Aditya-L1

High Energy L1 Orbiting X-ray Spectrometer (HEL1OS)

Data Analysis User Manual
Version 1.2

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Prepared by:
HEL1OS Team

Change Record:

Issue	Revision	Date	Remarks
1	0	December 06, 2024	New document
1	1	December 23, 2024	Updated the energy ranges recommended for temporal and spectral analysis in the “Parameter specifications” table. Included the sub-section break-up of the Section 5.
1	2	January 31, 2025	Changes based on End-User feedback: (a) For OSPEX users re-introduced instructions to copy response and reader files in separate directories. (b) Copied the contents of README file into section 2, in which the updated output directory structure is included.

1. Introduction:

HEL1OS (High Energy L1 Orbiting X-ray Spectrometer) (Anuj et al, 2024, under review) is one of the remote sensing payloads onboard Aditya-L1 mission with the objective to continuously monitor and measure the time-resolved spectra of solar flares between 8 keV and 150 keV. For this broad energy range two types of semiconductor detectors are used: Cadmium Telluride (CdTe: 8 – 70 keV) and Cadmium Zinc Telluride (CZT: 20 – 150 keV). Two single pixel CdTe detectors (0.25 cm^2) provide a combined geometric area of 0.5 cm^2 , while a pair of pixelated CZT detectors (256 pixels each) afford a total geometric area of 32 cm^2. The instrument has a field-of-view of 6° x 6° while a pair of ^{241}Am radioactive sources are used to spectrally calibrate both sets of detectors using the 59.5 keV gamma-ray line. Analysis of onboard data have indicated that spectral resolution of ~ 1 keV at 14 keV (CdTe) and ~7 keV at 60 keV (CZT) have been achieved.

HEL1OS was switched ON in the fourth week of October, 2023. Eventually, various tunable parameters of the two detectors, energy threshold values and other essential onboard logics were set by the end of June, 2024.

The achieved specifications of some of the operating parameters of the HEL1OS instrument are listed in the Table below:

Parameter	Specifications
Energy Range (keV)	Total coverage ~ 8 to 150 keV Light curve/Time Profile Analysis: CdTe ≳ 8 keV; CZT ≳ 20 keV Spectral Analysis: CdTe ≳ 9.5 keV; CZT ≳ 35 keV
Energy Resolution (keV)	~1 keV @14 keV; ~7 keV @60 keV
Temporal Cadence	Event cadence: 10 millsec Light curve/Time Profile: 1 seconds Time resolved Spectroscopy: 20 seconds
Field of View (FOV)	5.6° x 5.6°
Operating Temperature	–40 °C to –30 °C (CdTe detector) +15 °C to +25 °C (CZT detector) +10 °C to +15 °C (CZT Tray)

2. Data Products:

By default, the observed data is downlinked once a day from the spacecraft. At ISSDC, the raw-data downloaded at the ground station is converted to Level-0, packing the payload data with auxiliary data like the time correlation table and the SPICE kernels. The Level-0 data made available at the data server of ISSDC are transferred to the Payload Operation Centre (POC) at ISITE campus of URSC, where the data pipeline processes these to generate higher level products – Level-1 and Level-2 data.

The HEL1OS data product primarily comprises light curves in different hard X-ray bands and Type II spectral files, both following the OGIP FITS format. The Type II spectral format is an OGIP (Office of Guest Investigators Program) standard employed for time-resolved spectroscopy[1] .

The Level-2 data products are generated after correcting for the pile-up in the CdTe events, and the CZT event-lists are filtered for saturation.

The Level-1 Type II spectral files are generated by default at 20 sec time-intervals and for sub-keV energy resolution. These spectral files are packed along with the relevant response files for spectral analysis and disseminated on the ISSDC's PRADHAN[2] portal for the Aditya-L1 mission.

1 Data Format: Type II - multiple datasets
2 https://pradan.issdc.gov.in/

2.1 Data Contents:

The HEL1OS Level-1 data products are provided as zip-files generated for different data-dumps. They are searchable in the ISSDC-PRADAN user interface at the 'Browse and Download' section for the time of observation. The zip file name will be of the kind:

HLS_20240716_235956_43191sec_lev1_V11.zip

In the filename above, '20240716_235956' denotes the start date-time of the data in YYYYMMDD_hhmmss format. '43191sec' denotes the total length of the data in seconds.

The zip-file contents will be a directory tree, such as:

```
HLS_20240716_235956_43191sec_lev1_V11.zip:
2024/
└── 07
    └── 01
        └── HLS_20240701_000211_43057sec_lev1_V111
            ├── aux
            │   ├── cztdis
            │   │   ├── czt1dispix.txt
            │   │   └── czt2dispix.txt
            │   ├── gticdte1.fits
            │   ├── gticdte2.fits
            │   ├── gticzt1.fits
            │   ├── gticzt2.fits
            │   └── hk.fits
            ├── cdte
            │   ├── hel1os_cdte_spectra_cdte1.fits
            │   ├── hel1os_cdte_spectra_cdte2.fits
            │   ├── lightcurve_cdte1.fits
            │   └── lightcurve_cdte2.fits
            ├── czt
            │   ├── hel1os_czt_spectra_czt1.fits
            │   ├── hel1os_czt_spectra_czt2.fits
            │   ├── lightcurve_czt1.fits
            │   └── lightcurve_czt2.fits
            └── events
                └── evt.fits
```

Here:
.../aux/gti*.fits: Good Time Interval (GTI) files (FITS)
.../aux/hk.fits: Housekeeping (HK) parameters in the data-dump (FITS)
.../caldb/cztdis/czt*.txt: Noisy CZT pixels list (ASCII) (events on these are ignored while creating the products)
.../events/evt.fits: Events list of all photons detected in the four detectors, provided as different extensions (FITS)
.../lightcurves/lightcurve_*.fits: Lightcurves for the four detectors, at 1 sec cadence (FITS)
.../spectra/hel1os_*spectra*.fits: Type-II spectra for the four detectors (details are provided below)

The GTI, HK FITS and Event-list files can be used to refine the good time intervals for generating data products. This will be part of higher level data generation.

2.2 FITS Viewer Utility

Note that all the FITS files can be viewed in FITS viewer ('fv') utility. 'fv' allows one to also plot, check some statistics of the data, manipulate rows and columns, etc. It can be downloaded from:
https://heasarc.gsfc.nasa.gov/docs/software/ftools/fv/fv_download.html

The HEL1OS spectral data are provided as Type-II PHA files:
CdTe1 Detector ---- hel1os_cdte_spectra_cdte1.fits
CdTe2 Detector ---- hel1os_cdte_spectra_cdte2.fits
CZT1 Detector ---- hel1os_czt_spectra_czt1.fits
CZT2 Detector ---- hel1os_czt_spectra_czt2.fits

Composition of these Type-II PHA files are:
CdTe PHA files: 511 channels, 20 sec cadence
CZT PHA files: 341 channels, 20 sec cadence
The number of time intervals in these files depend on the data-dump duration.

The HEL1OS lightcurve data provided as FITS files are:
CdTe1 Detector ---- lightcurve_cdte1.fits
CdTe2 Detector ---- lightcurve_cdte2.fits
CZT1 Detector ---- lightcurve_czt1.fits
CZT2 Detector ---- lightcurve_czt2.fits

The lightcurves are generated at 1 sec cadence for the data duration.

2.3 CALDB Response Files

In the metadata of the data product zip file is the parameter 'caldb' whose value indicates which epoch of the Calibration Response bundle needs to be used for data analysis for that product. For example, the very first epoch is 'CAL_epoch20231001' (the date 20231001 in YYYYMMDD format indicates the beginning of this epoch). This keyword 'CAL_epoch20231001' can be searched for in 'filename' in the 'Browse and Download' section on the PRADAN portal, and the two sets of zip files for the two kinds of detectors need to be separately downloaded.

Alternately, one can search for just 'CAL' in the filename and based on the observation date OF THE DATA PRODUCT, pick the appropriate pair of CalDB zip files for the two detectors, based on the following list:

```
# Epoch_start_time          Epoch_end_time              Epoch
2023-10-01T00:00:00.000     2100-12-31T23:59:59.999     epoch20231001
```

For example, in the first epoch following two files need to be downloaded:
CAL_epoch20231001_CdTeResponseReader.zip -- for the two CdTe detectors
CAL_epoch20231001_CZTResponseReader.zip -- for the two CZT detectors

The contents of these CalDB zip files are:
For both CdTe1 and CdTe2:
`CdTeResponseReader/`

`hel1os_cdte_data.pro`	OSPEX Reader code
`hel1os_cdte_arf_v03.fits`	Ancillary Response File
`hel1os_cdte_srf_v03.fits`	Spectral Redistribution Matrix File

For both CZT1 and CZT2:
`CZTResponseReader/`

`hel1os_czt_data.pro`	OSPEX Reader code
`hel1os_czt_arf_v03.fits`	Ancillary Response File
`hel1os_czt_srf_v03.fits`	Spectral Redistribution Matrix File

2.4 Analysis of the data using SolarSoft OSPEX package

(1) Recommended that you create separate folders for CdTe data analysis and CZT data analysis.
(2) Move the relevant files to the folder you generated for CdTe data analysis (see step 1)
   (a) Spectral: hel1os_cdte_spectra_cdte1.fits, hel1os_cdte_spectra_cdte2.fits
   (b) Response: hel1os_cdte_arf_v03.fits, hel1os_cdte_srf_v03.fits
   (c) Data Reader (i.e. interface routine): hel1os_cdte_data.pro
(3) Please repeat the same for the relevant CZT files, that is:
   (a) Spectral: hel1os_czt_spectra_czt1.fits, hel1os_czt_spectra_czt2.fits
   (b) Response: hel1os_czt_arf_v03.fits, hel1os_czt_srf_v03.fits
   (c) Data Reader (i.e. interface routine): hel1os_czt_data.pro
(4) Then the data are read by the following commands:
   (a) Launch OSPEX, e.g.: IDL> o=ospex()
   (b) Register the interface routine,
      e.g.: IDL> o->set, spex_file_reader='hel1os_cdte' (in the CdTe folder)
      e.g.: IDL> o->set, spex_file_reader='hel1os_czt' (in the CZT folder)
   (c) In the SPEX -> Select Input panel (Spectrum or Image File -> Browse), open the necessary spectral FITS file (e.g. hel1os_cdte_spectra_cdte1.fits or hel1os_cdte_spectra_cdte2.fits for CdTe).
   (d) The response matrix will be loaded automatically.

2.5 Light curve FITS files with a Python script

The Python script hel1osLightCurvePlotDisplay_Ver1.1.py provided is meant for plotting of the CdTe and CZT Light curves (i.e. the FITS files). This will help one to read and perform basic functions to display and prepare the data for further quantative temporal analysis.

*** Analysis of Light Curves FITS files (1 second cadence) using a Python script (hel1osLightCurvePlotDisplay_Ver1.1.py).

*** OS currently tested with is Linux (Ubuntu 20.04.6 LTS).

*** The script currently works best using "ipython" interface (please see below)

```
(base) manju@ledzep:~/HLS_SampleData/2024Jul17_opl1_20241205/prod$ ipython
Python 3.10.9 (main, Mar  1 2023, 18:23:06) [GCC 11.2.0]
Type 'copyright', 'credits' or 'license' for more information
IPython 8.30.0 -- An enhanced Interactive Python. Type '?' for help.

In [1]:
```

*** Please make sure that you have installed astropy, pandas, numpy, matplotlib in your environment.

*** The script requires you to copy-paste certain blocks of code, and then run them. Later releases will be in the form of a notebook and with classes for you to be able to import.

Description of Script: Interactive display of HEL1OS light curve data.

- Prompts the user to select the file via a dilaog box. Each file corresponds to the time profile measured by either CdTe1, CdTe2, CZT1, CZT2
- Plots the light curve in the entire energy range.
- Prompts the user to zoom-in and select start-time (left mouse click) and end-time (right mouse click).
- Prompts user if they are satisfied with the selected time range. If not user is allowed to re-select the time range until they are satisfied.
- Start and End times are stored.
- User is prompted to select the energy range of interest, by selecting a number (e.g. "1" corresponds to the first energy range, "2" the second energy range, and so on). The user can select more than one energy range, and may indicate that they have completed the selection by typing "done".

- User will be prompted if they are interested to view the selected energies plotted within the selected time interval.
- The selected energies, within the time-range of interest will be stored as global dataframes, which are available for further analysis by the user.

An example is the "rebin_dataframe" function, which operates after the final selection of time range of interest and energies.

Usage: `newdataframe = rebin_dataframe('dataframe',binsize)`

Here,

- <dataframe> refers to any one of the dataframes saved/stored after running the main workflow section,
- binsize (in seconds) is an integer number which is a user-defined binsize for rebin: we have tested for 11, 15, 60,
- <newdataframe> is the return value which will be renamed appropriately and returned to the user for further analysis.

<dataframe> has three columns: TIME, COUNT_RATE, STAT_ERR

<newdataframe> has two columns: COUNT_RATE, STAT_ERR. The 'TIME' column is now the index.

3. A Short Introduction to X-ray data analysis:

3.1 The Concept of Event Lists:

X-ray detectors provide information on individual photons, including the energy deposited by the X-rays that the detector is sensitive to. Each recorded energy deposit or an attribute that is related to energy, will be referenced by the “time of arrival” and a spatial position, if the detector is position sensitive. Out of the two types of detectors used in HEL1OS, the CZT detectors provide positional information, i.e. it is pixelated and each pixel is referened by a unique “ID” number.
This information makes up an “event” list, which may be considered as a fundamental data product. You can think of it is a table whose rows represent “events” or a possible detected X-ray photon. The minimum cadence at which an “event” is recorded is 10 milliseconds for HEL1OS.
The columns of the table represent some property of the photon detection, as we discussed earlier. For example the time, the photon energy, its corresponding engineering parameter (known as “channel”), the position (in the case of CZT), or any other instrumental flag associated with the detection process.
We can generate “derived” data products from this event list by histogramming one or more columns, for example a spectrum can be generated by binning instrumental energy or a light curve by binning on event detection time.

3.2 What is a PHA file?

Depending upon the physical process by which an X-ray photon interacts with matter, the photon can either completely or partially deposit its energy. In either case, a proportional quantity of charge is generated, which is processed to produce a voltage pulse whose amplitude or “height” can be assigned digital value. This value may lie within a boundary or bin or “channel”, whose width corresponds to a small range of energies $\Delta = \mathrm{Energy}_{maxChannel} - \mathrm{Energy}_{minChannel} / \mathrm{number\ of\ Channels}$,
where $\mathrm{Energy}_{maxChannel}$, $\mathrm{Energy}_{minChannel}$ correspond to the energy deposit values proportional to the maximum and minimum channels, respectively.
Therefore, an X-ray detector generates a series of integer channel numbers or “Pulse Height Amplitude” (PHA), and as photons of different energies arrive and interact with the detector over time, a “spectrum” can be built by histogramming the different pulse heights over Δ. The frequency values corresponding to each channel is termed as a “count”. Thus, the measured energy deposit spectrum or PHA spectrum is a “count spectrum” and must be used to estimate the most likely source photon energy distribution by the method of “forward folding”.

3.3 What is Forward Folding?

A model spectrum, say a Gaussian or power-law or a physical model based on apriori information on the physical considerations of the source, is assumed and convolved with the “instrumental response”. The outcome of this process will be a “model counts spectrum” which is then compared with the “observed count spectrum” by means of an appropriate statistic (e.g. χ^2) and the model parameters (e.g. peak amplitude and width of a Gaussian, spectral index of a power-law, total integral electron flux for a Bremsstrahlung cold-thick-target physical model etc) are iteratively adjusted until the process converges to the best-fit model. This condition will correspond to obtaining the optimum value of the employed statistic (e.g. ~ 1 for χ^2). When best-fit result is still unacceptable, the previously assumed model may need to be altered.

3.4 Why do we need the instrumental response for X-ray analysis?

Earlier, we learned that the energy deposited by an X-ray is proportional to the measured PHA. The constant of proportionality between the two is known as the “gain” and can vary from detector to detector (i.e. CdTe1 and CdTe2 need not have the same gain), with detector position (i.e. different pixels in one CZT detector may have different gains) and temperature. Assuming a linear relation between these two parameters, the “energy vs channel” calibration curve can be fit using:

$$\boxed{\text{Energy}\left(keV\right) = \text{Gain}\left(keV/channel\right) \times \text{Channel} + \text{Offset}\left(keV\right)} \qquad \textbf{(3.1)}$$

This offset corresponds to the minimum detectable energy at the 0th channel.

If the differential photon flux F(E) emitted by the source has units of photons s^{-1} cm^{-2} keV^{-1} then how does observed PHA spectrum obtain units of counts s^{-1} channel^{-1}? This is because

- the flux was measured over the detector’s **effective area** A(E) cm^2, which is dependent on the energy of the incoming X-rays.
- photons of different energies were **redistributed** as counts in different PHA channels. This redistribution depends on their depth of interaction (DOI) and hence process of interaction, which is a function of energy.

These two important aspects are dependent on the type of detector material used, the geometic area, the filters used, any materials that are in the vicinity of the detector etc. We provide the instrument response as part of the Level-1 data bundle in two forms:

1. Anciliary Response File (ARF): This file includes the geometric photon-collecting area of the detector multiplied by the energy-dependent efficiencies of MLI (multi-layer insulation) thermal blanket, Aluminum shield, Light-tight filter, Berylium filter (in the case of CdTe), collimator open area fraction.
2. Spectral Redistribution File (SRF): This file consists of a dimensionless normalized matrix which represents the probability that a photon of a given energy (represented by each row of the matrix) is registered in a given channel (represented by each column of the matrix). An ideal SRF would provide a one-to-one mapping between detector channel and incident energy (Equation 3.1), i.e. a diagonal matrix.

3.5 Are only X-rays from solar flares detected by HEL1OS?

No, especially in the CZT detectors. Apart from solar flares, X-rays from the non-flaring Sun, the cosmic diffuse X-ray background, charged particles (primary and secondary) from the interaction of Solar Energetic Particles (SEPs) and Galactic Cosmic Rays can deposit energy in the detectors. The CdTe detectors have a very small area compared with the CZT (1:64) and hence the components of the background are negligible relative to the solar flare X-ray flux in that energy range (~10 keV to 40 keV). This is not the case for the CZT detectors, which you will see during the Walk Through section.

4. Spectral Analysis:

The distribution of HEL1OS Level-1 Type II spectral data is meant for time-resolved spectroscopic fitting using the OSPEX (Object Spectral Executive) spectral package in SolarSoft.

Requirements:

1. Linux (*For version information, please refer ssw installation requirements*)
2. IDL Version > 7.1 (64 bit)
3. SSW, minimum requirement in **packages** is "**spex**", "**chianti**" and "**x-ray**".

The HEL1OS Level-1 package will include

1. an "events" list (FITS): The "evt.fits" provided as part of the Level-1 data package includes a 4 extensions, each one corresponding to CdTe1, CdTe2, CZT1, CZT2.
2. "good time interval" or "gti" files (FITS): these are data products that are in the form of a tables, giving times during which events were not filtered out due to sub-optimal detector configuration (e.g. fluctuating device temperature, high voltage etc), high background (i.e. during an solar energetic particle event) etc. For the Level-1 data, the "gticdte1.fits", "gticdte2.fits", "gticzt1.fits" and "gticzt2.fits" include the entire data dump duration. These files will have relevance only for the Level-2 data and can be ignored for Level-1 analysis purposes.
3. Housekeeping files (fits): This file contains different operating parameters of the instrument with a cadence of 1 second, for example device temperature, operating voltage, broad band detector count rates etc.
4. four individual Type II spectral files (OGIP FITS) for CdTe1, CdTe2, CZT1, CZT2 binned at 20 seconds over the full duration of the data dump,
5. four individual light curves (in OGIP FITS format) binned at 1 seconds, over the full duration of the data dump:
    a. CdTe1, CdTe2: consisting of default broad energy bands 5-20 keV, 20-30 keV, 30-40 keV, 40-60 keV and the full SRF energy range (1.8 keV to 90 keV);
    b. CZT1, CZT2: consisting of default broad energy bands 20-40 keV, 40-60 keV, 60-80 keV, 80-150 keV and the full SRF energy range (18 keV to 160 keV).

6. Response files: spectral redistribution files (SRF) and ancillary response files (ARF) for CdTe and CZT detectors, separately:
    a. CdTe1, CdTe2 will use “hel1os_cdte_srf_v03.fits” and “**hel1os_cdte_arf_v03.fits**”
    b. CZT1, CZT2 will use “hel1os_czt_srf_v03.fits” and “**hel1os_czt_arf_v03.fits**”
7. IDL “reader files”, to enable the Type II spectra and the response files to be read into OSPEX: “**hel1os_cdte_data.pro**” and “**hel1os_czt_data.pro**”

Notes:

- As it stands now, we recommend that the lowest energy to be used for spectral fitting of the CdTe detectors ~9.5 keV and for CZT detectors ~35 keV.
- **OSPEX** (https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm) does not allow simultaneous fitting of spectra from two different detectors, say two CdTe together or CdTe+CZT. So you can use the Level-1 data to perform spectral analysis for each detector separately.
- If you are familiar with using **XSPEC** (https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XspecManual.html) or **Sherpa** (https://sherpa.readthedocs.io/en/latest/), then you may attempt simultaneous fitting of two detectors (Level-1). If you are not familiar with these tools, the HEL1OS team is planning to include these details in an updated version of this user manual in a future revision.
- **For OSPEX users**: After downloading the tarball with the relevant data files to your home directory, we recommend that you move the relevant files pertaining to CdTe detectors (spectral files, response, reader files) to a separate folder. The same applies to CZT.
- Please make sure that the data reader files are always copied into the location of the spectra and response files.

5. Walk-through using a test data set- GOES M5.0-class flare July 17, 2024:

Let us attempt fitting the CZT data corresponding to this flare.

5.1 Loading the Spectral Data:

Start by typing “tcsh” in your terminal (if you aren’t already using C-shell). If SolarSoft is setup properly in your system, you should see something similar to this:

```
manju@ledzep:~/HLSXXN18P1AL10015809NNNN24200053414630_N00_0000_000211_V1_1/opl1/prod/CdTeSpectra$ tcsh
SSW  setup will include: <gen hessi packages demreg xray spex stereo secchi aia hmi hinode xrt chianti ontology>


Type <sswidl> to start SSW IDL
```

You are now in the C-shell and can start the analysis process. As you can see here

```
ledzep:~/HLSXXN18P1AL10015809NNNN24200053414630_N00_0000_000211_V1_1/opl1/prod/CdTeSpectra>ls
hel1os_cdte_arf_v03.fits                     hel1os_cdte_data.pro
     hel1os_cdte_spectra_cdte1.fits
     hel1os_cdte_spectra_cdte2.fits
     hel1os_cdte_srf_v03.fits
ledzep:~/HLSXXN18P1AL10015809NNNN24200053414630_N00_0000_000211_V1_1/opl1/prod/CdTeSpectra>sswidl
```

This starts an SSWIDL command line session, with an IDL prompt. Here you will type:

```
IDL> o=ospex()
```

The SPEX Main Window widget (Figure 5.1) will appear. Back at the command prompt you will need to set the “hel1os_czt” data reader.

```
IDL> o->set, spex_file_reader='hel1os_czt'
```

Once these steps are completed, let us get a look at the SPEX Main Window (Figure 5.1)

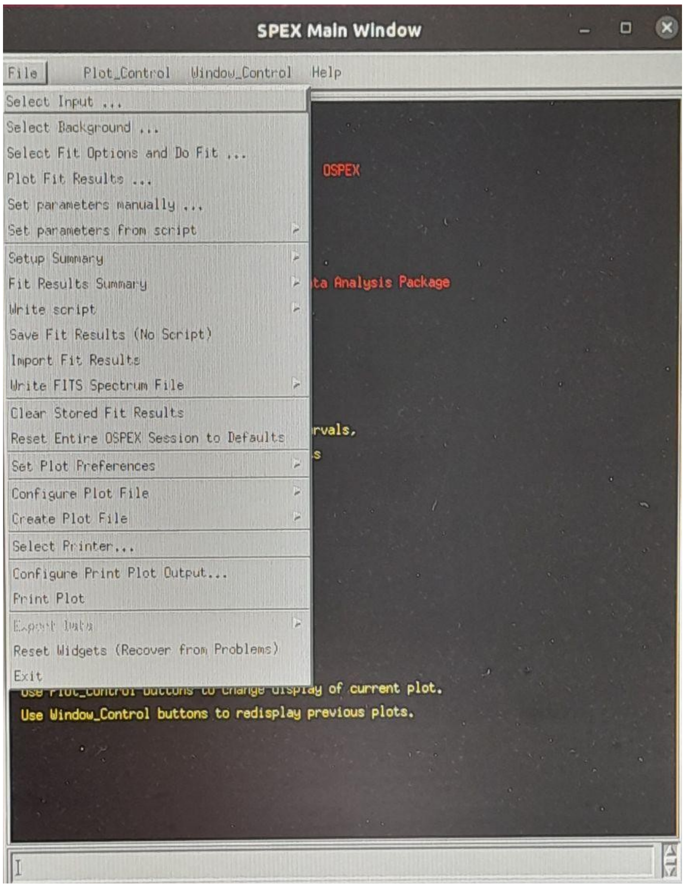


Figure 5.1: The SPEX Main window indicating the different items in the "File" dropdown menu.

First, click on "Select Input" which allows the following widget to pop up, as shown in (Figure 5.2)

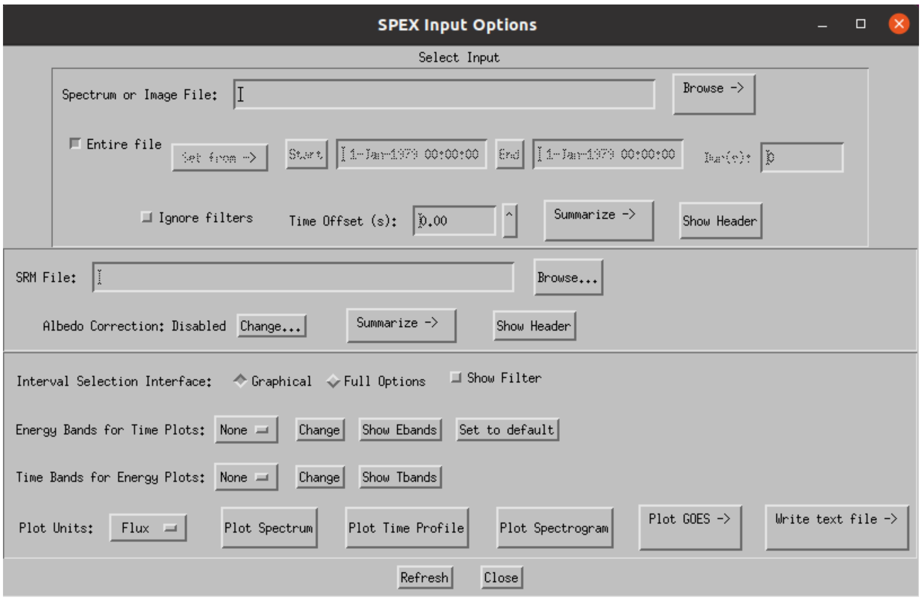


Figure 5.2: Widget to select the input file.

Click on “Browse”, and then “On this computer…” and you get the following “file pick” dialog box.

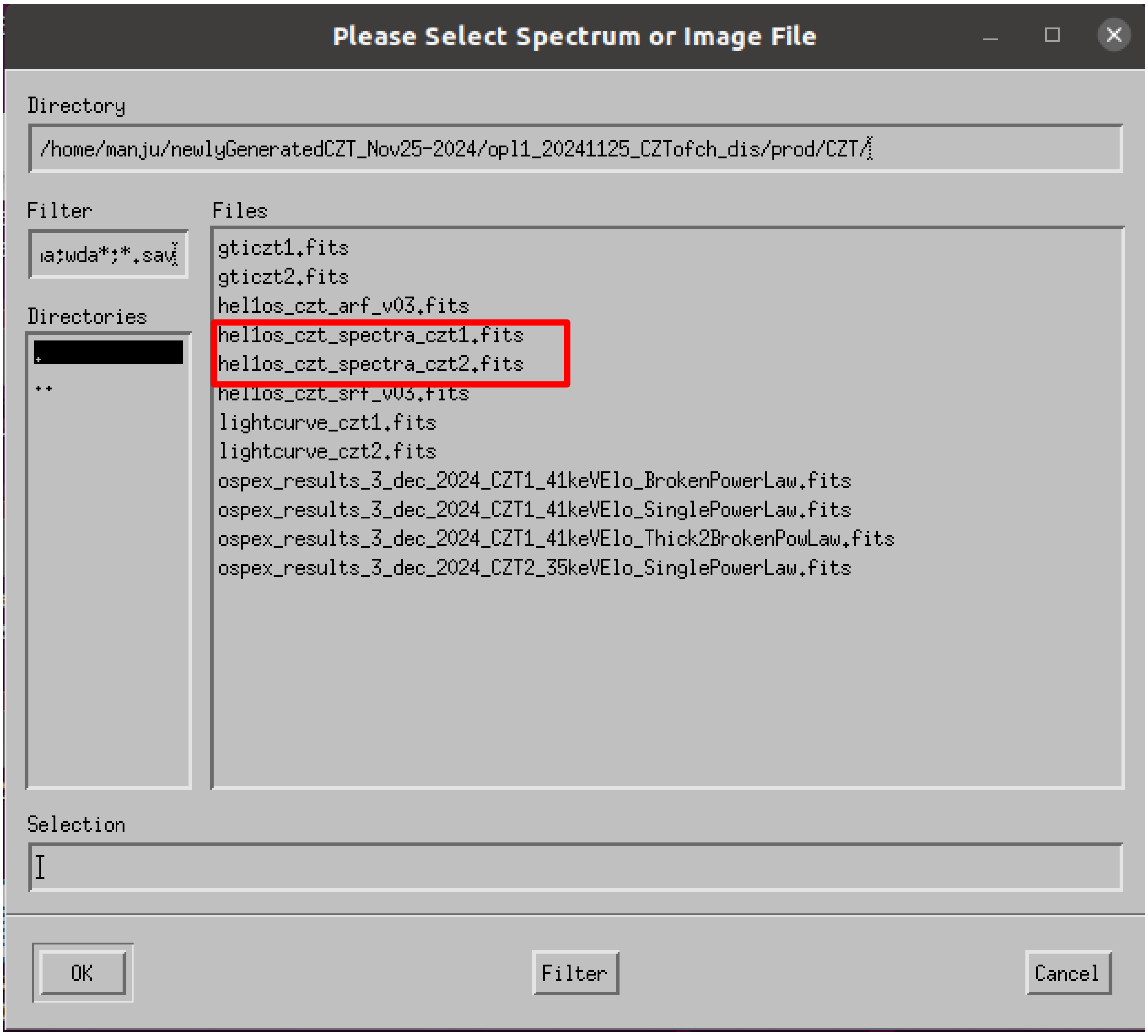


Figure 5.3: File pick dialog box.

As you can see, the spectral files corresponding to both CZT1 and CZT2 have been highlighted in the red box. Let’s pick CZT1 for this example. Click on “hel1os_czt_spectra_czt1.fits” and then click “OK”.

The OSPEX czt data reader that had been set earlier will ensure that information about both response files are included in the OSPEX object and the “hel1os_czt_srf_v03.fits” and “hel1os_czt_arf_v03.fits” are automatically loaded into the “Input Options” widget. If the response files are not in the same location as the spectral files, the reader would throw an error indicating that it could not find the response files.

If the loading process is successful, you should see something similar to this in your IDL prompt terminal/work-bench:

```
% SPEX_ANY_SPECFILE::READ_DATA: Using routine hel1os_czt_data to read data.
% Compiled module: HEL1OS_CZT_DATA.
MRDFITS: Binary table.  8 columns by  2158 rows.
% Compiled module: FITS_KEYWORD_VALUE.
% Compiled module: FITS2RM.
% Compiled module: FITS_OPEN.
% Compiled module: SXDELPAR.
% Compiled module: FITS_CLOSE.
% Compiled module: GET_FITS_EXTNO.
% Compiled module: REQUIRED_TAGS.
% Compiled module: GT_TAGVAL.
% Compiled module: STR_TAGVAL.
% Compiled module: TAG_INDEX.
% Compiled module: N_DIMENSIONS.
MRDFITS: Binary table.  3 columns by  520 rows.
Propagation time is unknown. The satellite time will be used.
% Compiled module: STR_LASTPOS.
% Compiled module: GETUTBASE.
% Compiled module: GETUT.
% Compiled module: INT2SEC.
% Compiled module: UTIME.
% Compiled module: GET_EDGES.
% Compiled module: EDGE_PRODUCTS.
% Compiled module: ANYTIM2INTS.
% Compiled module: GT_DAY.
% Compiled module: GT_TIME.
% Compiled module: ATIME.
% Compiled module: FCHECK.
% Compiled module: F_ATIME.
% Compiled module: MINMAX.
% Compiled module: MATCH_STRUCT.
% Compiled module: FSTRING.
IDL>
```

This indicates that the spectral file and responses are correctly read by the “reader” file into OSPEX.

Now, go back to the “SPEX Input Options” (Figure 5.2) and click on the button “Plot Time Profile”. As seen in Figure 5.4, the full duration “light curves” or time profiles corresponding to CZT1 Type II data are displayed in the SPEX Main Window in 5 default energy bands. OSPEX has inbuilt functions that display these time profiles, where the cadence between each point corresponds to the cadence of each time-resolved spectrum in the Type II file (20 seconds in this case).

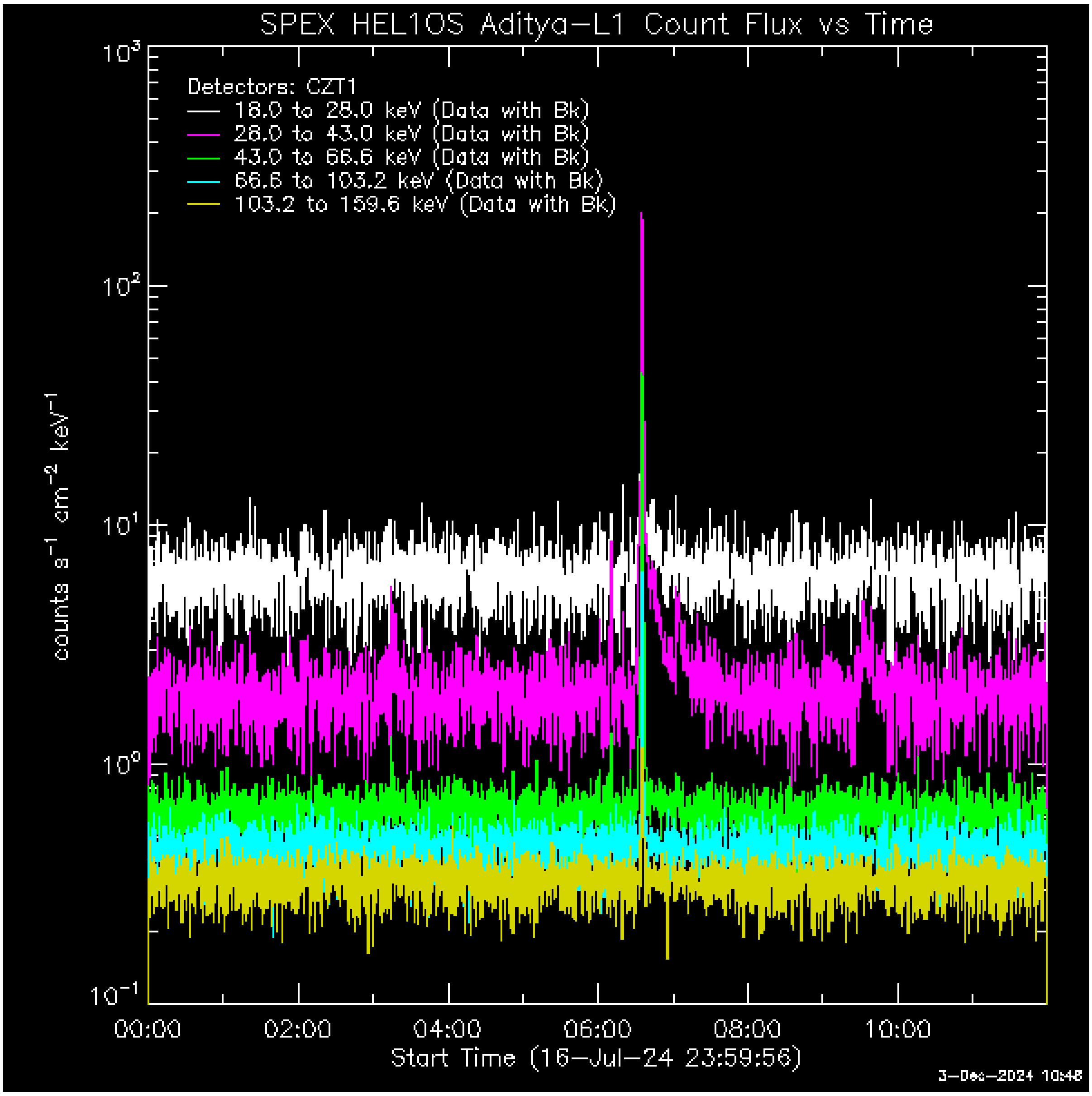


Figure 5.4*: 12 hour CZT1 light curve/time profile. The X-rays >20 keV which correspond to the GOES M5.0 class flare are seen within the "spike" profile*.

In Figure 5.4, zoom in by left-clicking and dragging in the plot over your region of interest (Figure 5.5) and zoom out by a single left click on the plot.

If you want to identify coordinates on the plot, right click.

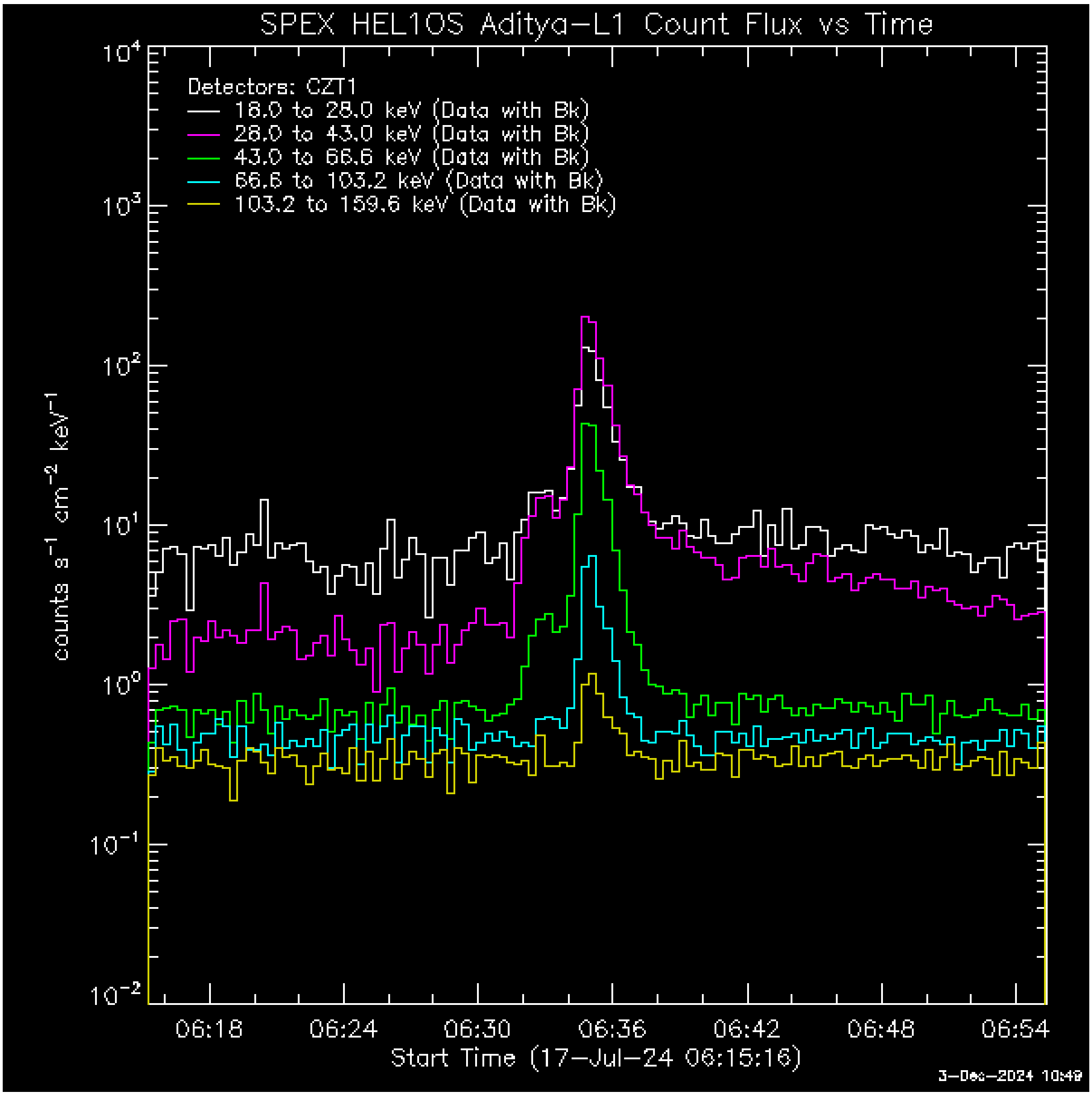


Figure 5.5*: CZT1 Light Curve of the GOES M5.0-class flare. This emission is part of the impulsive phase of the flare and as observed, is extremely energetic with photons detected up to ~100 keV*.

5.2 Subtracting the Background:

The next item in the "File" dropdown menu in Figure 5.1 is "Select Background…" Once you click that item the following widget will pop-up:

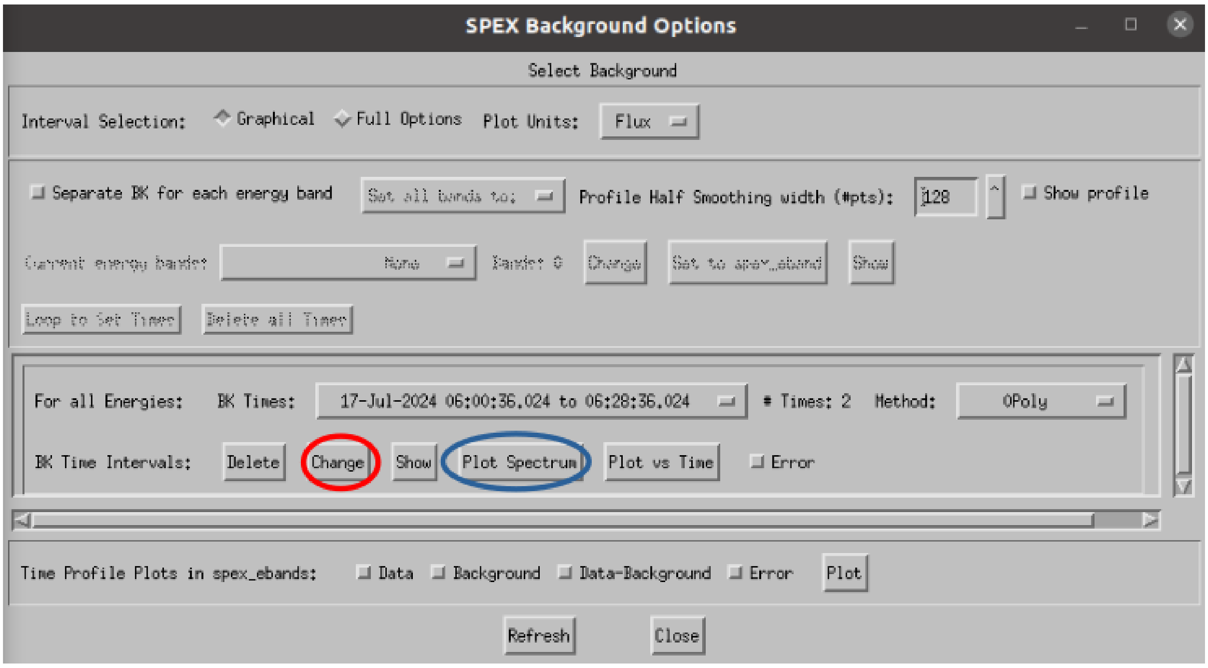


***Figure 5.6**: The "Background Options" widget*.

This widget is used to select regions of non-flaring emissions from the complete 12 hour light curve to generate a "background spectrum" (see **Section 3.5**). We then subtract this background spectrum from the data to ensure that we are dealing with counts generated only due to the flaring region.

We generally select the background by first zooming in on the region of interest in the time profile (Figure 5.5). Then we click on the "*Change*" button highlighted in red in Figure 5.6. We then get a pop-up as shown in Figure 5.7:

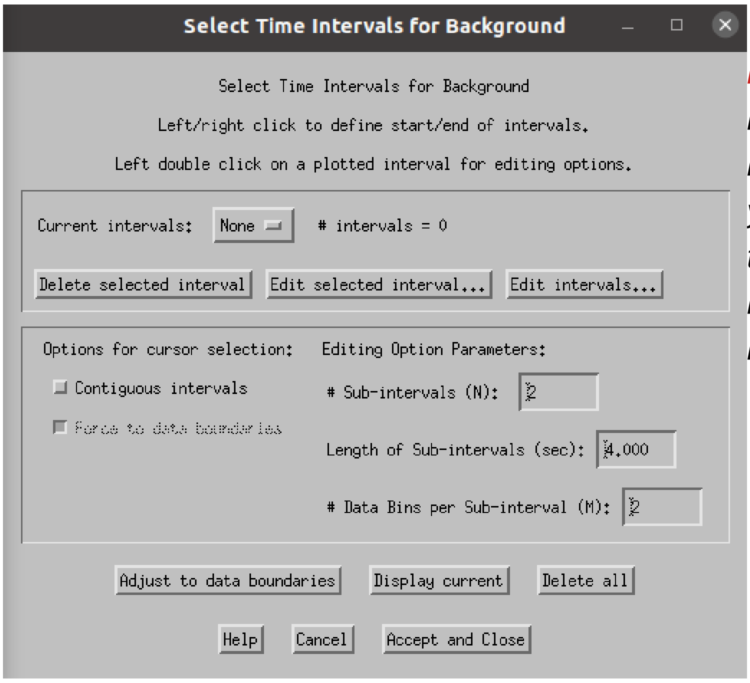
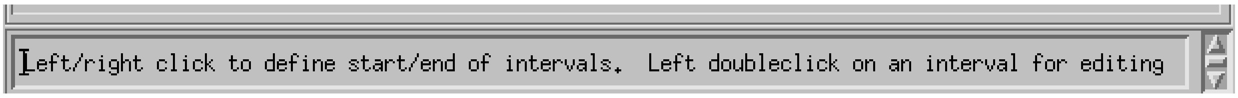


Figure 5.7: Selecting time intervals for generation of the background spectrum. Note that you can select any number of time intervals you think is needed and as long a time interval you require.

Once the pop-up appears, you will see the following message displayed in the bottom panel of your "SPEX Main Window" with the zoomed in time profile:



What that implies is you can use the GUI to select the start and end times of the background, and then fine tune the values by clicking on "*Edit selected interval...*" or "*Edit intervals...*".

An example of two selected intervals for the background is shown in Figure 5.8:

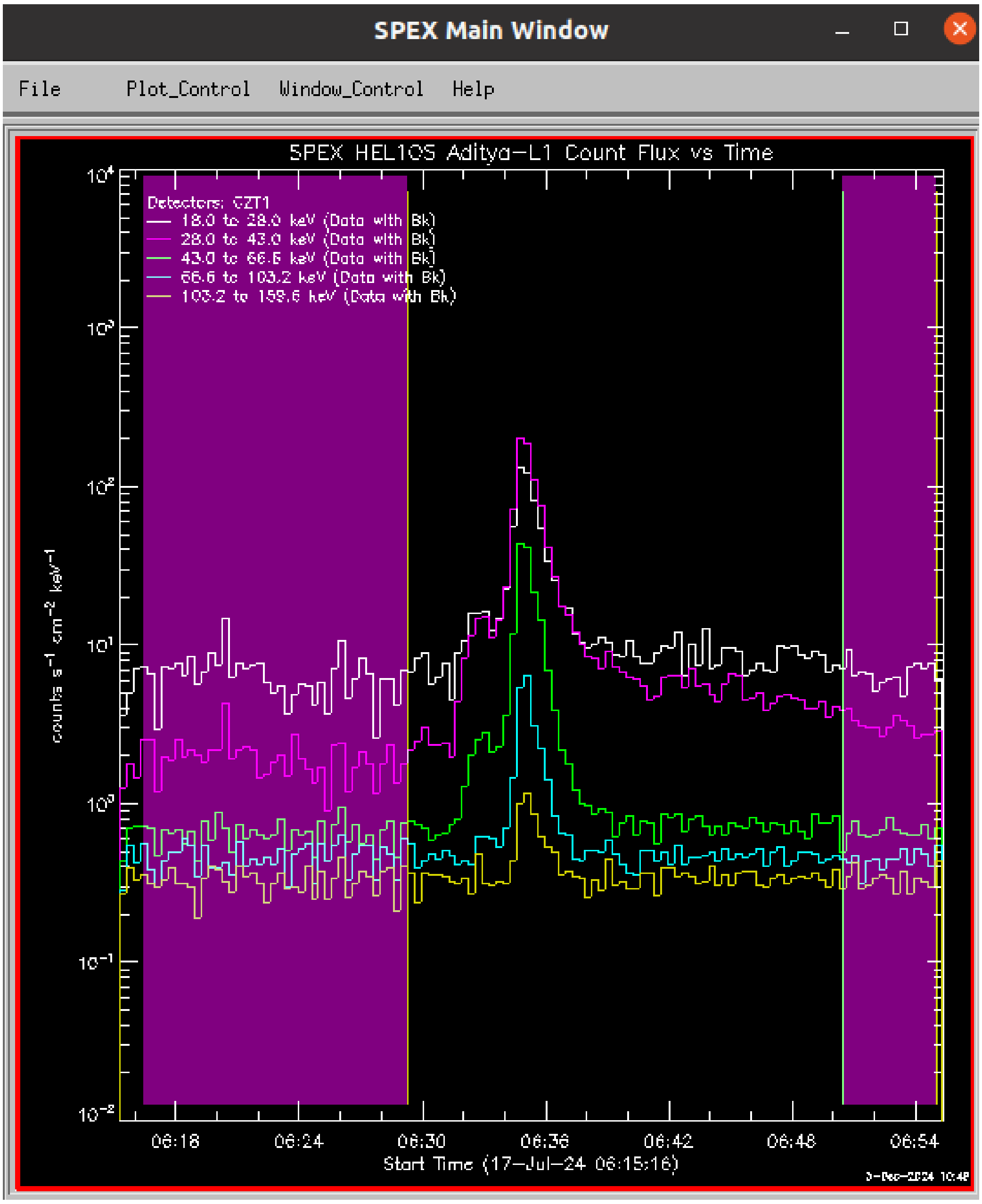


Figure 5.8: The shaded regions show the time intervals selected for generation of background spectrum in CZT1.

Once you are satisfied with the selection, you can click “*Accept and Close*” in Figure 5.7, This causes the widget to disappear, bringing you back to Figure 5.6. Click “*Plot Spectrum*” highlighted in blue and you get the background spectra for both time intervals, as shown in Figure 5.9.

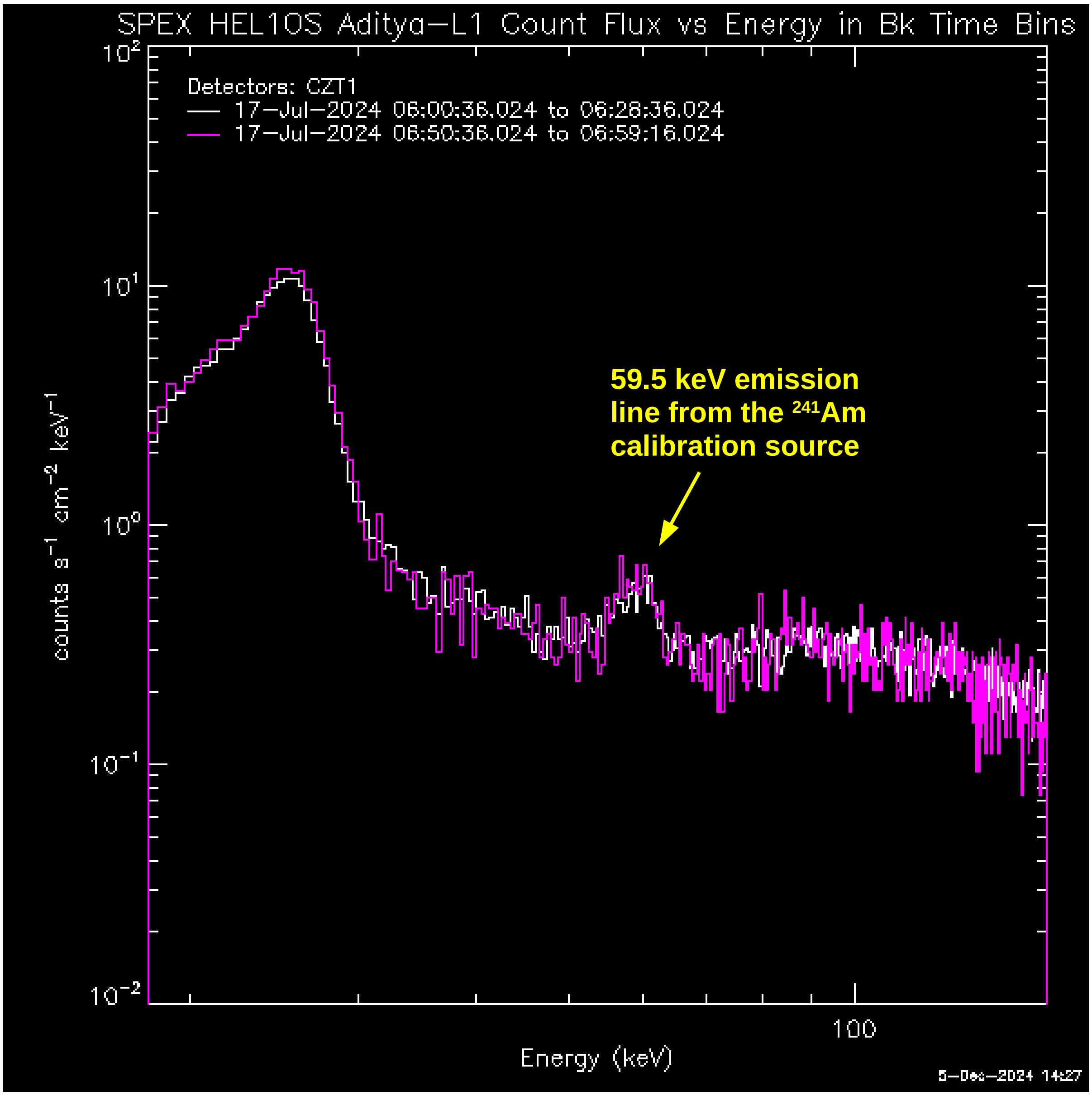


***Figure 5.9**: CZT1 background spectra accumulated during the two intervals labeled in the plot. The calibration line ~59.5 keV due to ^{241}Am is visible in the spectrum.*

5.3: Performing forward-fitting on the spectra:

After inspecting the background, we can now Click on "*Close*" in the widget in Figure 5.6. We are now back to the SPEX Main Window in Figure 5.1, where we select the third item in the Menu, "*Select Fit Options and Do Fit...*" Once you click on that, you get the following widget (Figure 5.10):

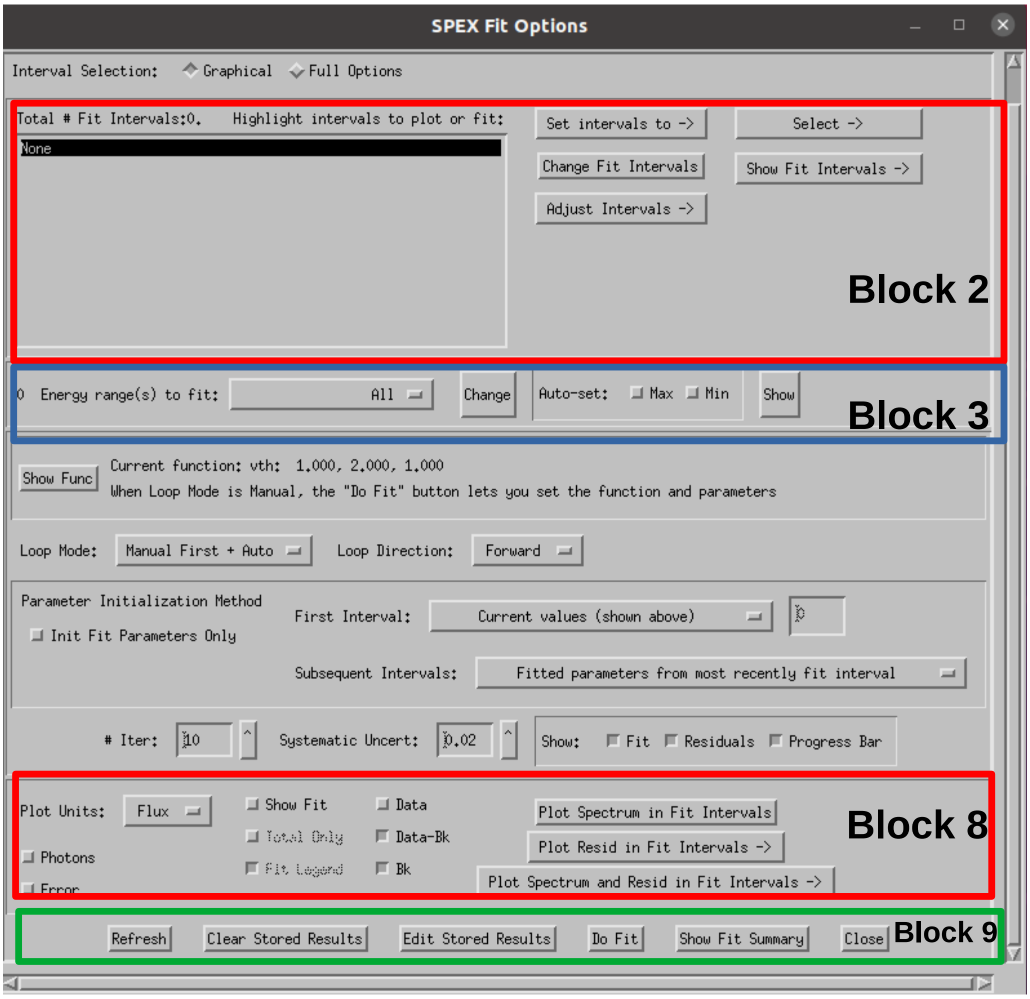


***Figure 5.10**: This widget can be considered to consist of 9 "Blocks"; **Block 1**: "Interval Selection", **Block 2**: "Fit Intervals", **Block 3**: "Energy Ranges to Fit", **Block 4**: "Show Func", **Block 5**: "Loop", **Block 6**: "Parameter Initialization", **Block 7**: "Iter etc", **Block 8**: "Plotting", **Block 9** "Fitting".*

For basic spectral analysis, we use only the following “blocks” as highlighted in Figure 5.10:

1. Block 2: Select the time intervals for fitting;
2. Block 3: Set the energy range for fitting;
3. Block 8: Plotting the Spectrum for visualization purposes,
4. Block 9: Fitting (will take you to another widget).

First, click the “*Change Fit Intervals*” button in Block 2; once you do this, the full 12 hour CZT1 background-subtracted time profile in the 5 default energy bands will be displayed in the “SPEX Main Window” and a new widget “*Select Time Intervals for Analysis*” will appear (Figure 5.11)

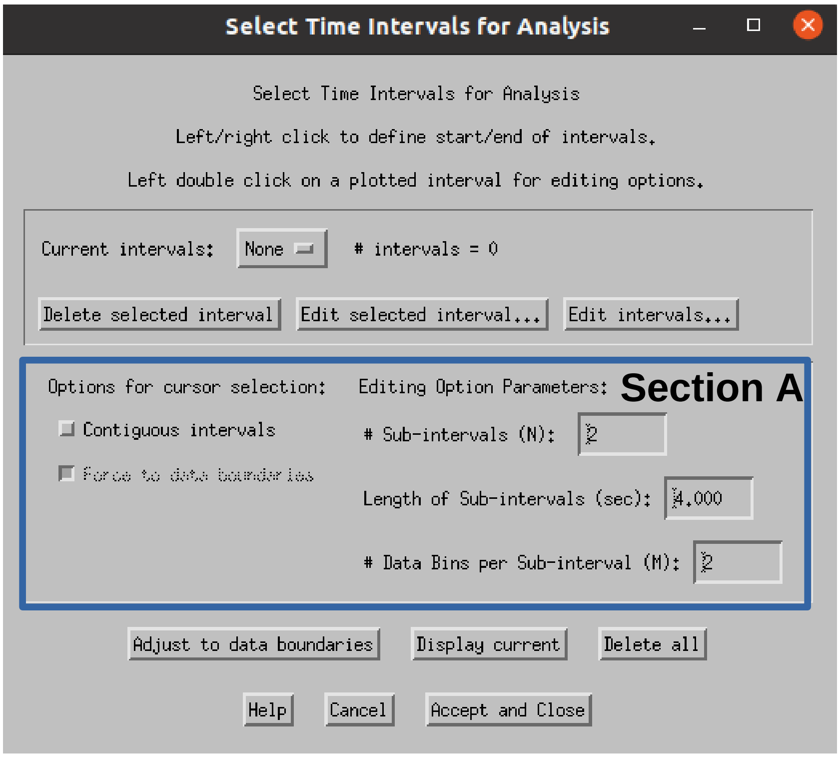


***Figure 5.11**: Widget to allow you to select the time intervals for fitting.*

Similar to the procedure outlined in the Background Selection, Left/Right click to select the start and end times of the flare of your interest. Then, in the Section A (outlined in blue), you have multiple options: you can either divide the flare interval into a desired number of sub-intervals or into desired length of sub-intervals. For our example, since the duration of the impulsive phase is short (~7 minutes), we will select one time interval around the peak, as shown in Figure 5.12.

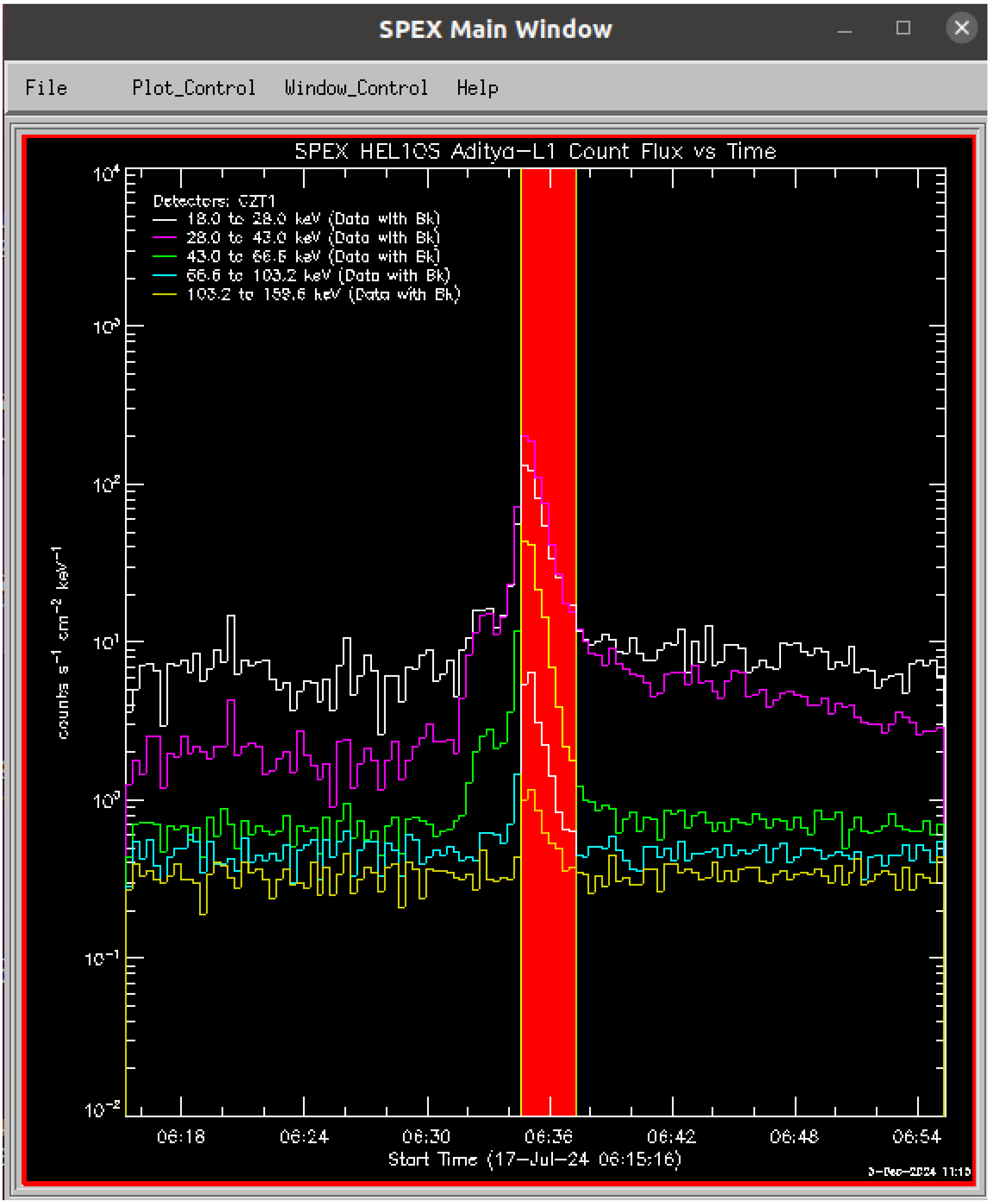


Figure 5.12*: Selected time interval shaded in red used for generating and fitting the flare spectrum (06:34:36.024 to 06:37:16.024 UT)*.

Next click "*Accept and Close*" in Figure 5.11 and you are back to "SPEX Fit Options" widget (Figure 5.10), with the included "*Fit Time Intervals*" listed as shown in Figure 5.13:

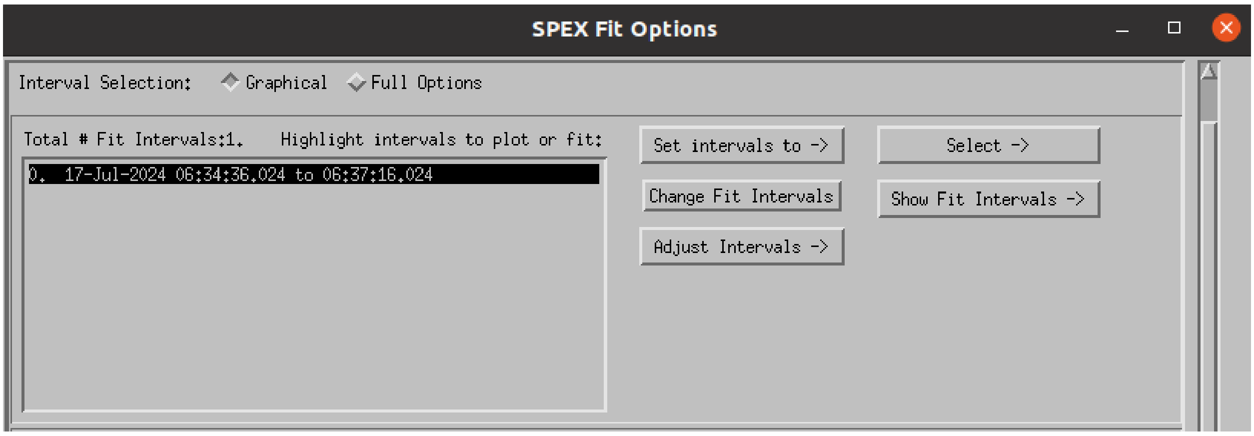


***Figure 5.13**: Block 2 of the SPEX Fit Options widget where the selected time-interval is indicated*.

Click on "*Plot Spectrum in Fit Intervals*" in Block 8 of Figure 5.10, after selecting the "*Data-Bk*" button. Please note that the subsequent spectrum will have units of flux, in the counts space, i.e. units of flux will be counts cm^{-2} s^{-1} keV^{-1}. If you want to display it in units of photons cm^{-2} s^{-1} keV^{-1}, then click on the "*Photons*" button.

As of this version of the Level-1 data, it is recommended to set the lowest energy range for fitting >30 keV due to more investigation of the spectrum < 30 keV. The highest energy value may be set based on that energy at which the count flux dominates the background, as shown in Figure 5.14. Click on the "*Change*" button in Block 3 and select the values based on the instructions available in the ensuing widget (similar procedure for setting time intervals for background and fitting). This will ensure that you set the energy range for fitting correctly, which is important.

For our example, we have set the energy range for fitting from ~33 keV to ~106 keV.

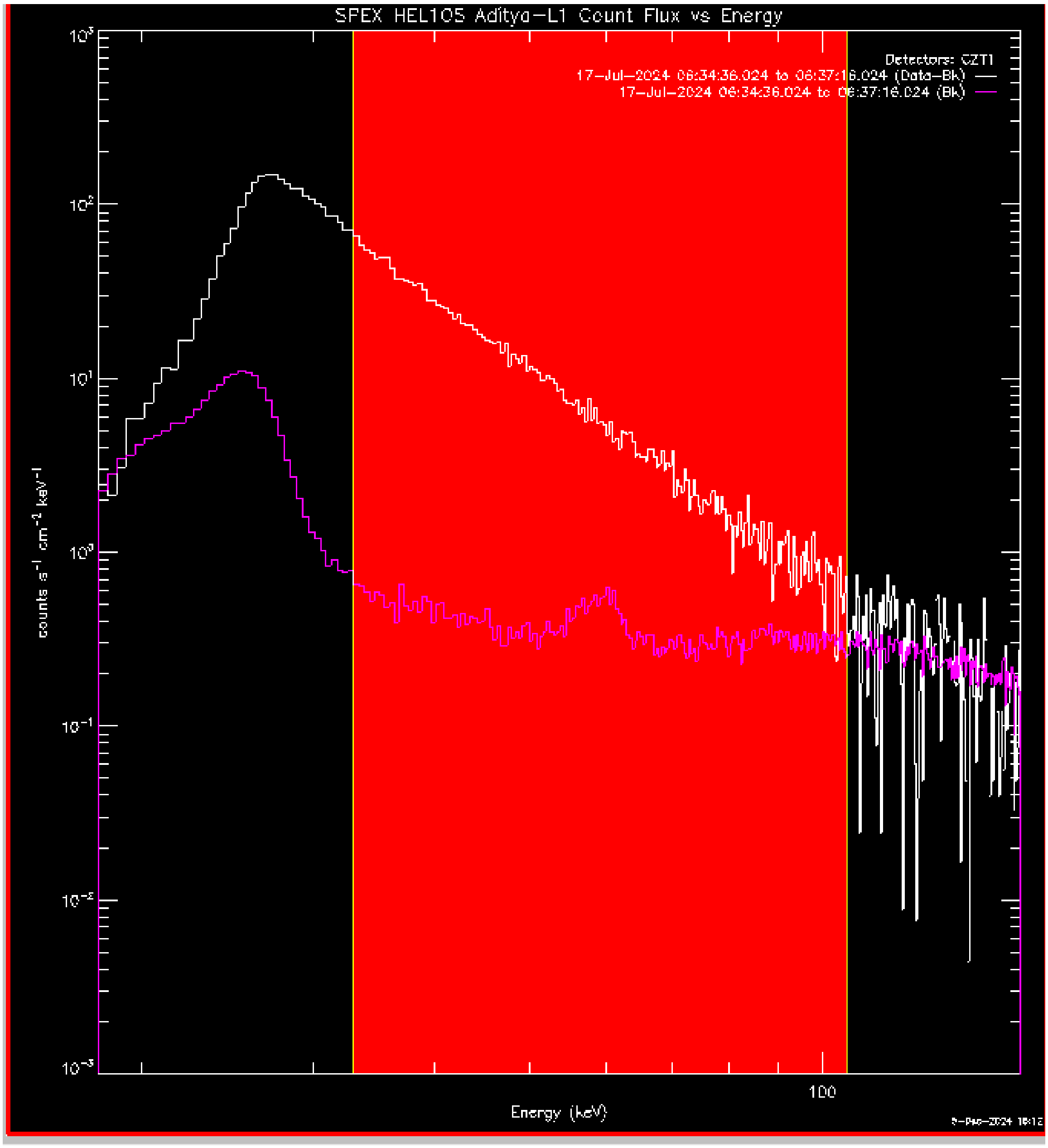


Figure 5.14: Observed/Measured Count spectrum is indicated by the white solid line, while the background spectrum is the magenta line. The energy range for fitting is highlighted by the red box (~33 keV to 106 keV).

Let us now navigate to Block 9 in Figure 5.10 and click on “*Do Fit*” button. This will bring you to the widget shown in Figure 5.15,

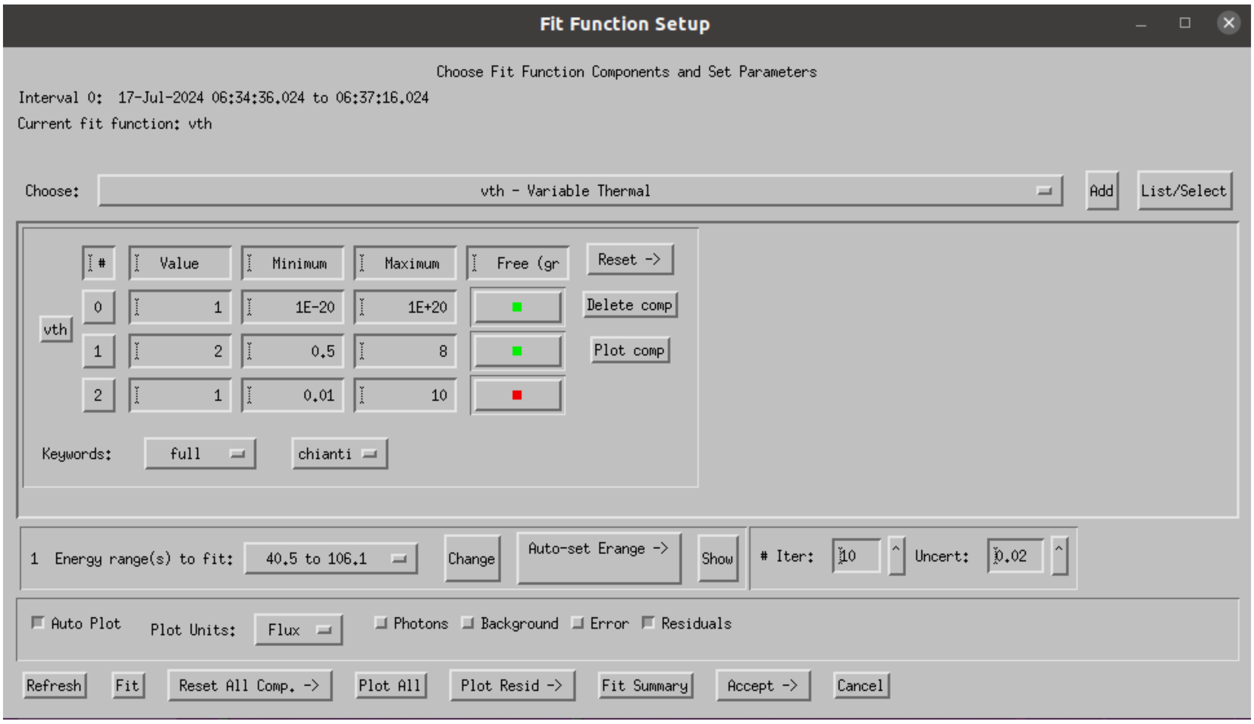


***Figure 5.15**: The “Fit Function Setup” widget. Note that the energy range can be adjusted in this widget as well*.

You can choose any empirical or physical model from the drop down menu or by clicking the “List/Select” button. The default model is “vth” which is a thermal model not relevant for the energy ranges covered by CZT detectors. We will use it in the analysis of the CdTe data (***the details will be elaborated in the HEL1OS Cookbook***). The list of models is shown in Figure 5.16 – beginners are recommended to stick to using models like single power law (“1pow”) or broken power law (“bpow”) instead of starting with the physical model (see caption in Figure 5.16). These models will help you study the behavior of the photons at different stages of flare evolution. Advanced users and those who have had prior experience may certainly use any of the physical models available for deriving the physical parameters of the non-thermal electron population responsible for generation of these high energy X-rays.

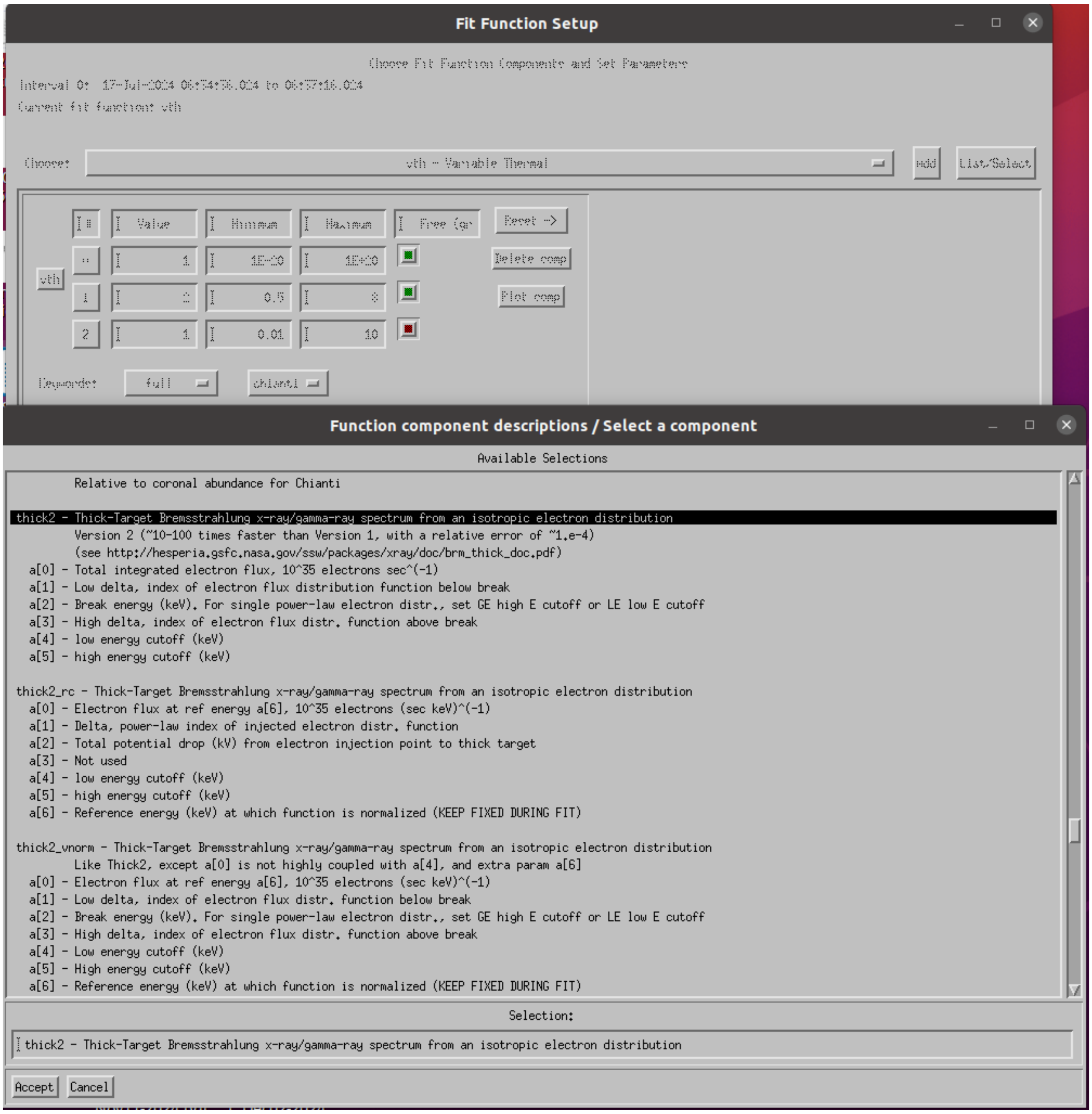


Figure 5.16: The list of models available for forward modeling. As shown here, the "thick2" model has been selected, which is a physical model used to derive the spectral parameters of the electron spectrum responsible for emission of high-energy X-rays. The list has a description of the various parameters, which can be "frozen" or left free while fitting.

5.3.1: Fitting with an empirical model: The Single Power-law

Suppose you want to start with a single power law. Make sure you delete the default "vth" model by clicking the "*Delete comp*" button. Then after clicking "*List/Select*" and selecting the "1pow" model, click the "*Accept*" button.

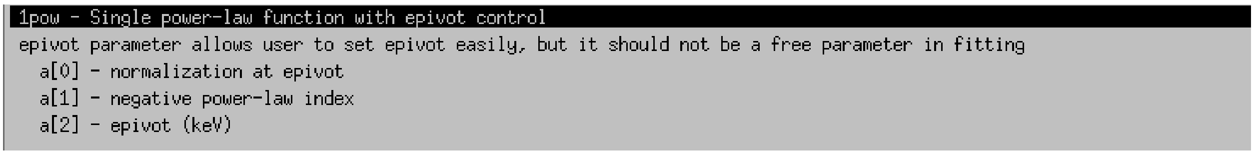

```
1pow - Single power-law function with epivot control
epivot parameter allows user to set epivot easily, but it should not be a free parameter in fitting
  a[0] - normalization at epivot
  a[1] - negative power-law index
  a[2] - epivot (keV)
```

***Figure 5.17**: Single power law or "1pow" as described in the List/Select Model widget. Here, a[2] or "Epivot" is fixed at 50 keV.*

Then the widget in Figure 5.15 changes to this:

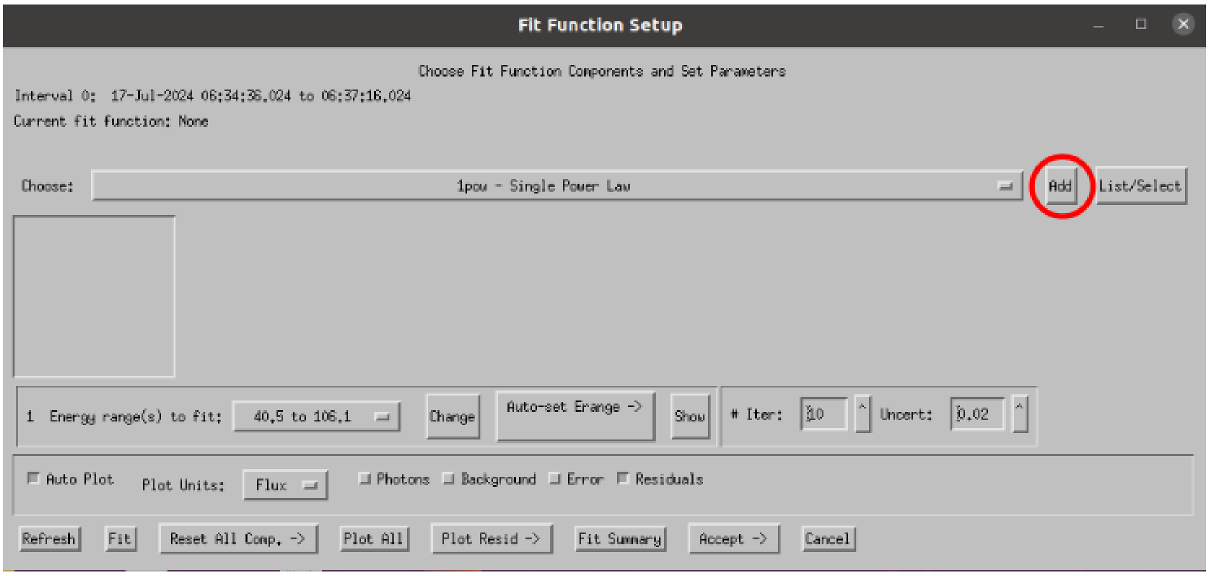


***Figure 5.18**: Widget after selecting the model of interest.*

Make sure you click "*Add*"; otherwise the model will not be included for the forward fitting. After this is done, the model will be displayed, as shown in the Figure 5.19. The boxes labeled "0", "1", "2" denote the 3 parameters used to describe "1pow", and these parameters are described in Figure 5.17. Make sure that the energy range for fitting is between 40 keV and 106 keV, click on the "Fit" button, highlighted in red in Figure 5.19.

You will be able to see the forward fitting procedure as it occurs on your IDL terminal/work bench (Figure 5.20).

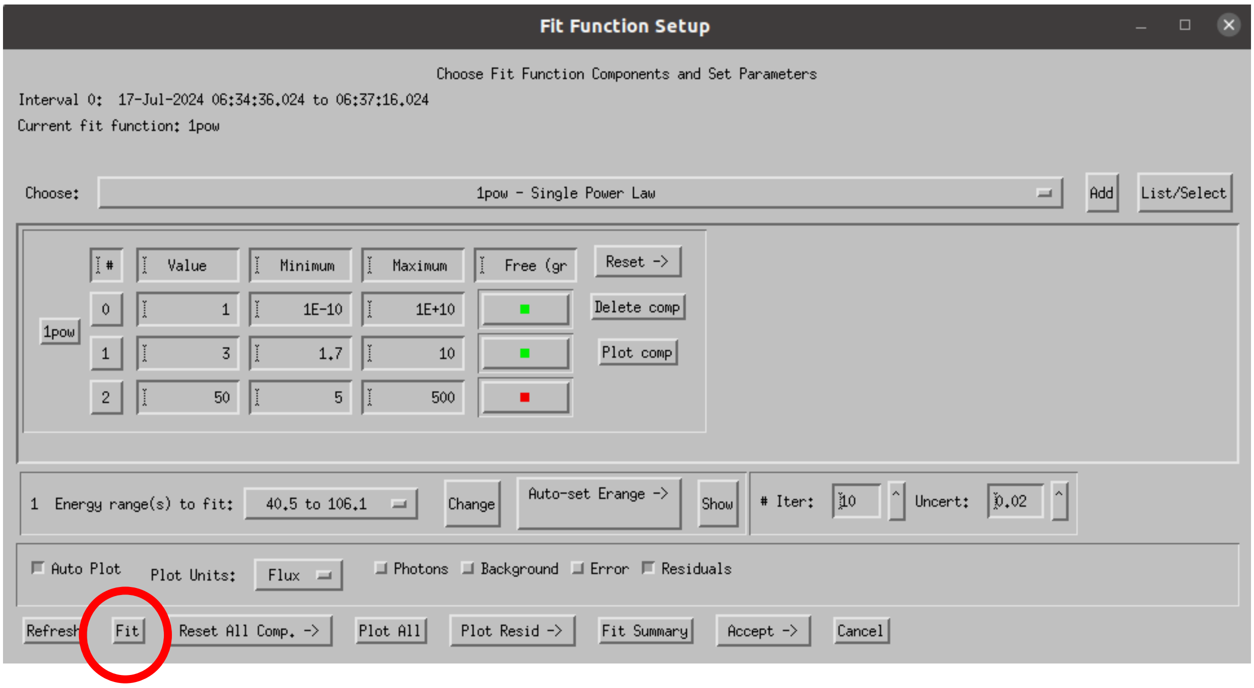


Figure 5.19: After adding "1pow" to the model list for fitting.

```
Fitting Interval 0 17-Jul-2024 06:34:36.024 to 06:37:16.024
% Compiled module: SPEX_FIT::XFIT_COMP.
% Compiled module: GET_HANDLER_ID.
% Compiled module: WIDGET_ID.
% Compiled module: CHECK_FUNC_ELECTRON.
% Compiled module: GET_ABUN_TABLE.
% Compiled module: GET_FE_ABUN_REL2H.
% Compiled module: XR_RD_ABUNDANCE.
% Compiled module: XR_RD_ABUNDANCE_TYPE.
% Compiled module: RESTGEN.
% Compiled module: F_1POW_DEFAULTS.
 in spex_drm::process
% Compiled module: F_1POW.
% Compiled module: COMPARE_FLOAT.
% Compiled module: MCURVEFIT.
% Program caused arithmetic error: Floating underflow
% Compiled module: SPEX_FITALG_MCURVEFIT_EVAL.
 Iterating... Chisq = 0.330  Full Chisq = 57.0  Parameters = 0.1100, 3.028, 50.00
 Iterating... Chisq = 0.141  Full Chisq = 24.4  Parameters = 0.1082, 3.281, 50.00
 Iterating... Chisq = 0.140  Full Chisq = 24.2  Parameters = 0.1079, 3.273, 50.00
 Iterating... Chisq = 0.140  Full Chisq = 24.2  Parameters = 0.1079, 3.272, 50.00

Mcurvefit results for Interval 0,   Chisq= 0.1399,   Full Chisq= 24.20,   # DoF= 173,   #Iter=4,   Function 1pow
Params= 0.1079, 3.272, 50.00
Sigmas= 0.003283, 0.05898, 0.000

Re-enter fit procedure with errors calculated from best-fit parameters...
 Iterating... Chisq = 1.04  Full Chisq = 180.  Parameters = 0.1080, 3.267, 50.00

Mcurvefit results for Interval 0,   Chisq= 1.043,   Full Chisq= 180.5,   # DoF= 173,   #Iter=1,   Function 1pow
Params= 0.1080, 3.267, 50.00
Sigmas= 0.001145, 0.02155, 0.000

Re-enter fit procedure with errors calculated from best-fit parameters...
 Iterating... Chisq = 1.04  Full Chisq = 180.  Parameters = 0.1080, 3.267, 50.00

Mcurvefit results for Interval 0,   Chisq= 1.043,   Full Chisq= 180.4,   # DoF= 173,   #Iter=1,   Function 1pow
Params= 0.1080, 3.267, 50.00
Sigmas= 0.001146, 0.02156, 0.000
```

Figure 5.20: The fit results in the IDL workbench.

As indicated in Figure 5.20, the best-fit values of the free parameters are listed in order as they appear in Figure 5.17, as "*Params*", while the corresponding 1σ errors on the best-fit values are listed under "*Sigmas*" [*It is typically recommended to use the parameter uncertainty analysis for estimating error on the fit parameters (please refer A.3)*]. The value of reduced χ^2 is also printed out (1.043), and the name of the fit function is also shown. Figure 5.21 shows you how the best-fit model spectrum compares with the observed count spectrum (see the Figure caption for details).

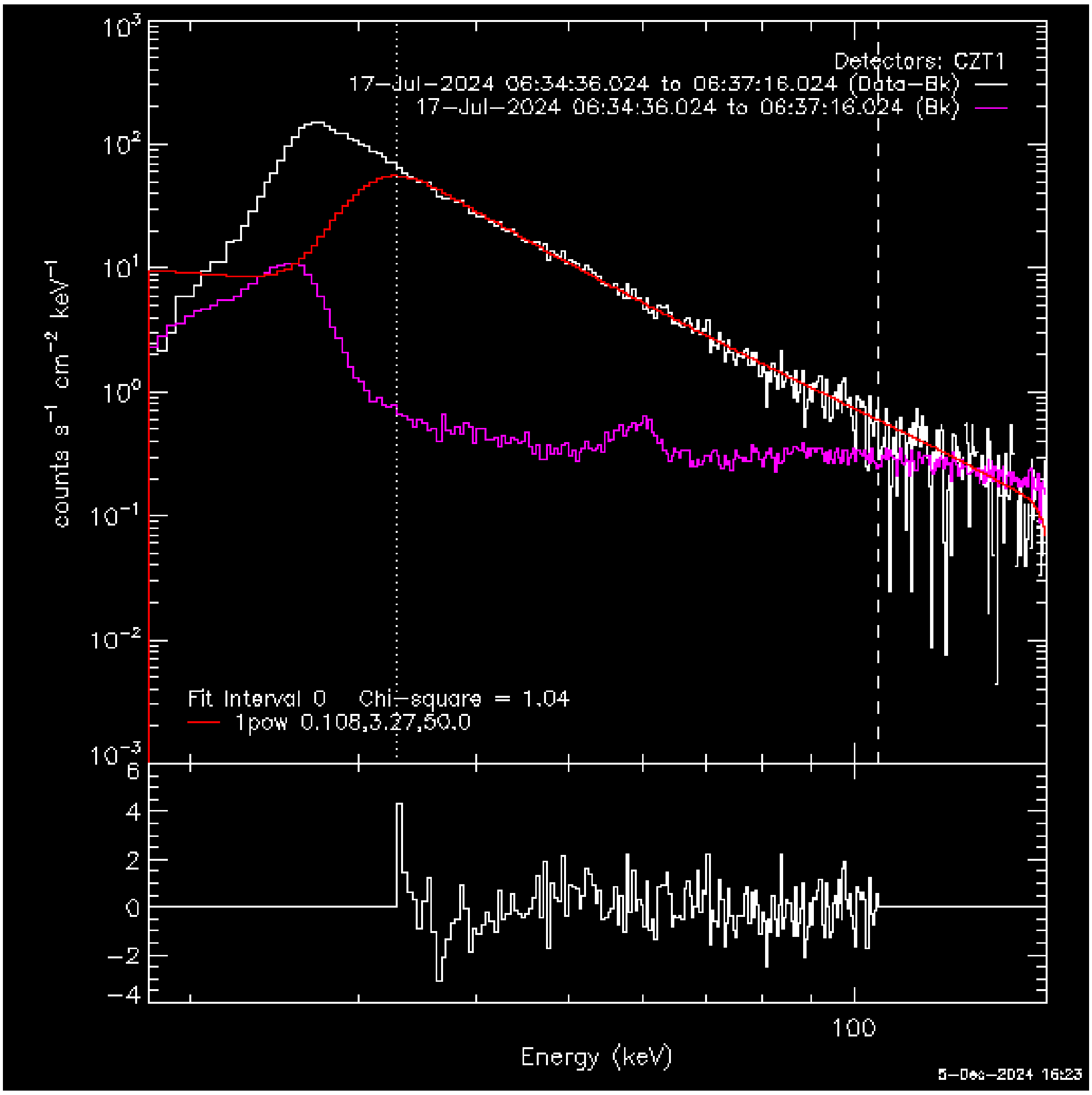


Figure 5.21*: The upper panel shows the observed background subtracted count spectrum (Data–Bk) in white, the background spectrum in magenta (Bk), the best-fit "1pow" function in red. The vertical dotted and dashed lines indicate the lower and upper energy ranges used for fitting. The lower panel shows the energy distribution of the normalized residuals in units of σ = (observed count spectrum–modeled count spectrum)/error, where error denotes the statistical error on each count.*

There is a $\pm 4\,\sigma$ residual between ~33 keV and ~36 keV which could be due to the effect of the lower-energy end of the spectrum, as mentioned previously. The details of this region of the spectrum will be elaborated in the HEL1OS Cookbook and in future releases of the User Manual.

5.3.2: Fitting with a Physical Model: Cold-Thick-Target Bremsstrahlung

If you are interested in extracting the physical parameters of the electron distribution that generates the high-energy X-rays, you can use “thick2” model (please see Figure 5.16 and the associated caption). In this example, we consider that the electron spectrum is a “single power law” and follow the instructions recommended in the widget in Figure 5.16:

- we set the value of a[2] (break energy) to be equal to a[5] (high-energy cut-off) and freeze the parameter;
- we freeze the value of a[3] (spectral index above the break energy).

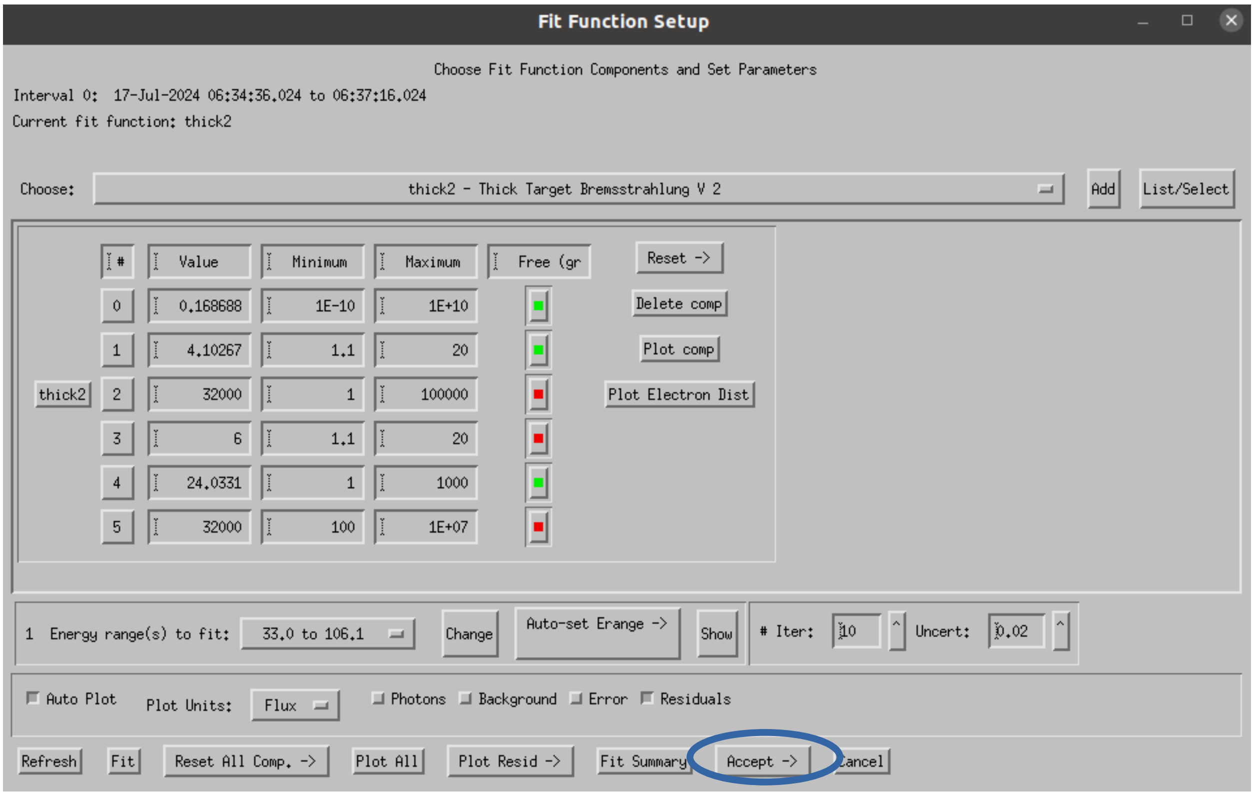


***Figure 5.22**: The best-fit parameters after applying “thick2” physical model. Note that the values of a[2], a[3] and a[5] are set appropriately and frozen (the buttons are “red”).*

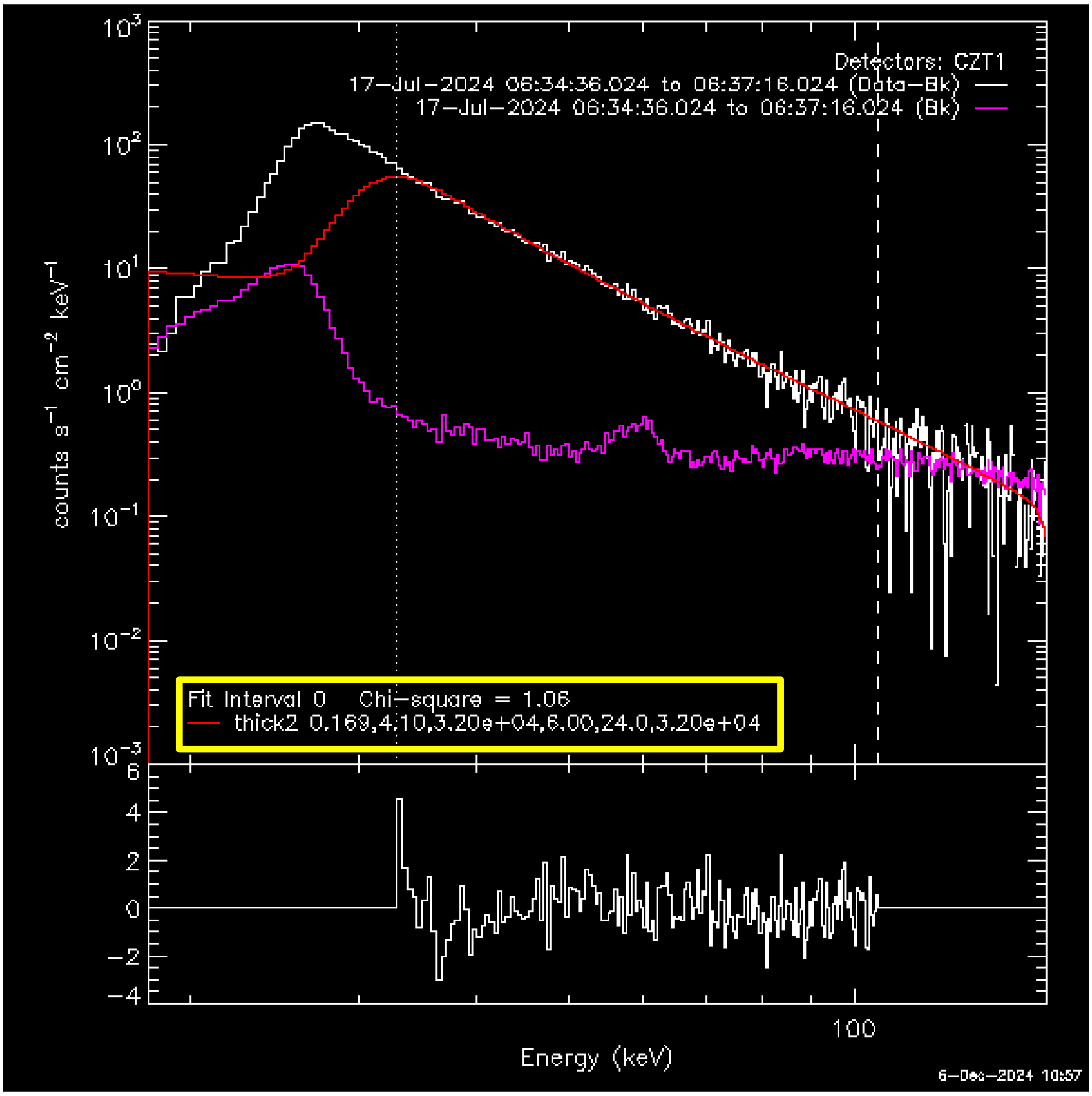


***Figure 5.23**: The upper panel shows the observed background subtracted count spectrum (Data–Bk) in white, the background spectrum in magenta (Bk), the best-fit "thick2" function in red. The vertical dotted and dashed lines indicate the lower and upper energy ranges used for fitting. The lower panel shows the energy distribution of the normalized residuals in units of = (observed count spectrum–modeled count spectrum)/error, where error denotes the statistical error on each count*.

The best-fit parameters are printed on the upper panel of the Figure 5.23 (yellow box). Once you are satisfied with the fit, then Click "*Accept*", and then "*Store Fit....*" (highlighted in blue in Figure 5.22). You will be prompted via a file dialog box, where you can rename (if required) and save the results file.

For CZT1 using "thick2" model, the best-fit parameters are:

1. total integrated electron flux (x 10^{35} electron/sec) = 0.17 (+/- 0.13)
2. low-energy cutoff = 24 (+/- 6) keV
3. delta (electron spectral index) = 4.10 (+/- 0.026)

5.3.3: What happens when you change the model?

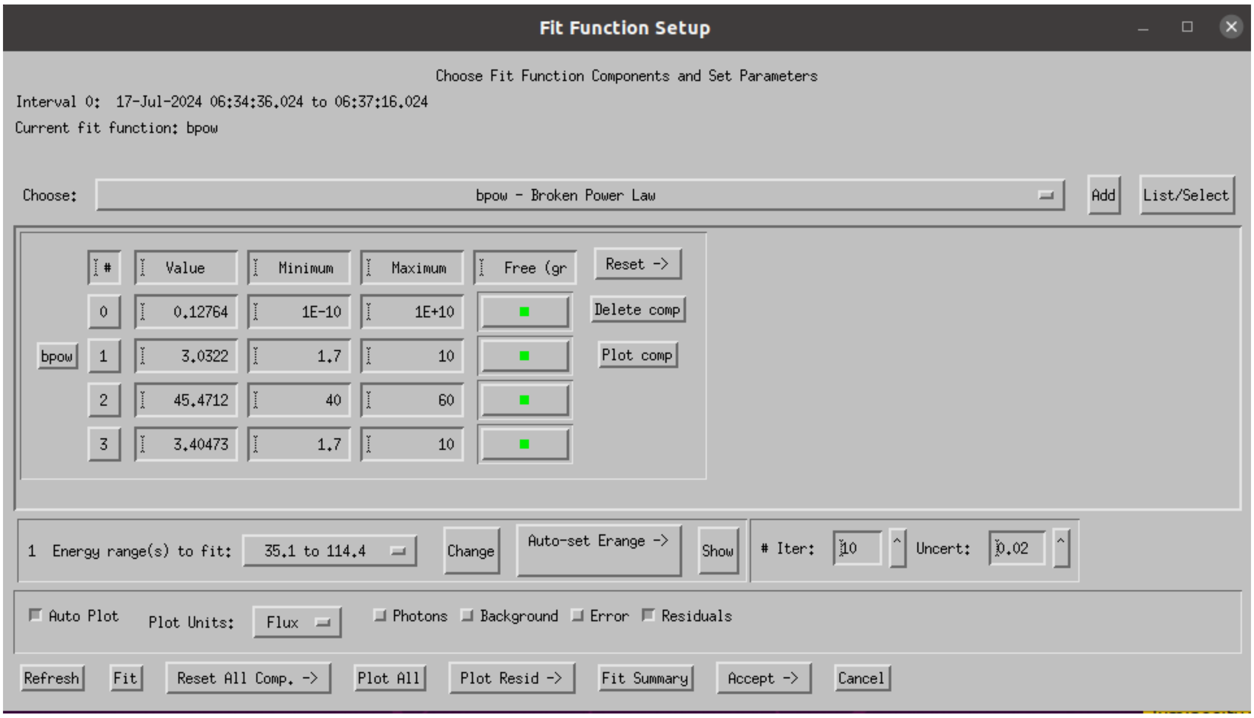


Figure 5.24: Broken power-law model fit for the CZT2 spectrum between ~35 keV and ~114 keV. Notice that all the model parameters are available for fitting (green buttons). We have also constrained the range [Minimum & Maximum columns] of the parameter space within which a[2] of the "bpow" model (the break energy) can vary during the fit. Details will be elaborated in the HEL1OS Cookbook.

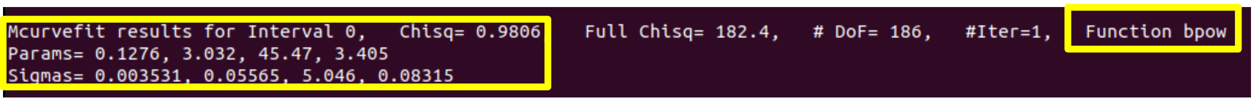


Figure 5.25: Screenshot of the IDL workbench, indicating the best-fit parameters and their corresponding $\pm 1\,\sigma$ errors corresponding to Figure 5.24.

We have repeated the entire forward-fitting excercise for CZT2 using the same background intervals as used for CZT1 and the same time interval for fitting. The best energy range was determined to be between 35 keV and 114 keV for CZT2 (we are working on understanding the spectral behavior <30 keV). However, we have changed the empirical model from "1pow" to a broken power-law or "bpow".

As can be seen from the highlighted best-fit values, the photon spectral power-law index above the break-energy, i.e. a[3] (γ_{HI}) is slightly steeper than that below the break-energy, i.e. a[1] (γ_{LO}) ; the photon spectrum may as well be fit using a single power-law.

However, if you fit the photon spectrum using "1pow" and "bpow" and study the residuals (Figure 5.26), you see that any systematic trend in the residuals are taken care of by changing the model.

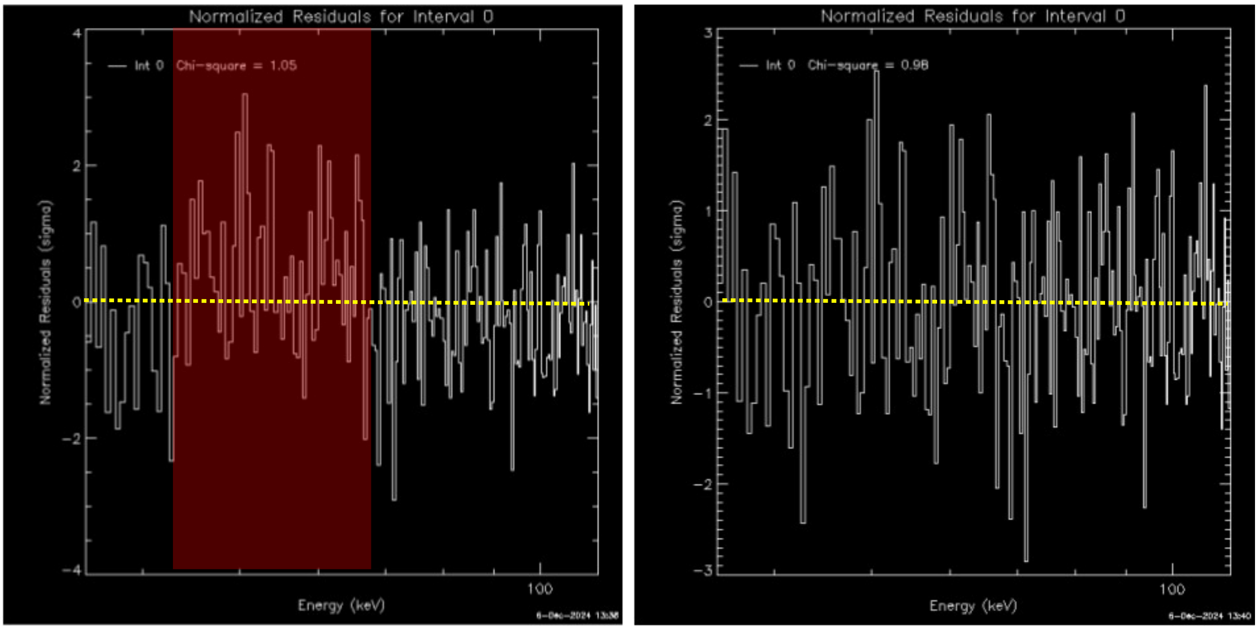


Figure 5.26*: (left) residuals after fitting "1pow" to the CZT2 spectrum (right) residuals after fitting "bpow" to the CZT2 spectrum. The energy range highlighted in the left panel corresponding to "1pow" shows a systematic distribution of residuals above the zero line (dashed yellow horizontal line). The residual distribution has become significantly statistical about the zero line in the right panel, after "bpow" fit*.

So, please keep in mind that selecting a model for forward folding should rely as much on scientific intuition regarding the on-going physics as well as knowledge of the instrument recording the X-ray photons.

Let's try and fit the CZT2 spectrum with the "thick2" model and compare the best-fit (red χ^2 = 1.04) parameters with those dervied by using CZT1, we see:

1. total integrated electron flux (x 10^{35} electron/sec) = 0.07 (+/- 0.01)
2. low-energy cutoff = 32.5 (+/- 1.83) keV
3. delta (electron spectral index) = 4.07 (+/- 0.033)

5.4: Spectral Analysis of the CdTe data:

Let's sample CdTe1 spectral analysis now. The entire process is similar to what was described for the CZT data analysis. We are just going to demonstrate the spectral modeling for the same time interval used for the CZT spectral analysis (*06:34:36.024 to 06:37:16.024 UT*). This is highlighted by the red rectangle in Figure 5.27:

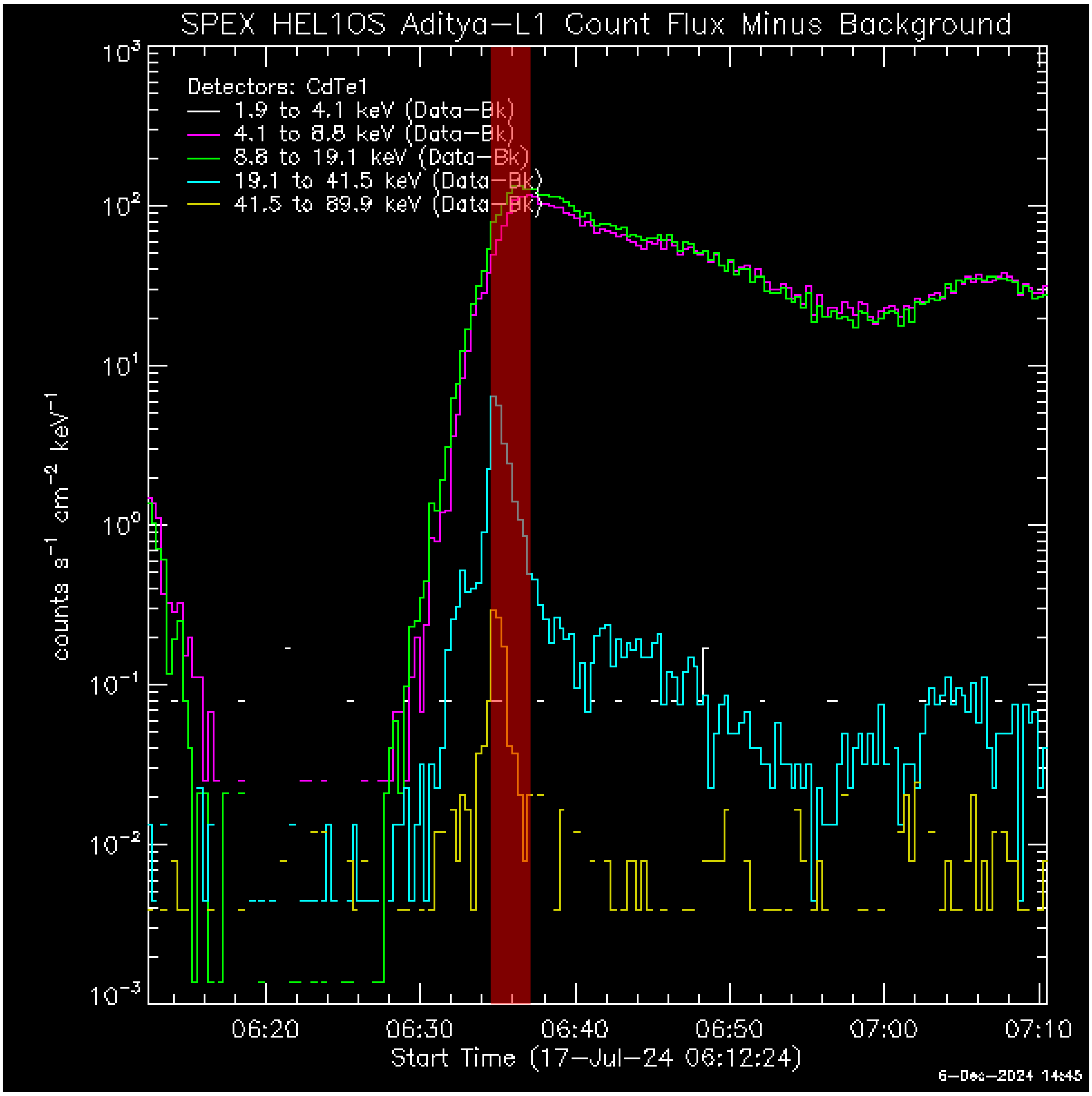


***Figure 5.27**: The light curve/time profile of CdTe1 detector for the GOES M5.0-class flare and the time interval used for spectral fitting is highlighted by the red rectangle. This is the impulsive phase of the flare*.

The energy range used for the spectral fitting has been determined as 9.5 keV to 38 keV and as shown in Figure 5.28, we have used the "vth" physical model for the thermal part of the spectrum <19 keV (the "gradual" part of the light curve as shown in Figure 5.27) and the emipircal “1pow” model for non-thermal photons in energy range >19 keV (see the “impulsive” peak in Figure 5.27). The physical parameters derived from “vth” are the volume emission measure (x 10^{49} cm^{-3}) and the plasma temperature in keV (1 keV ~ 11 MK).

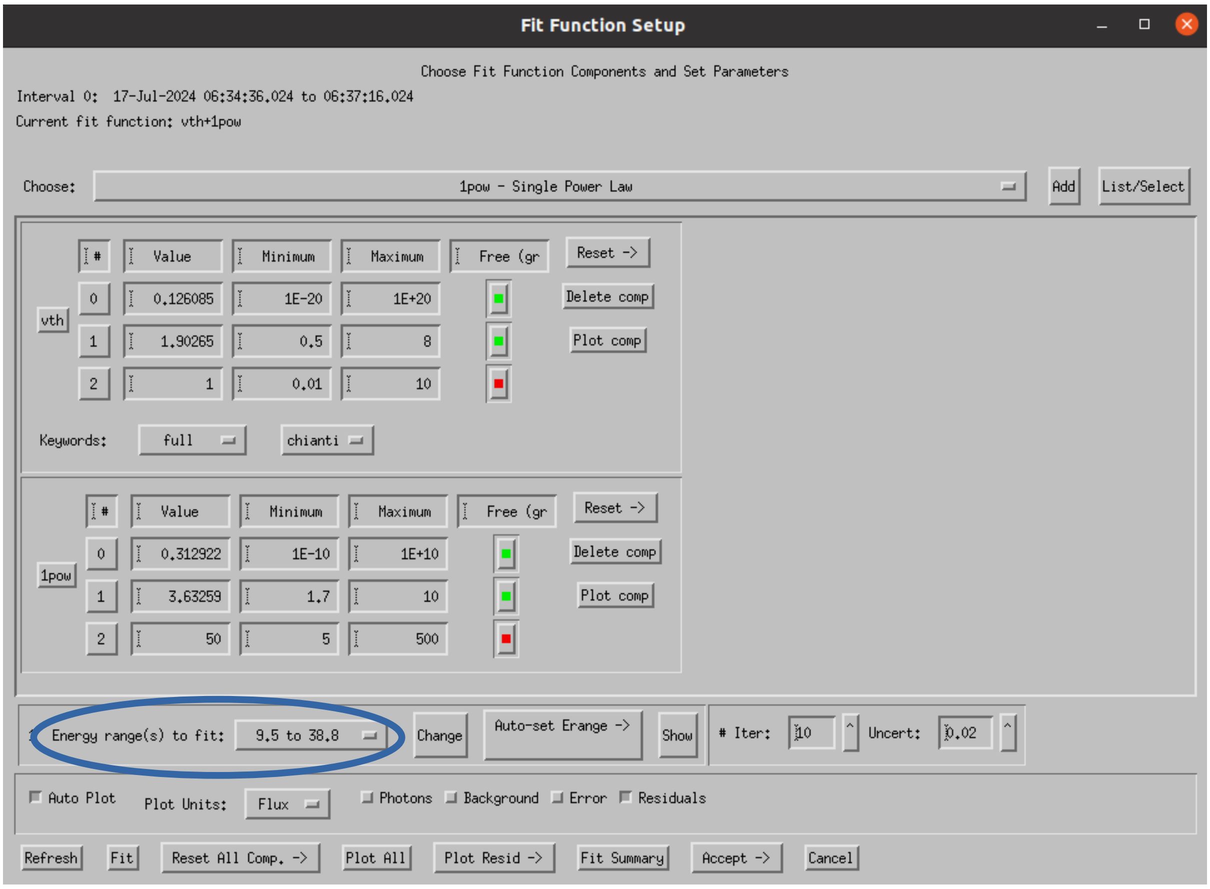


***Figure 5.28**: The model set-up in the “Fit Function Setup” widget, showing the energy range used to the model (highlighted in blue)*.

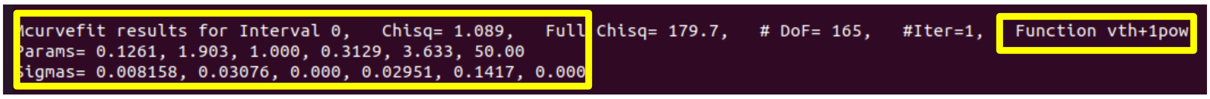


***Figure 5.29**: Best-fit parmeters with their associated errors.*

1. Emission Measure (x 10^{49} cm^{-3})= 0.13 (+/- 0.008);
2. Temperature = 1.9 (+/- 0.03) keV;
3. Normalization at Epivot = 0.31 (+/- 0.03);
4. Gamma (photon spectral index) = 3.6 (+/- 0.14).

The best-fit model along with the data and residuals are shown in Figure 5.30.

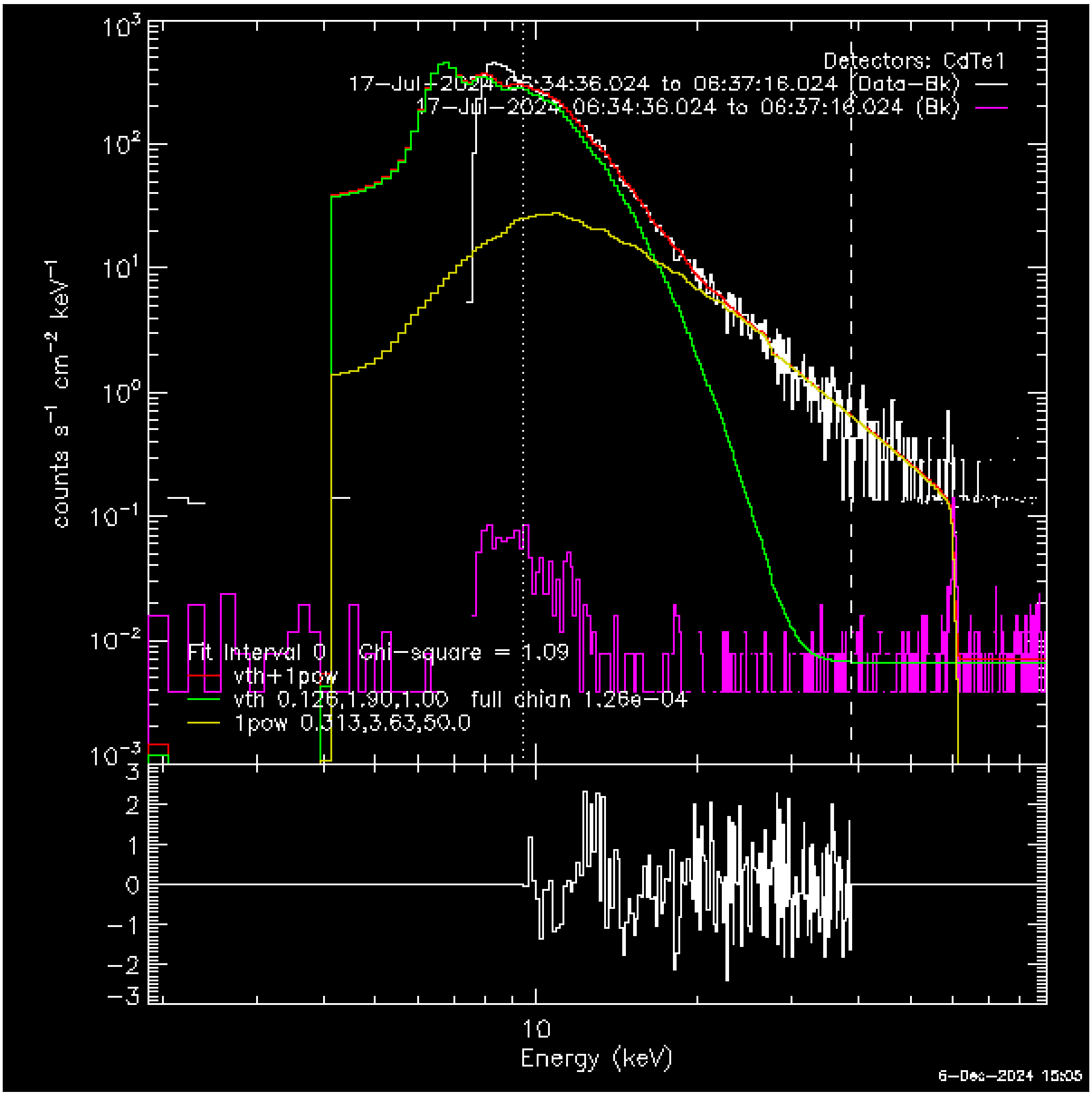


***Figure 5.30**: The upper panel shows the observed background subtracted count spectrum (Data–Bk) in white, the background spectrum in magenta (Bk), the best-fit "total" function in red. The different fit components are also indicated: the thermal "vth" is shown in green, while the non-thermal empirial "1pow" is shown in yellow. The vertical dotted and dashed lines indicate the lower and upper energy ranges used for fitting. The lower panel shows the energy distribution of the normalized residuals in units of = (observed count spectrum–modeled count spectrum)/error, where error denotes the statistical error on each count. The "vth" and "1pow" best fit parameters along with the value of reduced χ^2 are printed in the upper panel.*

Let us try and fit this with “vth + thick2” and check the parameters.

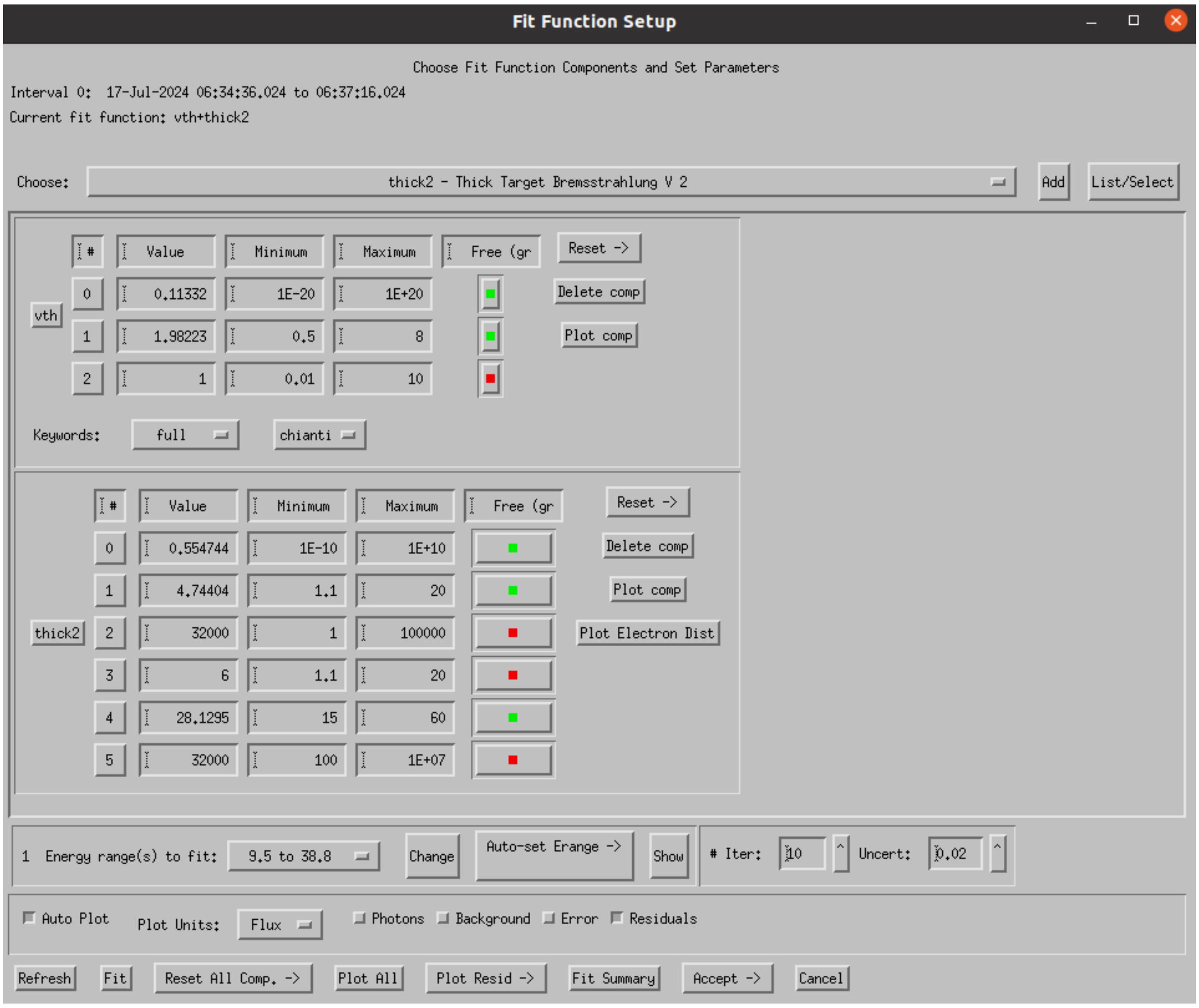


***Figure 5.31**: The model set-up in the “Fit Function Setup” widget, showing the energy range used to the model*.

The best-fit parameters are as follows:

1. Emission Measure (x 10^{49} cm^{-3}) = 0.11 (+/- 0.007);
2. Temperature = 1.98 (+/- 0.03) keV
3. Total integrated electron flux (x 10^{35} electron/sec) = 0.56 (+/- 0.16)
4. low-energy cutoff = 28.1 (+/- 3.5) keV
5. delta (electron spectral index) = 4.7 (+/- 0.33)

Note: for the cold-thick-target Bremsstrahlung model that is represented by “thick2”, the delta = gamma+1 (please verify!)

The best-fit model along with the data and residuals are shown in Figure 5.32.

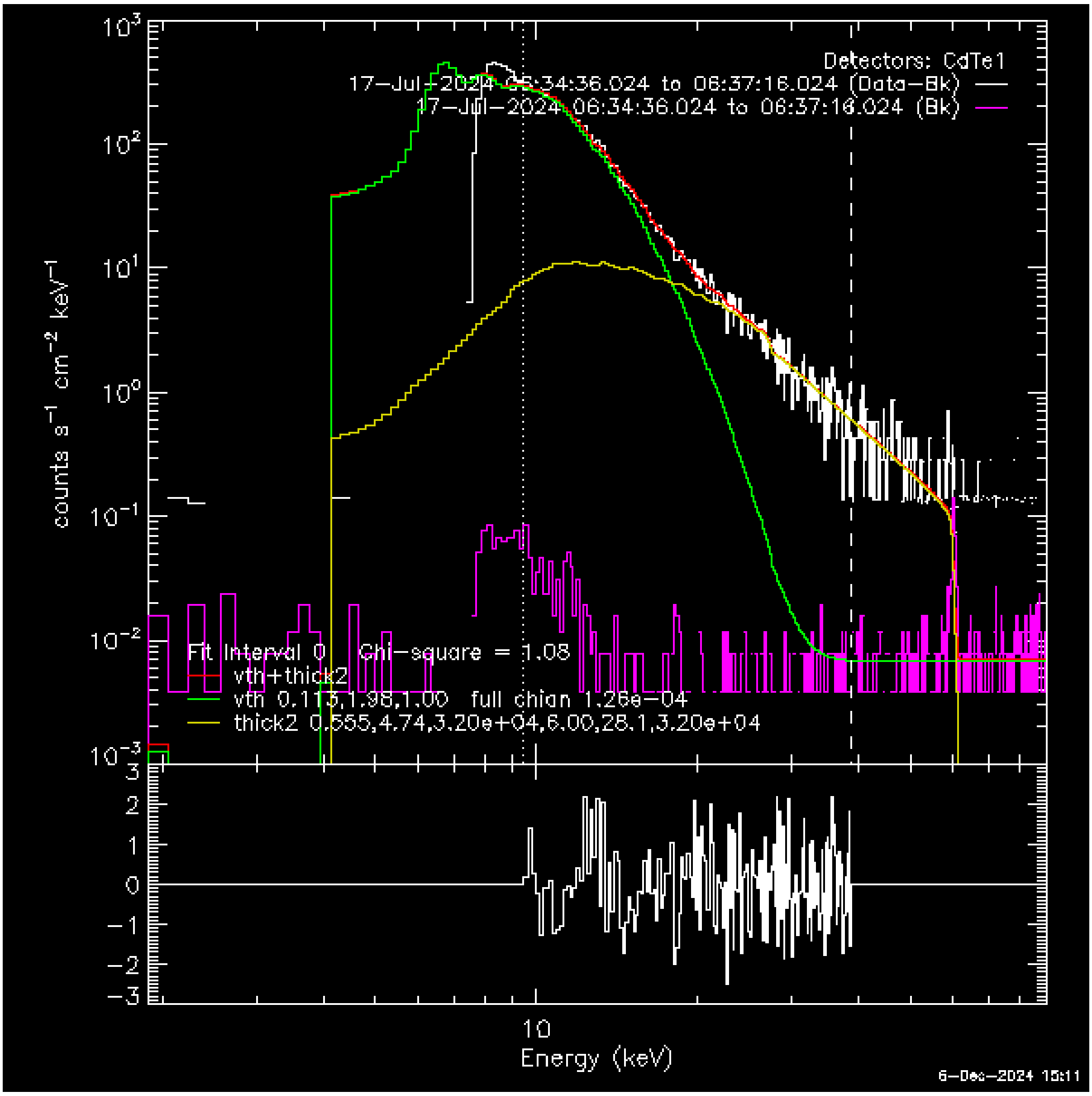


***Figure 5.32**: The upper panel shows the observed background subtracted count spectrum (Data–Bk) in white, the background spectrum in magenta (Bk), the best-fit "total" function in red. The different fit components are also indicated: the thermal "vth" is shown in green, while the non-thermal empirial "thick2" is shown in yellow. The vertical dotted and dashed lines indicate the lower and upper energy ranges used for fitting. The lower panel shows the energy distribution of the normalized residuals in units of = (observed count spectrum–modeled count spectrum)/error, where error denotes the statistical error on each count. The "vth" and "thick2" best fit parameters along with the value of reduced χ^2 are printed in the upper panel*.

The same procedure is to be repeated for CdTe2. You can fit the CdTe spectra for different time intervals, and study the evolution of the different physical parameters a function of time.

6. Timing Analysis:

T.B.D

Appendix A:

If you are interested in using other features of OSPEX, please refer to the following links:

1. Saving and Restoring an OSPEX Session

   https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm#Saving%20and%20Restoring%20OSPEX%20Session

2. Saving and Restoring OSPEX Results

   https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm#Saving%20and%20Restoring%20OSPEX%20Results

3. Fit Parameter Uncertainty Analysis

   https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm#Fit%20Parameter%20Uncertainty%20Analysis

4. OSPEX routines for additional analysis:

   https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm#More%20OSPEX%20Routines

Appendix B: FITS Headers

Listed below are the header keyword-list of the FITS files in the HEL1OS Level-1 data product. These give an account of the metadata information provided for the data analysis. Note that the FITS keywords in the spectral data products are OGIP standard compliant.

B.1 Events FITS files

B.1.1 Sample Header of CdTe Event FITS file

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                   57 / length of dimension 1
NAXIS2  =               574654 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    6 / number of table fields
EXTNAME = 'CDTE1-EVENTS'       / extension name
DETNAM  = 'CdTe1   '           / HEL1OS detector that this Event-List belongs to
TTYPE1  = 'mjd     '           / Modified Julian Date
TFORM1  = 'D       '
TTYPE2  = 'hlsobt  '           / HEL1OS clock, unit: seconds
TFORM2  = 'D       '
TUNIT2  = 's       '
TTYPE3  = 'currtemp'           / Current CdTe1 temperature, in degree Celsius
TFORM3  = 'D       '
TUNIT3  = 'degC    '
TTYPE4  = 'chn     '           / ADC Channel Number
TFORM4  = 'I       '
TZERO4  =                32768
TTYPE5  = 'ener    '           / Energy corresponding to the channel, in keV
TFORM5  = 'D       '
TUNIT5  = 'keV     '
TTYPE6  = 'utc-isot'           / UTC in ISO-T format corresponding to the MJD
TFORM6  = '23A     '
TSTART  =    60507.99995398406 / First MJD, i.e. 2024-07-16T23:59:56.024 UT
TSTOP   =    60508.49978053633 / Last MJD, i.e. 2024-07-17T11:59:41.038 UT
STARETIM=    43185.01411643811 / Total Time duration of this Event List, seconds
CHECKSUM= 'WEhjaBfjYBfjaBfj'   / HDU checksum updated 2024-12-24T21:35:45
DATASUM = '2600844367'         / data unit checksum updated 2024-12-24T21:35:45
END
```

B.1.2 Sample Header of CZT Event FITS file

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                   60 / length of dimension 1
NAXIS2  =              1359831 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    8 / number of table fields
EXTNAME = 'CZT1-EVENTS'        / extension name
DETNAM  = 'CZT1    '           / HEL1OS detector that this Event-List belongs to
TTYPE1  = 'mjd     '           / Modified Julian Date
TFORM1  = 'D       '
TTYPE2  = 'hlsobt  '           / HEL1OS clock, unit: seconds
TFORM2  = 'D       '
TUNIT2  = 's       '
TTYPE3  = 'currtemp'           / Current CZT1 temperature, in degree Celsius
TFORM3  = 'D       '
TUNIT3  = 'degC    '
TTYPE4  = 'pix     '           / CZT1 Pixel Number; range [0:255]
TFORM4  = 'B       '
TTYPE5  = 'chn     '           / ADC Channel Number
TFORM5  = 'I       '
TZERO5  =                32768
TTYPE6  = 'offsetchn'          / ADC Offset Channel Number
TFORM6  = 'I       '
TTYPE7  = 'ener    '           / Energy corresponding to the channel, in keV
TFORM7  = 'D       '
TUNIT7  = 'keV     '
TTYPE8  = 'utc-isot'           / UTC in ISO-T format corresponding to the MJD
TFORM8  = '23A     '
TSTART  =    60507.99995398406 / First MJD, i.e. 2024-07-16T23:59:56.024 UT
TSTOP   =    60508.49987238371 / Last MJD, i.e. 2024-07-17T11:59:48.974 UT
STARETIM=    43192.94972957578 / Total Time duration of this Event List, seconds
CHECKSUM= 'IAaOL8YOIAaOI5WO'   / HDU checksum updated 2024-12-24T21:35:46
DATASUM = '1867386811'         / data unit checksum updated 2024-12-24T21:35:46
END
```

B.2 Spectra FITS files

B.2.1 Sample Header of CdTe Spectra FITS file

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                12308 / length of dimension 1
NAXIS2  =                 2158 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    8 / number of table fields
EXTNAME = 'SPECTRUM'           / extension name
DETNAM  = 'CdTe1   '           / HEL1OS detector that this spectra belong to
CHANTYPE= 'PHA     '           / Channel Type: PHA
TSTART  =    60507.99995398406 / MJD, i.e. 2024-07-16T23:59:56.024 UT
TSTOP   =    60508.49972250257 / MJD, i.e. 2024-07-17T11:59:36.024 UT
TTYPE1  = 'SPEC_NUM'           / Index to each Spectrum
TFORM1  = 'K       '
TTYPE2  = 'CHANNEL '           / Channel Number; limits: [0:510]
TFORM2  = '511K    '
TDIM2   = '(511)   '
TTYPE3  = 'COUNTS  '           / PHA Counts
TFORM3  = '511D    '
TUNIT3  = 'cts     '           / unit: counts
TDIM3   = '(511)   '
TTYPE4  = 'STAT_ERR'           / Uncertainty on the PHA Counts
TFORM4  = '511D    '
TDIM4   = '(511)   '
TTYPE5  = 'ROWID   '           / Label of each Spectrum
TFORM5  = '12A     '
TTYPE6  = 'TSTART  '           / Relative Start-time of each spectrum, seconds
TFORM6  = 'D       '
TUNIT6  = 's       '           / unit: secconds
TTYPE7  = 'TSTOP   '           / Relative Stop-time of each spectrum, seconds
TFORM7  = 'D       '
TUNIT7  = 's       '           / unit: secconds
TTYPE8  = 'EXPOSURE'           / Exposure Time of each spectrum, seconds
TFORM8  = 'D       '
TUNIT8  = 's       '           / unit: secconds
RESPFILE= 'none    '           / Spec. Redis. Matrix File not set
ANCRFILE= 'none    '           / Ancillary Response File not set
HDUCLASS= 'OGIP    '           / OGIP standard compliant
HDUCLAS1= 'SPECTRUM'           / The extension content: SPECTRUM
HDUCLAS2= 'TOTAL   '           / Gross PHA Spectrum: source + bkgd
HDUCLAS3= 'COUNT   '           / PHA data stored as counts
HDUCLAS4= 'TYPE:II '           / Type-II PHA, i.e. Multiple spectra
```

```
TELESCOP= 'Aditya-L1'          / Indian Solar Mission by ISRO at L1
INSTRUME= 'HEL1OS  '           / High Energy L1 Orbiting Spectromete
BACKFILE= 'none    '           / Corresponding Background file
CORRFILE= 'none    '           / Corresponding Correction file
CORRSCAL=                  0.0 / Correction Scaling Factor applied on CORRFILE
AREASCAL=                  1.0 / Area Scaling Factor
BACKSCAL=                  1.0 / Background scale factor
HDUVERS = '1.2.1   '           / Version number of the format
HDUVERS1= '1.2.1   '           / Obsolete - included for backwards compatibility
DETCHANS=                  511 / Total number of detector channels available
TLMIN2  =                    0 / Lowest Legal Channel Number present in column 2
TLMAX2  =                  510 / Highest Legal Channel Number present in column
DATE_OBS= '2024-07-16'         / Start Date of this PHA in YYYY-MM-DD format
TIME_OBS= '23:59:56.024'       / Start Time of this PHA in hh:mm:ss.sss format
DATE_END= '2024-07-17'         / Start Date of this PHA in YYYY-MM-DD format
TIME_END= '11:59:36.024'       / Start Time of this PHA in hh:mm:ss.sss format
CHECKSUM= 'acPidZMiabMiaZMi'   / HDU checksum updated 2024-12-24T21:35:49
DATASUM = '4291204559'         / data unit checksum updated 2024-12-24T21:35:49
HISTORY Creation Time: 2024-12-24T21:35:49.551008
END
```

B.2.2 Sample Header of CZT Spectra FITS file

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                 8228 / length of dimension 1
NAXIS2  =                 2158 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    8 / number of table fields
EXTNAME = 'SPECTRUM'           / extension name
DETNAM  = 'CZT1    '           / HEL1OS detector that this spectra belong to
CHANTYPE= 'PHA     '           / Channel Type: PHA
TSTART  =    60507.99995398406 / MJD, i.e. 2024-07-16T23:59:56.024 UT
TSTOP   =    60508.49972250257 / MJD, i.e. 2024-07-17T11:59:36.024 UT
TTYPE1  = 'SPEC_NUM'           / Index to each Spectrum
TFORM1  = 'K       '
TTYPE2  = 'CHANNEL '           / Channel Number; limits: [0:340]
TFORM2  = '341K    '
TDIM2   = '(341)   '
TTYPE3  = 'COUNTS  '           / PHA Counts
TFORM3  = '341D    '
TUNIT3  = 'cts     '           / unit: counts
TDIM3   = '(341)   '
TTYPE4  = 'STAT_ERR'           / Uncertainty on the PHA Counts
TFORM4  = '341D    '
TDIM4   = '(341)   '
```

```
TTYPE5  = 'ROWID   '           / Label of each Spectrum
TFORM5  = '12A     '
TTYPE6  = 'TSTART  '           / Relative Start-time of each spectrum, seconds
TFORM6  = 'D       '
TUNIT6  = 's       '           / unit: secconds
TTYPE7  = 'TSTOP   '           / Relative Stop-time of each spectrum, seconds
TFORM7  = 'D       '
TUNIT7  = 's       '           / unit: secconds
TTYPE8  = 'EXPOSURE'           / Exposure Time of each spectrum, seconds
TFORM8  = 'D       '
TUNIT8  = 's       '           / unit: secconds
RESPFILE= 'none    '           / Spec. Redis. Matrix File not set
ANCRFILE= 'none    '           / Ancillary Response File not set
HDUCLASS= 'OGIP    '           / OGIP standard compliant
HDUCLAS1= 'SPECTRUM'           / The extension content: SPECTRUM
HDUCLAS2= 'TOTAL   '           / Gross PHA Spectrum: source + bkgd
HDUCLAS3= 'COUNT   '           / PHA data stored as counts
HDUCLAS4= 'TYPE:II '           / Type-II PHA, i.e. Multiple spectra
TELESCOP= 'Aditya-L1'          / Indian Solar Mission by ISRO at L1
INSTRUME= 'HEL1OS  '           / High Energy L1 Orbiting Spectromete
BACKFILE= 'none    '           / Corresponding Background file
CORRFILE= 'none    '           / Corresponding Correction file
CORRSCAL=                  0.0 / Correction Scaling Factor applied on CORRFILE
AREASCAL=           0.81640625 / Area Scaling Factor
BACKSCAL=                  1.0 / Background scale factor
HDUVERS = '1.2.1   '           / Version number of the format
HDUVERS1= '1.2.1   '           / Obsolete - included for backwards compatibility
DETCHANS=                  341 / Total number of detector channels available
TLMIN2  =                    0 / Lowest Legal Channel Number present in column 2
TLMAX2  =                  340 / Highest Legal Channel Number present in column
DATE_OBS= '2024-07-16'         / Start Date of this PHA in YYYY-MM-DD format
TIME_OBS= '23:59:56.024'       / Start Time of this PHA in hh:mm:ss.sss format
DATE_END= '2024-07-17'         / Start Date of this PHA in YYYY-MM-DD format
TIME_END= '11:59:36.024'       / Start Time of this PHA in hh:mm:ss.sss format
CHECKSUM= 'GfZYIdYVGdYVGdYV'   / HDU checksum updated 2024-12-24T21:35:55
DATASUM = '3278889532'         / data unit checksum updated 2024-12-24T21:35:55
HISTORY Creation Time: 2024-12-24T21:35:55.018038
END
```

B.3 Lightcurve FITS files

B.3.1 Sample Header of CdTe Lightcurve FITS file

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                   54 / length of dimension 1
NAXIS2  =                43176 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    4 / number of table fields
EXTNAME = 'CDTE1_LC_BAND_5.00KEV_TO_20.00KEV' / extension name
DETNAM  = 'CdTe1   '           / HEL1OS detector that this lightcurve belongs to
TTYPE1  = 'MJD     '           / Modified Julian Date
TFORM1  = 'D       '
TUNIT1  = 'MJD     '           / Modified Julian Date
TTYPE2  = 'ISOT    '           / UTC in ISO-T format
TFORM2  = '30A     '
TUNIT2  = 'UT      '           / UTC in ISO-T format
TTYPE3  = 'CTR     '           / Count Rate
TFORM3  = 'D       '
TUNIT3  = 'cts/sec '           / Count Rate
TTYPE4  = 'STAT_ERR'           / Uncertainty on the Count Rate
TFORM4  = 'D       '
TUNIT4  = 'cts/sec '           / Uncertainty on the Count Rate
TSTART  =    60507.99995398406 / MJD, i.e. 2024-07-16T23:59:56.024 UT
TSTOP   =    60508.49967620628 / MJD, i.e. 2024-07-17T11:59:32.024 UT
STARETIM=     43176.0000000475 / Total Time duration of this light curve, second
TIMEBIN =                  1.0 / Lightcurve Cadence in seconds
ELOW    =                  5.0 / Lightcurve Energy Band Lower limit, in keV
EHIGH   =                 20.0 / Lightcurve Energy Band Upper limit, in keV
DATAMIN =                  0.0 / Least Count Rate in this lightcurve, cts/sec
DATAMAX =                898.0 / Highest Count Rate in this lightcurve, cts/sec
CHECKSUM= 'ZmHgelHeZlHedlHe'   / HDU checksum updated 2024-12-24T21:35:49
DATASUM = '3173359725'         / data unit checksum updated 2024-12-24T21:35:49
HISTORY Creation Time: 2024-12-24T21:35:48.084887
END
```

B.3.2 Sample Header of CZT Lightcurve FITS file

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                   54 / length of dimension 1
NAXIS2  =                43192 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    4 / number of table fields
EXTNAME = 'CZT1_LC_BAND_18.00KEV_TO_160.00KEV' / extension name
DETNAM  = 'CZT1    '           / HEL1OS detector that this lightcurve belongs to
TTYPE1  = 'MJD     '           / Modified Julian Date
TFORM1  = 'D       '
TUNIT1  = 'MJD     '           / Modified Julian Date
TTYPE2  = 'ISOT    '           / UTC in ISO-T format
TFORM2  = '30A     '
TUNIT2  = 'UT      '           / UTC in ISO-T format
TTYPE3  = 'CTR     '           / Count Rate
TFORM3  = 'D       '
TUNIT3  = 'cts/sec '           / Count Rate
TTYPE4  = 'STAT_ERR'           / Uncertainty on the Count Rate
TFORM4  = 'D       '
TUNIT4  = 'cts/sec '           / Uncertainty on the Count Rate
TSTART  =    60507.99995398406 / MJD, i.e. 2024-07-16T23:59:56.024 UT
TSTOP   =    60508.49986139146 / MJD, i.e. 2024-07-17T11:59:48.024 UT
STARETIM=    43192.00000001583 / Total Time duration of this light curve, second
TIMEBIN =                  1.0 / Lightcurve Cadence in seconds
ELOW    =                 18.0 / Lightcurve Energy Band Lower limit, in keV
EHIGH   =                160.0 / Lightcurve Energy Band Upper limit, in keV
DATAMIN =                  0.0 / Least Count Rate in this lightcurve, cts/sec
DATAMAX =               1386.0 / Highest Count Rate in this lightcurve, cts/sec
CHECKSUM= '5g5e7g2c5g2c5g2c'   / HDU checksum updated 2024-12-24T21:35:55
DATASUM = '910150890'          / data unit checksum updated 2024-12-24T21:35:55
HISTORY Creation Time: 2024-12-24T21:35:54.250913
END
```

B.4 Housekeeping (HK) FITS files

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                  360 / length of dimension 1
NAXIS2  =                 7150 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                   53 / number of table fields
EXTNAME = 'HLSHK   '           / extension name
TTYPE1  = 'l0recnum'           / Level-0 Record Number
TFORM1  = 'J       '
TTYPE2  = 'l0grtyr '           / Level-0 Ground Receive Time Year
TFORM2  = 'J       '
TTYPE3  = 'l0grtmon'           / Level-0 Ground Receive Time Month
TFORM3  = 'J       '
TTYPE4  = 'l0grtdy '           / Level-0 Ground Receive Time Day
TFORM4  = 'J       '
TTYPE5  = 'l0grthr '           / Level-0 Ground Receive Time Hour
TFORM5  = 'J       '
TTYPE6  = 'l0grtmin'           / Level-0 Ground Receive Time Minute
TFORM6  = 'J       '
TTYPE7  = 'l0grtsc '           / Level-0 Ground Receive Time Second
TFORM7  = 'J       '
TTYPE8  = 'l0grtmsc'           / Level-0 Ground Receive Time Millisecond
TFORM8  = 'J       '
TTYPE9  = 'l0utcyr '           / Level-0 UTC Year
TFORM9  = 'J       '
TTYPE10 = 'l0utcmon'           / Level-0 UTC Month
TFORM10 = 'J       '
TTYPE11 = 'l0utcdy '           / Level-0 UTC Day
TFORM11 = 'J       '
TTYPE12 = 'l0utchr '           / Level-0 UTC Hour
TFORM12 = 'J       '
TTYPE13 = 'l0utcmin'           / Level-0 UTC Minute
TFORM13 = 'J       '
TTYPE14 = 'l0utcsc '           / Level-0 UTC Second
TFORM14 = 'J       '
TTYPE15 = 'l0utcmsc'           / Level-0 UTC Millisecond
TFORM15 = 'J       '
TTYPE16 = 'l0framecnt'         / Level-0 Frame Count
TFORM16 = 'J       '
TTYPE17 = 'l0dhobt '           / Level-0 Data-Handling subsystem clock
TFORM17 = 'K       '
TTYPE18 = 'mjd     '           / Modified Julian Date
TFORM18 = 'D       '
TTYPE19 = 'czt1temp'           / CZT1 Temperature, in degree Celsius
TFORM19 = 'D       '
TUNIT19 = 'degC    '
TTYPE20 = 'czt2temp'           / CZT2 Temperature, in degree Celsius
```

```
TFORM20 = 'D       '
TUNIT20 = 'degC    '
TTYPE21 = 'czt1bunpxst'        / CZT1: Status of the Bunched Pixel Logic
TFORM21 = 'K       '
TZERO21 =  9223372036854775808
TTYPE22 = 'czt2bunpxst'        / CZT2: Status of the Bunched Pixel Logic
TFORM22 = 'K       '
TZERO22 =  9223372036854775808
TTYPE23 = 'pagestim'           / Page Start Time (HEL1OS clock)
TFORM23 = 'D       '
TTYPE24 = 'cdte1ctr'           / CdTe1 Count Rate at 1 sec cadence
TFORM24 = 'D       '
TUNIT24 = 'c/s     '
TTYPE25 = 'pagenum '           / HEL1OS FPGA 2k-Page Number
TFORM25 = 'K       '
TZERO25 =  9223372036854775808
TTYPE26 = 'czt1ctr '           / CZT1 Count Rate at 1 sec cadence
TFORM26 = 'D       '
TUNIT26 = 'c/s     '
TTYPE27 = 'czt1enth'           / CZT1 Low Energy Threshold in keV
TFORM27 = 'D       '
TUNIT27 = 'keV     '
TTYPE28 = 'czt2ctr '           / CZT2 Count Rate at 1 sec cadence
TFORM28 = 'D       '
TUNIT28 = 'c/s     '
TTYPE29 = 'czt2enth'           / CZT2 Low Energy Threshold in keV
TFORM29 = 'D       '
TTYPE30 = 'cdte2ctr'           / CdTe2 Count Rate at 1 sec cadence
TFORM30 = 'D       '
TUNIT30 = 'c/s     '
TTYPE31 = 'czt1pktm'           / CZT1 Peaking Time in microsec
TFORM31 = 'D       '
TTYPE32 = 'czt2pktm'           / CZT2 Peaking Time in microsec
TFORM32 = 'D       '
TTYPE33 = 'fehkstat'           / HEL1OS FE HK Status
TFORM33 = 'K       '
TZERO33 =  9223372036854775808
TTYPE34 = 'czt1hotpix'         / CZT1 Latest Hot Pixel ID disabled onboard
TFORM34 = 'K       '
TZERO34 =  9223372036854775808
TTYPE35 = 'czt1hotpixcnt'      / CZT1 Total Count of Hot Pixels disabled onboard
TFORM35 = 'K       '
TZERO35 =  9223372036854775808
TTYPE36 = 'czt1hotpixlgcstat'  / CZT1 Hot Pixel Logic Status
TFORM36 = 'K       '
TZERO36 =  9223372036854775808
TTYPE37 = 'czt1hotpixthr'      / CZT1 Hot Pixel Threshold
TFORM37 = 'K       '
TZERO37 =  9223372036854775808
TTYPE38 = 'czt2hotpix'         / CZT2 Latest Hot Pixel ID disabled onboard
TFORM38 = 'K       '
```

```
TZERO38 =  9223372036854775808
TTYPE39 = 'czt2hotpixcnt'      / CZT2 Total Count of Hot Pixels disabled onboard
TFORM39 = 'K       '
TZERO39 =  9223372036854775808
TTYPE40 = 'czt2hotpixlgcstat'  / CZT2 Hot Pixel Logic Status
TFORM40 = 'K       '
TZERO40 =  9223372036854775808
TTYPE41 = 'czt2hotpixthr'      / CZT2 Hot Pixel Threshold
TFORM41 = 'K       '
TZERO41 =  9223372036854775808
TTYPE42 = 'cdte1enerthr'       / CdTe1 Low Energy Threshold
TFORM42 = 'D       '
TTYPE43 = 'cdte2enerthr'       / CdTe2 Low Energy Threshold
TFORM43 = 'D       '
TTYPE44 = 'czthvmon'           / CZT HV Monitor
TFORM44 = 'D       '
TUNIT44 = 'V       '
TTYPE45 = 'cdtehvmon'          / CdTe HV Monitor
TFORM45 = 'D       '
TUNIT45 = 'V       '
TTYPE46 = 'cdte1temp'          / CdTe1 Temperature in degree Celsius
TFORM46 = 'D       '
TUNIT46 = 'degC    '
TTYPE47 = 'cdte2temp'          / CdTe2 Temperature in degree Celsius
TFORM47 = 'D       '
TUNIT47 = 'degC    '
TTYPE48 = 'cdte1pilectr'       / CdTe1 Pileup Counter
TFORM48 = 'K       '
TZERO48 =  9223372036854775808
TTYPE49 = 'cdte2pilectr'       / CdTe2 Pileup Counter
TFORM49 = 'K       '
TZERO49 =  9223372036854775808
TTYPE50 = 'czt1satctr1'        / CZT1 Saturation Counter
TFORM50 = 'K       '
TZERO50 =  9223372036854775808
TTYPE51 = 'czt2satctr1'        / CZT2 Saturation Counter
TFORM51 = 'K       '
TZERO51 =  9223372036854775808
TTYPE52 = 'czt1bunpxctr'       / CZT1 Bunched Pixel Counter
TFORM52 = 'K       '
TZERO52 =  9223372036854775808
TTYPE53 = 'czt2bunpxctr'       / CZT2 Bunched Pixel Counter
TFORM53 = 'K       '
TZERO53 =  9223372036854775808
TSTART  =    60507.99995527352 / First MJD, i.e. 2024-07-16T23:59:56.136 UT
TSTOP   =    60508.49987231433 / Last MJD, i.e. 2024-07-17T11:59:48.968 UT
STARETIM=    43192.83232551534 / Total Time duration of this HK Data, seconds
CHECKSUM= '9fEAHcC49cC9GcC9'   / HDU checksum updated 2024-12-24T21:35:23
DATASUM = '238831723'          / data unit checksum updated 2024-12-24T21:35:23
END
```