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XMM-Newton data reduction tutorial by Samaresh Mondal (smondal@camk.edu.pl). The commands you have to execute in the terminal are marked in boldface.

First install HEASoft, SAS and download the XMM CCF files from the link given below
https://www.cosmos.esa.int/web/xmm-newton/current-calibration-files

After that, initialize the following paths (the given examples are for bash).

source /export/work/kalypso/software/heasoft-6.27.2/x86_64-pc-linux-gnu-libc2.27/headas-init.sh
source /export/work/kalypso/software/xmm/xmmsas_20170112_1337/setsas.sh
export SAS_CCFPATH=/export/work/kalypso/calibration/xmm/ccf/

"SAS_CCFPATH" is the path where you downloaded the XMM calibration files.

Download the data from the HEASARC archive (https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl). For practice, you can download the data of the M82 galaxy. It is a very well-known object.

Go to the ODF directory unzip all the files using the command **gunzip ***

Now you have to set the paths of "SAS_ODF", "SAS_ODFPATH", "SAS_CCF" and these paths will be link to where your data is downloaded. For example,

export SAS_ODF=/export/work/kalypso/ULXdata/M82/xmm/0657802101/ODF/
export SAS_ODFPATH=/export/work/kalypso/ULXdata/M82/xmm/0657802101/ODF/

Now type the command **odfingest**. It will run for a couple of seconds to minutes, depending on how big your observation is. At the end, it will create a ".SAS" extension file. Now update the path of "SAS_ODF" by,

export SAS_ODF=/export/work/kalypso/ULXdata/M82/xmm/0657802101/ODF/*.SAS

After that, run the command **cifbuild**, and it will create a "ccf.cif" file that you set the path of

export SAS_CCF=/export/work/kalypso/ULXdata/M82/xmm/0657802101/ODF/ccf.cif

Now create a new directory to store the clean event files, spectra, and light curves. I usually create a directory **reproc** inside the observation id. There are four directories inside the reproc directory: **PN**, **MOS**, **RGS**, **OM**. Each of these directories is for different detectors. Now go to each directory and type the following command,

epproc	inside PN directory
emproc	inside MOS directory
rgsproc	inside RGS directory
omichain	inside OM directory

These commands will create clean event files for each detector. The rest of this tutorial will provide a guide to extract spectra and light curves from PN and MOS detectors.

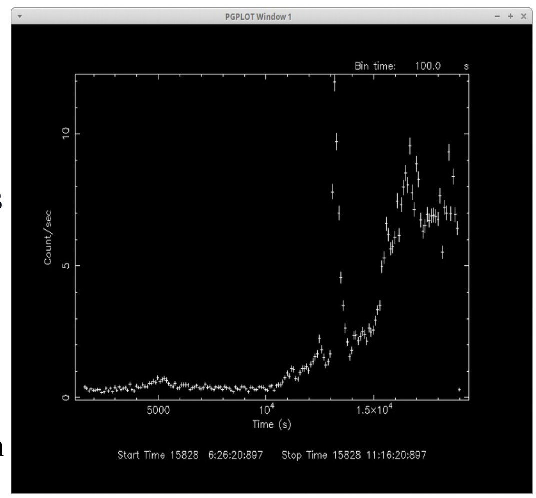
In the PN directory, you will find a file named “*_ImagingEvts.ds”. We will copy this file to be safe, and whatever we do will be on the copied file.

cp *_ImagingEvts.ds pn.evt

Now run the following command to create the spectra and light curves.

evselect table=pn.evt energycolumn=PI expression='#XMMEA_EP && (PI>10000 && PI<12000) && (PATTERN==0)' withrateset=yes rateset="lcurve_sup100.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes

This command creates a light curve in the energy band 10-12 keV from the whole PN CCD chip. Open the light curve using the **lcurve** command. See if there are any giant flares due to South Atlantic Anomaly (SSA). If the flares are present, we will create a good time interval (gti) that does not include those flares in the following command. In the image right, you see such giant flares. We can remove these flares by choosing a threshold value of Counts/s. For this case, it is like 1 Counts/s



tabgtigen table=lcurve_sup100.lc gtiset=good_bkg.gti expression='RATE<1.0'

We can also create the gti by choosing the exact time in the light curve without flares. The initial observation time in the light curve plot is set to zero. However, the actual observation time is not zero. So you have to get the actual time value by opening the light curve using the command **fv lcurve_sup100.lc**

tabgtigen table=lcurve_sup100.lc gtiset=good_bkg.gti expression='TIME>=433232780.897326 && TIME<=433232780.897326+10000.0'

The following command creates a new event file pn_new.evt free from proton flares using the gti file.

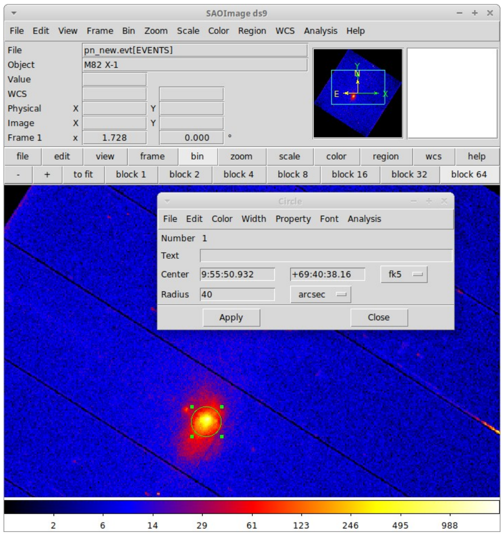
evselect table=pn.evt expression='#XMMEA_EP && (PI > 150) && (GTI(good_bkg.gti,TIME))' withfilteredset=yes keepfilteroutput=yes filteredset=pn_new.evt updateexposure=yes cleandss=yes writedss=yes

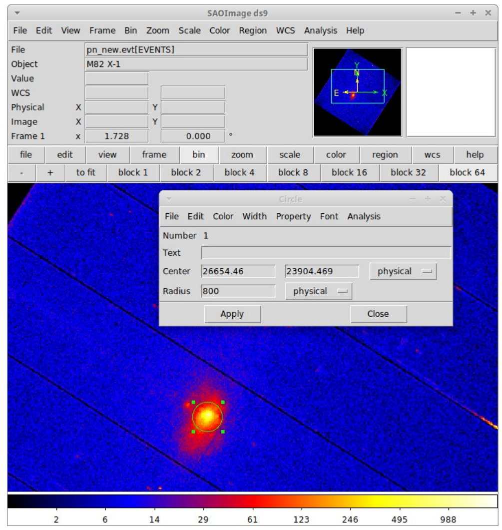
The following command is optional unless you are searching for pulsation from NS. For pulsation search, you have to do the barycenter correction. Please look at Wikipedia for barycenter correction; it’s due to the Earth's rotation around the Sun.

barycen table=pn_new.evt:EVENTS

In the next command, we will create a figure to see any pile up in the source region. For bright sources, the pileup is a pain in the neck. Open the pn_new.evt using **ds9 pn_new.evt** and select scale: log, color:

b and bin: block 32 or 64. Select a circular region centered at the source with a radius of 40 arcsec. Usually, people choose 80% of the PSF, and for XMM, the 80% is 40 arcsec. Now change those coordinates to physical coordinates because the evselect command only takes coordinates in physical units.

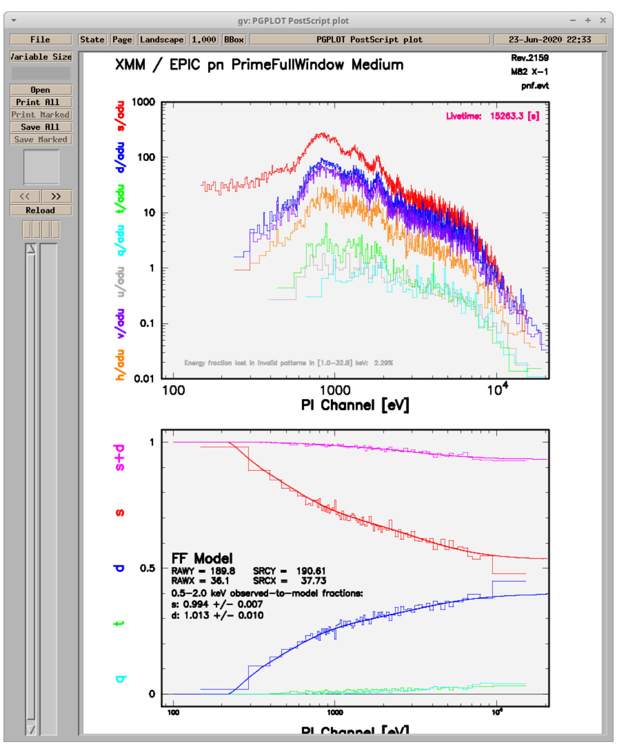


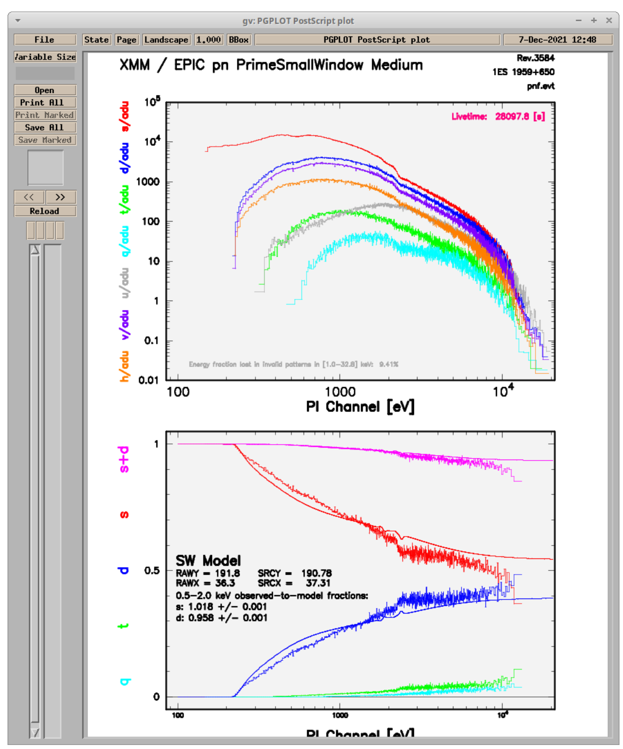


evselect table=pn_new.evt withfilteredset=yes filteredset=pnf.evt keepfilteroutput=yes expression="((X,Y) IN circle(26654.46,23904.469,800.0))"

epatplot set=pnf.evt device="/CPS" plotfile="pnf_pat.ps"

Now open the figure pnf_pat.ps using the command **gv pnf_pat.ps**. You will see a figure (left figure) like this wherein the bottom panel the data follows very close to the theoretical curve. This indicates there is no pile-up, and you are good to go. However, suppose your data do not follow the theoretical curve (for example, the right plot is for BL Lac 1ES 1959+650). In that case, you have to choose an annulus.





evselect table=pn_new.evt withspectrumset=yes spectrumset=src_spectrum.fits energycolumn=PI spectralbinsize=5 withspecranges=yes specchannelmin=0 specchannelmax=20479 expression='(FLAG==0) && (PATTERN<=4) && ((X,Y) IN circle(26654.46,23904.469,800.0))'

evselect table=pn_new.evt withspectrumset=yes spectrumset=bkg_spectrum.fits energycolumn=PI spectralbinsize=5 withspecranges=yes specchannelmin=0 specchannelmax=20479 expression='(FLAG==0) && (PATTERN<=4) && ((X,Y) IN circle(20766.502,27168.469,1600.0))'

The above two commands create source and background spectra. I choose a large region like 80 arcsec (1600 in physical units) for background. Some people choose the background same area as the source region but multiple regions like east, west, and north, but it is personal choice.

The next commands calculate the geometric area of the source and background region and write in the header file of the source and background spectrum. This is necessary as the flux is given as per unit area. Therefore, one has to normalize the source and background spectra given the extent of the extraction region in the CCD. Otherwise, there will be an error in the flux calculation.

backscale spectrumset=src_spectrum.fits badpixlocation=pn_new.evt
backscale spectrumset=bkg_spectrum.fits badpixlocation=pn_new.evt

The following subsequent commands create the response and auxiliary files.

rmfgen spectrumset=src_spectrum.fits rmfset=pn.rmf
arfgen spectrumset=src_spectrum.fits arfset=pn.arf withrmfset=yes rmfset=pn.rmf badpixlocation=pn_new.evt detmaptype=psf

The following command is from HEASoft, not from SAS. It groups the spectra with a minimum of 20 counts per bin for a higher signal to noise.

grppha src_spectrum.fits pn_20.grp comm= "chkey RESPFILE pn.rmf & chkey ANCRFILE pn.arf & chkey BACKFILE bkg_spectrum.fits & group min 20 & exit"

The following subsequent commands are to create the light curves. To get the light curves in different bands, you have to change the PI value given in eV units.

evselect table=pn_new.evt energycolumn=PI expression='#XMMEA_EP &&(PATTERN<=4)&&((X,Y) IN circle(26654.46,23904.469,800.0))&&(PI in [300:10000])' withrateset=yes rateset='pn_src_lc_raw.lc' timebinsize=10.0 maketimecolumn=yes makeratecolumn=yes

evselect table=pn_new.evt energycolumn=PI expression='#XMMEA_EP &&(PATTERN<=4)&&((X,Y) IN circle(20766.502,27168.469,1600.0))&&(PI in [300:10000])' withrateset=yes rateset='pn_bkg_lc_raw.lc' timebinsize=10.0 maketimecolumn=yes makeratecolumn=yes

epiclccorr srctslist=pn_src_lc_raw.lc eventlist=pn_new.evt outset=pn_lc_0.3_10keV.lc bkgtslist=pn_bkg_lc_raw.lc withbkgset=yes applyabsolutecorrections=yes

For MOS detectors go to the MOS directory and copy the following files,

cp *_EMOS1_S001_ImagingEvts.ds m1.evt
cp *_EMOS2_S005_ImagingEvts.ds m2.evt

The rest of the commands are very similar to PN except few changes.

evselect table=m1.evt energycolumn=PI expression='#XMMEA_EM && (PI>10000) && (PATTERN==0)' withrateset=yes rateset="m1lcurve_sup100.lc" timebinsize=100 maketimecolumn=yes makeratecolumn=yes

tabgtigen table=m1lcurve_sup100.lc gtiset=m1good_bkg.gti expression='RATE<0.5'

evselect table=m1.evt expression='#XMMEA_EM && (PI > 150) && (GTI(m1good_bkg.gti,TIME))' withfilteredset=yes keepfilteroutput=yes filteredset=m1_new.evt updateexposure=yes cleandss=yes writedss=yes

barycen table=m1_new.evt:EVENTS

evselect table=m1_new.evt withfilteredset=yes filteredset=m1f.evt keepfilteroutput=yes expression="((X,Y) IN circle(32141.087,29463.567,800.0))"

epatplot set=m1f.evt device="/CPS" plotfile="m1f_pat.ps"

evselect table=m1_new.evt withspectrumset=yes spectrumset=m1src_spectrum.fits energycolumn=PI spectralbinsize=15 withspecranges=yes specchannelmin=0 specchannelmax=11999 expression='(FLAG==0) && (PATTERN<=12) && ((X,Y) IN circle(32141.087,29463.567,800.0))'

evselect table=m1_new.evt withspectrumset=yes spectrumset=m1bkg_spectrum.fits energycolumn=PI spectralbinsize=15 withspecranges=yes specchannelmin=0 specchannelmax=11999 expression='(FLAG==0) && (PATTERN<=12) && ((X,Y) IN circle(25934.367,33859.346,800.0))'

backscale spectrumset=m1src_spectrum.fits badpixlocation=m1_new.evt
backscale spectrumset=m1bkg_spectrum.fits badpixlocation=m1_new.evt

rmfgen spectrumset=m1src_spectrum.fits rmfset=m1.rmf
arfgen spectrumset=m1src_spectrum.fits arfset=m1.arf withrmfset=yes rmfset=m1.rmf badpixlocation=m1_new.evt detmaptype=psf

grppha m1src_spectrum.fits m1_20.grp comm= "chkey RESPFILE m1.rmf & chkey ANCRFILE m1.arf & chkey BACKFILE m1bkg_spectrum.fits & group min 20 & exit"

```
evselect table=m1_new.evt energycolumn=PI expression='#XMMEA_EM
&&(PATTERN<=12)&&((X,Y) IN circle(32200.02,29228.141,800.0))&&(PI in [300:10000])'
withrateset=yes rateset='m1src_lc_raw.lc' timebinsize=10 maketimecolumn=yes
makeratecolumn=yes
```

```
evselect table=m1_new.evt energycolumn=PI expression='#XMMEA_EM
&&(PATTERN<=12)&&((X,Y) IN circle(27860.82,33221.741,800.0))&&(PI in [300:10000])'
withrateset=yes rateset='m1bkg_lc_raw.lc' timebinsize=10 maketimecolumn=yes
makeratecolumn=yes
```

```
epiclccorr srctslist=m1src_lc_raw.lc eventlist=m1_new.evt outset=m1_lc_0.3_10kev.lc
bkgtslist=m1bkg_lc_raw.lc withbkgset=yes applyabsolutecorrections=yes
```