximation as the flare and pre-flare spectra are scaled by respective effective area before subtraction. This may result is a slightly inaccurate background subtraction, but will not have major impact on the results as long as fitting is restricted to the energy range where the source dominates over background. Typical background rates in the 1 – 15 keV energy range is 0.15counts s^{-1} in comparison to at least 5counts s^{-1} from the Sun (at faintest cases). The effective area scaling factors are less than 0.5, thus the maximum error in the background rate due to this would be 0.075counts s^{-1}, which is negligible. Variations in background with time is more important issue to consider.

Refer to OSPEX user manual at `https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm` for more details on analysis using OSPEX.

6.3 Timing analysis

The light curve files generated by *xsmgenlc* are in standard format comaptible with timing analysis tools (XRONOS) provided as part of Heasoft distribution. For example, the tool *lcurve* can be used to load multiple light curve files and rebin them in whichever binsize needed and plot. Refer to XRONOS user manual at `https://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/xronos.html` for more details.

7 XSM data analysis: A walk-through

In this section, a walk-through of XSM data analysis for a sample data set is given. Generation of required products with XSMDAS module and higher level analysis with HEASOFT/XSPEC and OSPEX are demonstrated. XSM observation on 18-November-2019 is considered here and it is assumed all required software tools are already installed.

Download the data for this day of observation from PRADAN and unzip the file into desired location. In this example, it is unzipped in to the directory `~/xsm_analysis`

```
mithun@Thinkpad:xsm_analysis$ unzip ch2_xsm_20191118_v1.zip
```

This will create a directory structure with xsm as top level directory with year, month, day level sub-directory structure under data (as discussed in Section 2). The data files will be under raw and calibrated directories.

As a first step, we will examine the standard 1-s level-2 light curve available under the calibrated directory using fitsviewer (fv). Open the lc file using fv (after navigating to the calibrated directory):

```
mithun@Thinkpad:calibrated$ fv ch2_xsm_20191118_v1_level2.lc
```

Then, using the plot option, create a plot with x axis as 'TIME' and y axis as 'RATE'. The obtained plot is shown in Figure 7.1. You may use other tools like fplot or use python/IDL programs to visualize the light curve.

The plot shows a solar flare observed by the XSM with some periods when there were no observation, the rising phase of this flare is not seen by the XSM. By zooming in the plot (see Figure 7.2), note the start and end time of the flare in MET. We will use the following time ranges as the flare duration and pre-flare duration for the subsequent analysis.

Period	Tstart	Tstop
Flare	90853000	90856000
Pre-flare	90809000	90852000

Spectral analysis of this flare is now demonstrated using XSPEC and OSPEX in the folllowing subsections.

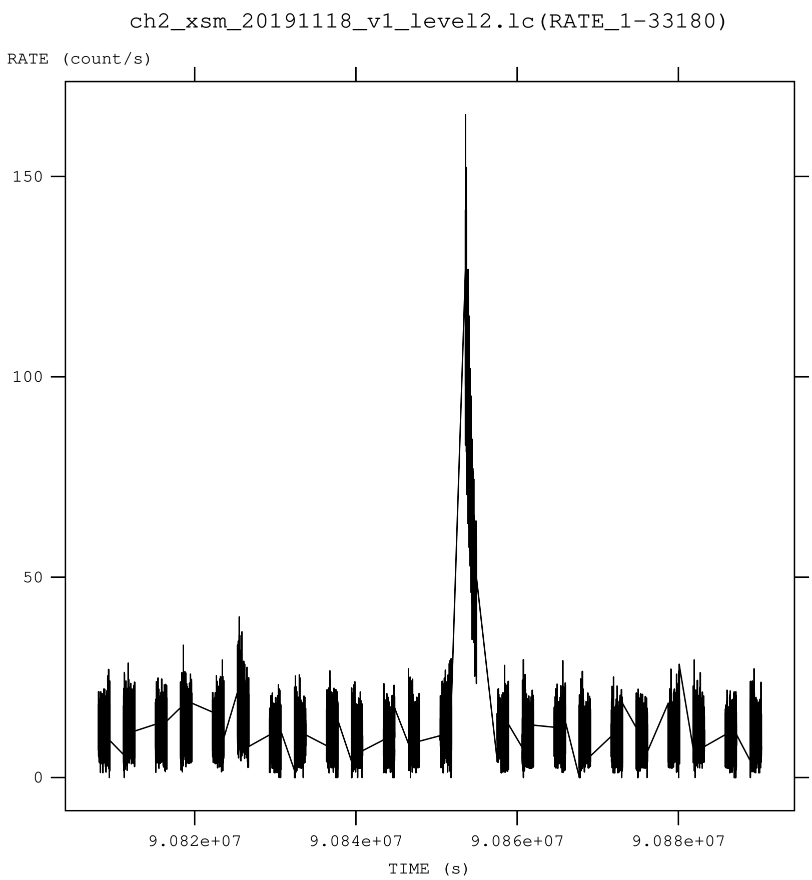

Figure 7.1: Plot of standard light curve for XSM data of 18-Nov-2019 using fv.

7.1 Analysis with XSPEC

For analysis in XSPEC we shall generate spectra for the flare and pre-flare duration separately using the XSMDAS module *xsmgenspec*. To generate spectrum for the flare duration, provide inputs to *xsmgenspec* as shown below with the tstart and tstop values as identified above.

```
mithun@Thinkpad:~/xsm_analysis/xsm/data/2019/11/18/calibrated$ xsmgenspec
-----------------------------------------------------------------------
  XSMDAS: Data Analysis Software for Chandrayaan-II Solar X-ray Monitor
                     XSMDAS Version: 1.1
                     Module : XSMGENSPEC
-----------------------------------------------------------------------
Enter Input Level-1 file [] : ../raw/ch2_xsm_20191118_v1_level1.fits
Enter Output Spectrum file [] : ch2_xsm_20191118_flare.pha
Enter output spectrum type <time-resolved or time-integrated> [time-resolved] : time-integrated
Enter start time for extracting spectrum [0] : 90853000
Enter stop time for extracting spectrum [0] : 90856000
Enter HK file [] : ../raw/ch2_xsm_20191118_v1_level1.hk
Enter Sun angle file [] : ../raw/ch2_xsm_20191118_v1_level1.sa
Enter GTI file [] : ch2_xsm_20191118_v1_level2.gti
----------------------------------------------------------------------
```

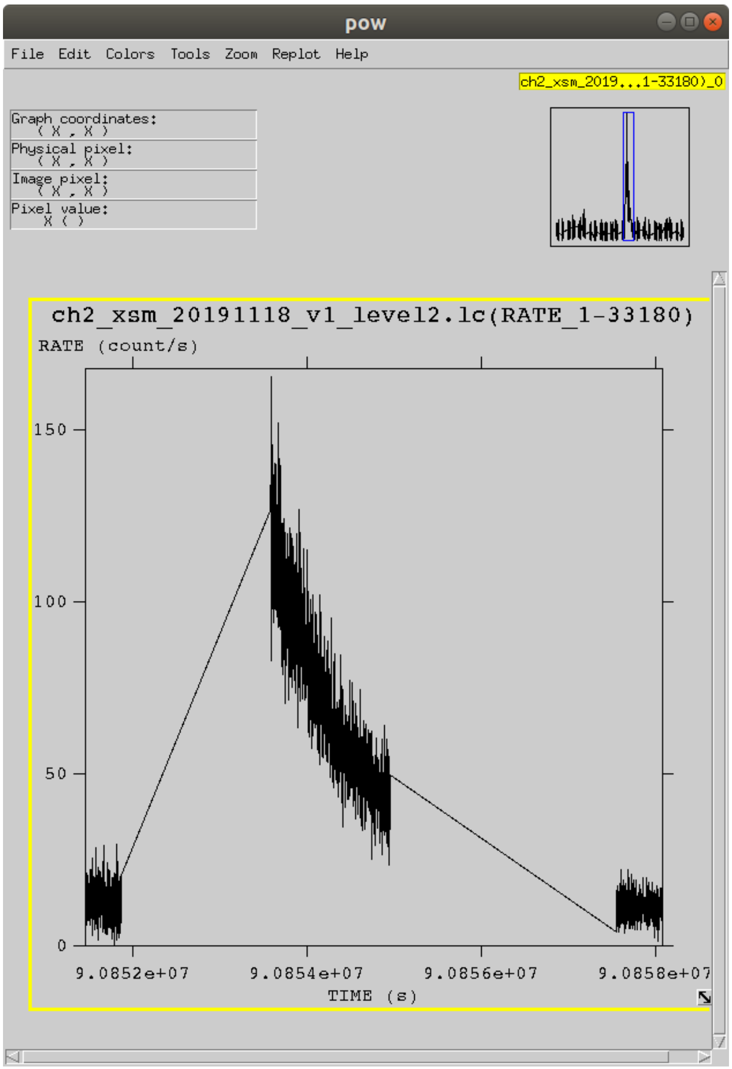

Figure 7.2: Zoomed version of the light curve shown in Figure 7.1 to identify start and end times for the flare.

```
MESSAGE: Ebounds CALDB file used is: /home/mithun/work/ch2/xsm/pipeline/XSM/xsmdas
/caldb/CH2xsmebounds20191214v01.fits
MESSAGE: Gain CALDB file used is: /home/mithun/work/ch2/xsm/pipeline/XSM/xsmdas
/caldb/CH2xsmgain20200330v02.fits
MESSAGE: Abscoef CALDB file used is: /home/mithun/work/ch2/xsm/pipeline/XSM/xsmdas
/caldb/CH2xsmabscoef20200410v01.fits
MESSAGE: Effareapar CALDB file used is: /home/mithun/work/ch2/xsm/pipeline/XSM/xsmdas
/caldb/CH2xsmeffareapar20200410v01.fits
MESSAGE: Syserror CALDB file used is: /home/mithun/work/ch2/xsm/pipeline/XSM/xsmdas
/caldb/CH2xsmsyserr20200410v01.fits

MESSAGE: XSMGENSPEC completed successully
MESSAGE: Output file = ch2_xsm_20191118_flare.pha
MESSAGE: Output ARF = ch2_xsm_20191118_flare.arf
```

At the end of execution a spectrum file and arf file will be generated. Similarly generate spectrum and arf for the pre-flare duration by providing appropriate start and stop times. Before proceeding to detailed spectral analysis, load both these spectra in XSPEC with a sample background file provided under `$xsmdas/caldb/bkgspec` as the background spectra (either copy the background pha to present working directory or give full path) using appropriate XSPEC commands as below:

```
XSPEC12>da 1:1 ch2_xsm_20191118_flare.pha

1 spectrum  in use

Spectral Data File: ch2_xsm_20191118_flare.pha  Spectrum 1
Net count rate (cts/s) for Spectrum:1  5.225e+01 +/- 4.628e-01
 Assigned to Data Group 1 and Plot Group 1
  Noticed Channels:  1-512
  Telescope: CH-2_ORBITER Instrument: CH2_XSM  Channel Type: PI
  Exposure Time: 1373 sec
 Using fit statistic: chi
 Using test statistic: chi
 Using Response (RMF) File            /home/mithun/work/ch2/xsm/pipeline/XSM
 /xsmdas/caldb/CH2xsmresponse20200423v01.rmf for Source 1
 Using Auxiliary Response (ARF) File  ch2_xsm_20191118_flare.arf

XSPEC12>back 1 ch2_xsm_20191128_bkg.pha
Net count rate (cts/s) for Spectrum:1  5.111e+01 +/- 4.629e-01 (97.8 % total)
XSPEC12>dat 2:2 ch2_xsm_20191118_pre-flare.pha

2 spectra  in use

Spectral Data File: ch2_xsm_20191118_pre-flare.pha  Spectrum 2
Net count rate (cts/s) for Spectrum:2  9.236e+00 +/- 8.546e-02
 Assigned to Data Group 2 and Plot Group 2
  Noticed Channels:  1-512
  Telescope: CH-2_ORBITER Instrument: CH2_XSM  Channel Type: PI
  Exposure Time: 1.714e+04 sec
 Using fit statistic: chi
 Using test statistic: chi
 Using Response (RMF) File            /home/mithun/work/ch2/xsm/pipeline/XSM
 /xsmdas/caldb/CH2xsmresponse20200423v01.rmf for Source 1
 Using Auxiliary Response (ARF) File  ch2_xsm_20191118_pre-flare.arf

XSPEC12>back 2 ch2_xsm_20191128_bkg.pha
Net count rate (cts/s) for Spectrum:2  8.093e+00 +/- 8.554e-02 (87.6 % total)
```

Plot the spectra after ignoring the data below 1 keV and above 5 keV using ignore, plot, and setplot commands in XSPEC (see XSPEC manual). Figure 7.3 shows the resulting plot. The black data points denote the flare spectrum, red data points correpond to pre-flare spectrum and the stars denote the background spectra.

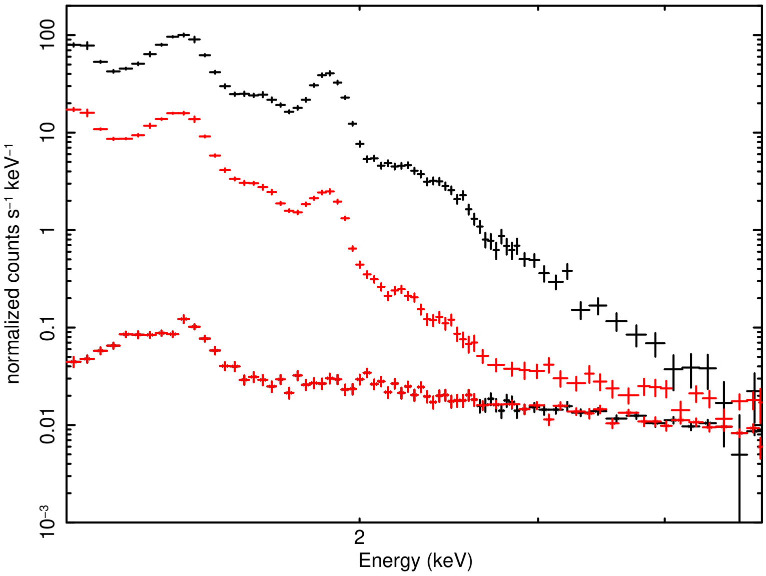

Figure 7.3: Spectra of flare (black) and pre-flare (red) duration along with representative background spectrum shown with star symbols.

As noted in Section 8, background in XSM shows slight variability and thus it is recommended to restrict the spectral analysis to energies where the source is well above background. In this example, we shall choose pre-flare spectrum up to 2.6 keV and flare spectrum up to 4.5 keV for spectral fitting. We also need to ignore the spectra below 1.3 keV as noted in Section 8 (this observation is before June 2020).

First, we need to fit the pre-flare spectrum with an isothermal plasma emission model *vapec*. The abundances shall be set to typical solar coronal abundances and that of elements Mg, Al, and Si shall be left free while fitting. Refer to XSPEC manual for the steps involved. The fitted spectrum along overplotted with data is shown in figure 7.4 for reference.

We can then fit the flare spectrum by using a two temperature model, as the sum of two *vapec* models. The parameters of the first component is frozen to that obtained for pre-flare duration whereas the parameters of the second component are left free. It may be noted that here we have integrated the spectrum for the full flare duration and thus the isothermal approximation will not be valid and very good fits cannot obtained. It would be more appropriate to further divide the flare duration into sub intervals such that there are enough counts in each interval and then carry out spectral analysis for each interval to obtain the parameters such as temperature, emission measure, and abundances as a function of time.

7.2 Analysis with OSPEX

Start a session of Solar Soft IDL and follow the instructions in Section 6.2 to load the standard time-resolved spectrum file (60 s cadence) available under the calibrated directory into OSPEX. After loading the file, on clicking plot time profile option, OSPEX window will plot the light

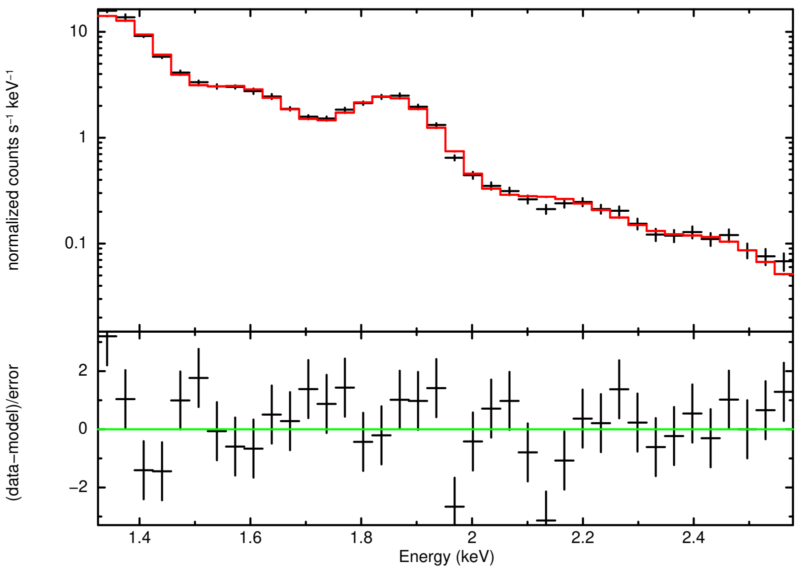

Figure 7.4: Fit to pre-flare spectrum using *vapec* model.

curves in different energy bands as shown in Figure 7.5

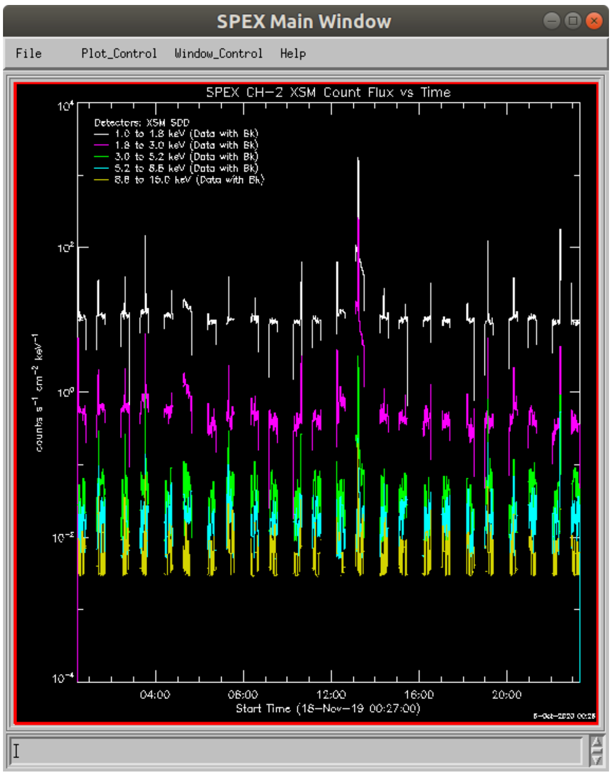

Figure 7.5: OSPEX window showing the time profile or light curve for the data on 18-Nov-2019.

For analysis of flare spectrum, we need to select a flare time interval and a pre-flare time interval (as background) using the select time interval options in the OSPEX window. An example of flare and pre-flare time selection is shown in Figure 7.6

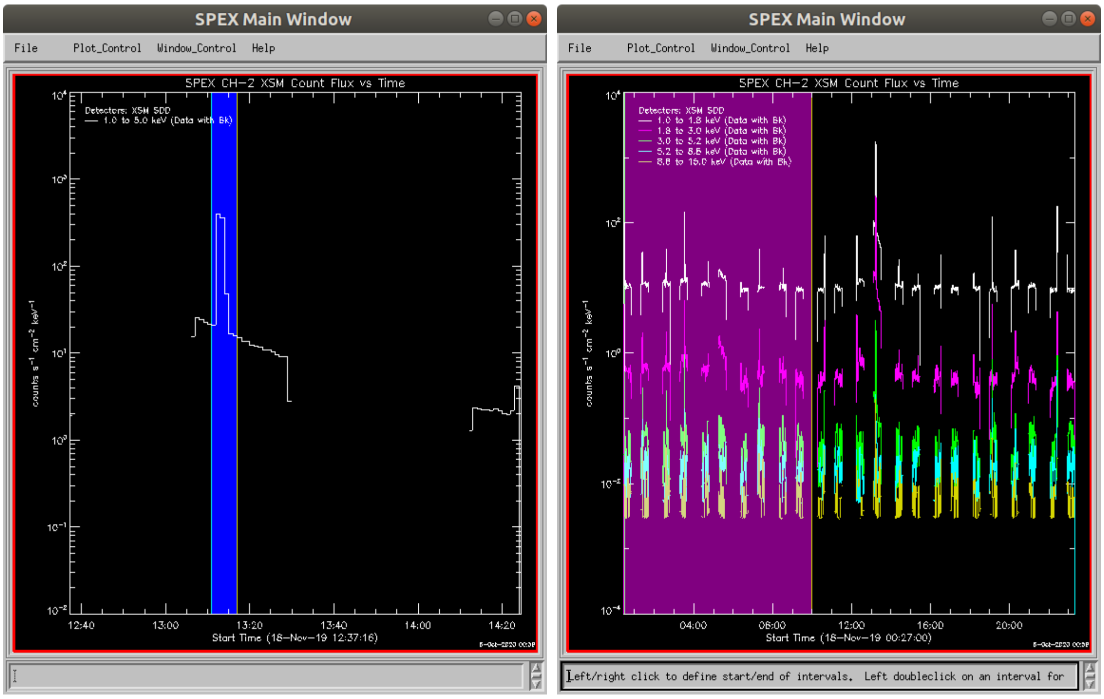

Figure 7.6: OSPEX windows showing the time interval selection for flare (left) period and pre-flare (right) background duration.

After selection, on plotting the spectrum for the selected flare duration, window will show the spectrum as given in Figure 7.7.

Now, one can proceed to fit the spectrum with available models in OSPEX, suitable one being *vth_abun*. It is required to restrict the spectral fits to energy ranges where the solar spectrum is dominat over background to get reliable results.

8 Notes on XSM Data Analysis

This section provides a set of notes to the users on the analysis of XSM data including important caveats.

General notes

- For observations in during Noon-Midnight seasons (see `https://www.prl.res.in/ch2xsm/xsm_observations#seasons`) where the data are sparse, uncertainities in calibration are larger, currently estimated to be 10-15%.

- For the observations before June 2020, it is known that the counts in the spectrum below 1.3 keV are less than predicted by the response due to the effect of low energy threshold. Thus, it is recommened to ignore spectrum below 1.3 keV for data acquired during the said period for any spectral fitting.

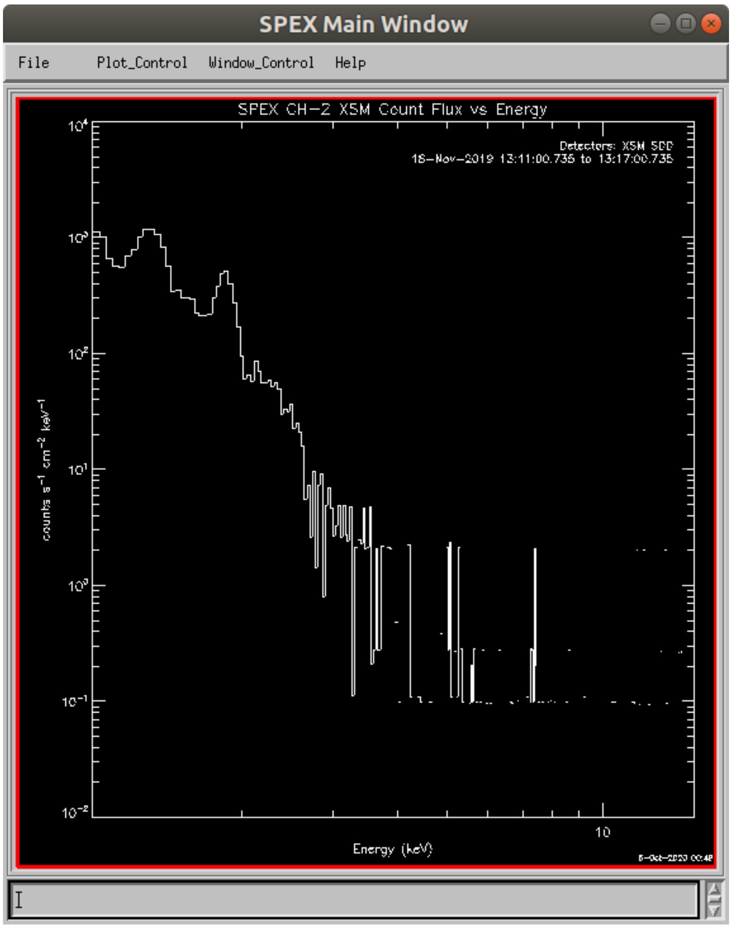

Figure 7.7: OSPEX window showing the XSM spectrum for the flare duration selection shown in Figure 7.6.

- During observations, the Sun angle with respect to the instrument boresight varies with a period of half the orbital period ($\sim$ 120 minutes). This causes effective area for Sun observations also to vary, which is corrected by the analysis software. However, it is likely that small residual effects of these variations may persist in the light curves. Thus, any periodicities seen in the data that matches the orbital period of Chandrayaan-2 or its harmonics shall be ignored.

- Sample background spectra are provided along with CALDB distribution. It is recommended that energy ranges where the source spectrum is dominant over background shall be identied by comparing the Sun spectrum with these sample background and spectral fitting shall be restricted to those energy ranges. It may be noted that as background is slightly variable, subtraction of the sample background spectrum from any source observation will not be very accurate where the background dominates over source counts (e.g. higher energy channels for quiet Sun data).

- Light curves generated are inclusive of background, which in the full energy range of 1 – 15 keV or at lower energies is negligible compared to solar X-rays even for the quietest X-ray emission from the Sun. However, beyond certain energy the background would dominate, which can be understood from comparing source and background spectra as discussed above. Light curves above that energy would be primarily background and does not provide much information about the source and shall be interpreted accordingly. As the background does not vary with sun angle systematically, the light curves corrected for effective area variation with angle would show systematic variation.

- In many cases, users may want to fit the spectrum during a flare subtracting the pre-flare solar emission. However, as the effective area of XSM in general varies with time (as the Sun travels across the FOV of XSM) , such simple subtractions may not be the best method, rather the following approach can be taken. Generate pre-flare spectrum and fit it with appropriate model. Now, while fitting the flare duration spectrum, consider two models - one for the pre-flare emission fixed to the parameters obtained for pre-flare spectrum and another for the flaring component which can be left free. In cases where the Sun angles between pre-flare and flare observations are not varying much, simple subtraction may be carried out.

Notes for advanced users

The below points are meant for advanced users and these are not recommended for typical analysis case.

- If a user finds that the gain offset correction applied by the analysis software needs some tweak, they may use the additional gain or offset correction options available in *xsmgenspec* module. In general, additional gain correction factor will not be required at all and small corrections in offset up to ±10 eV may be done in some cases. Note that the additional offset input in *xsmgenspec* is to be provided in keV. It is recommended that users who are not very sure of it shall not attempt to use this option.

- In case a user wishes to extend the spectral analysis to energies where background is dominated, they may note that it is observed that the background shows slight variability (see reference 2: Mithun *et al.*, 2020, *Sol Phy*). Users can generate custom background spectrum by selecting appropriate time intervals with filterfile as discussed in the previous section. However, it is likely that the background during Sun observation and background observation on the same day of observation need not match. Thus, users will have to identify appropriate background by ensuring that the counts at higher energies (say above 10 keV) for Sun and the selected background spectra match. In such cases appropriate care should be taken in background subtraction and interpretation of the background subtracted spectra. In case of doubt, users shall contact XSM POC (xsmpoc@prl.res.in).