NICER Analysis Workshop

May 2021

NICER

Neutron star Interior Composition ExploreR

How to Analyze NICER Data

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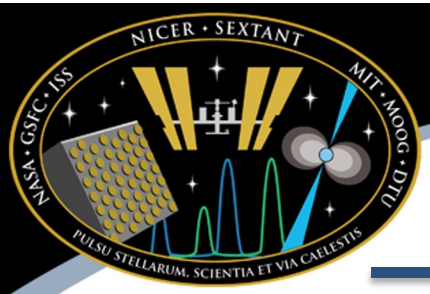
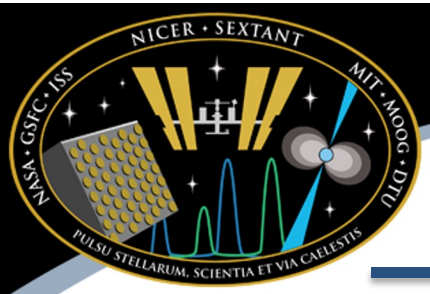
on behalf of NICER Team

NASA GSFC MIT KAVLI INSTITUTE DTU BROAD REACH MOOG



Overview

- This is a tutorial for scientists new to NICER data analysis
- Getting started with software and calibration data
- Retrieving data from the archive
- Important NICER data files
- How to process NICER observations
  - Nicerl2
  - Extract light curve
  - Extract spectrum
  - Response matrices (ARF/RMF)



What You Should Expect to Learn

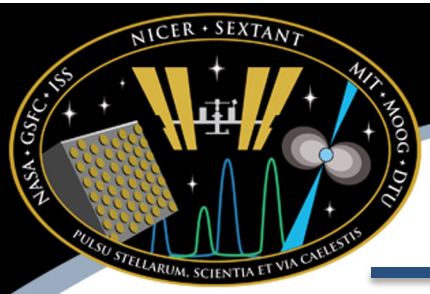
- This tutorial will show you how to start with NICER data processing
  - From archive data to final products
- Basic analysis steps
- Basic output products
  - Light curve
  - Spectra

Where to Find Help for NICER

- The NICER team provides analysis help to guest observers in a number of ways
  - On-line help
    https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_analysis.html
    deals with many common NICER analysis tasks, tips and caveats
  - The NICER help desk
    https://heasarc.gsfc.nasa.gov/cgi-bin/Feedback
    will route questions to NICER scientists
    - Please note that we are unable to provide scientific consultations
  - On-line help for software tasks
    https://heasarc.gsfc.nasa.gov/lheasoft/ftools/headas/nicer.html

NICER Analysis Help Forum

- This week Wednesday, we will be hosting an analysis help forum on Zoom (same meeting link)
  - 0900 – 1100 EDT
  - Submit your questions https://forms.gle/Wh12E34dZmZrYJCC8
  - We will try to answer your questions on Wednesday
  - After Wednesday we will not be able to answer further submitted questions
- You may also submit questions in the chat during all sessions this week, but we may defer more complicated answers to the help forum

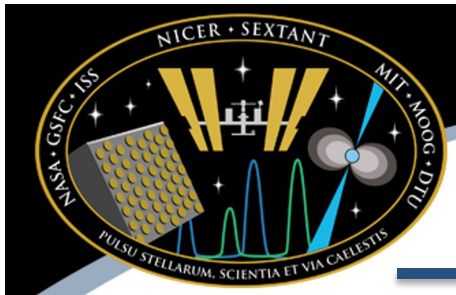


Getting Set Up for NICER Analysis

- You will need NICER software and calibration data in order to do standard processing
  - Software
    - NICERDAS, is part of the HEASoft package
    - HEASoft 6.28.2 is most recent version
  - Calibration Data
    - Released through Calibration Database (CALDB)
- Installation instructions
  https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/nicer-setup
- There are also separate downloads for response files

What You Will Need for Installation

- A ”unix-like” computer
  - Linux
  - Mac OS X
  - Windows (using WSL or WSL2)
- Installation instructions provide detailed steps and prerequisites to get software and calibration data



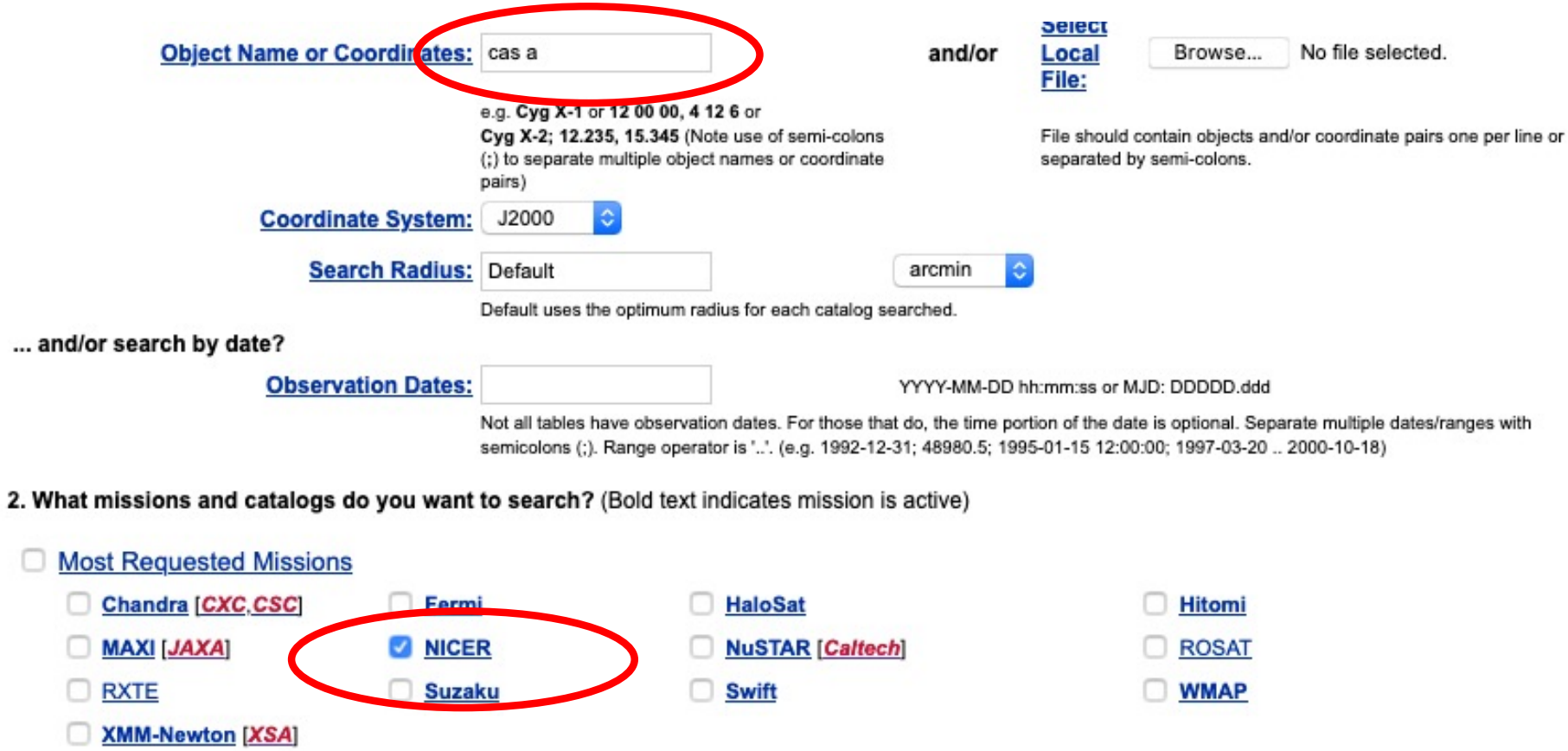
Testing That Your Installation is Working

- Software
  - Command:
    ```
    nicerversion
    ```
  - Response: (depends on software version)
    ```
    yyyy-mm-dd_Vnnn
    ```
- Calibration
  - Command:
    ```
    quzcif NICER XTI - - ALIGNMENT now now -
    ```
  - Response: (may change in future)
    ```
    /home/dtsops/caldb/prod/data/nicer/xti/bcf/pntmis/ni
    xtipntmis20170601v001.teldef   0
    ```

Retrieving Data from NICER Archive

- NICER data is typically transferred to HEASARC archive within two weeks of observation
  - GO-awarded observations may be encrypted
  - GO's will receive decryption instructions
- We will download a sample observation from HEASARC and process it
  - Cassiopeia A supernova remnant
- We will use the HEASARC Browse Interface
  - https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl

Entering a Basic Query

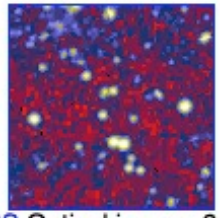


- You can also enter coordinates, alternate names, etc.
- Submit search with “Start Search” button

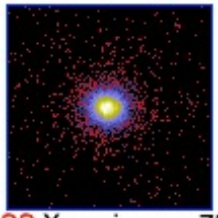
Query Search Results

Query Information | Query Results | Data Products Retrieval | Help

Images generated by *SkyView*
Click on image to see full *SkyView* image



DSS Optical image, 2.83'



RASS X-ray image, 75.0'

Images centered on requested position

Search was based on:

Object/Coordinates: cas a
resolved by SIMBAD (local cache) to [23 23 24.00, +58 48 54.0]
Using the coordinates from the SIMBAD resolver for cas a.
WARNING! The positions returned by SIMBAD and NED for cas a differ by 0.5 arcminutes!
Requery with coordinates found by NED
Coord. System: Equatorial, equinox 2000
Maximum Rows: 1000
Search Radius: Default arc minutes
Reissue Query | Save Query to File

Browse Tip: Do you know how to generate a script of commands to retrieve data products? Learn more on this topic or See all tips

Table Name and Row Count: 1 table queried. A total of 118 rows returned.

nicermastr:NICER Master Catalog	118

- Click “nicermastr” highlighted text (“NICER Master”)

Selecting Data to Download

NICER Master Catalog (nicermastr) Bulletin

Search radius used: 15.00'

Select All	Services	name	ra	dec	time	obsid	exposure [s]	processing status	processing date	public date	obs type	Search Offset ['] from (target)
☑	O R N S D	Cas_A	23 23 25.13	+58 48 35.6	2020-09-18 00:49:20.000004	3010080128	14058.00000	VALIDATED	2020-09-22 15:35:06	2020-10-02	CAL	0.340 (cas a)
☐	O R N S D	Cas_A	23 23 24.91	+58 48 36.4	2021-02-17 03:40:07.000000	3010080169	12025.00000	VALIDATED	2021-02-24 01:11:15	2021-03-03	CAL	0.317 (cas a)

118 rows retrieved from nicermastr

Data Product Retrieval

- **Select the checkboxes for the rows of interest above,**
- **Un-check any data products below you are not interested in**
- **Select the Data Product Retrieval tab for retrieval options**

Data Products available for nicermastr:

☑ **All**

☑ Full Observation Dataset (nicer.obs)

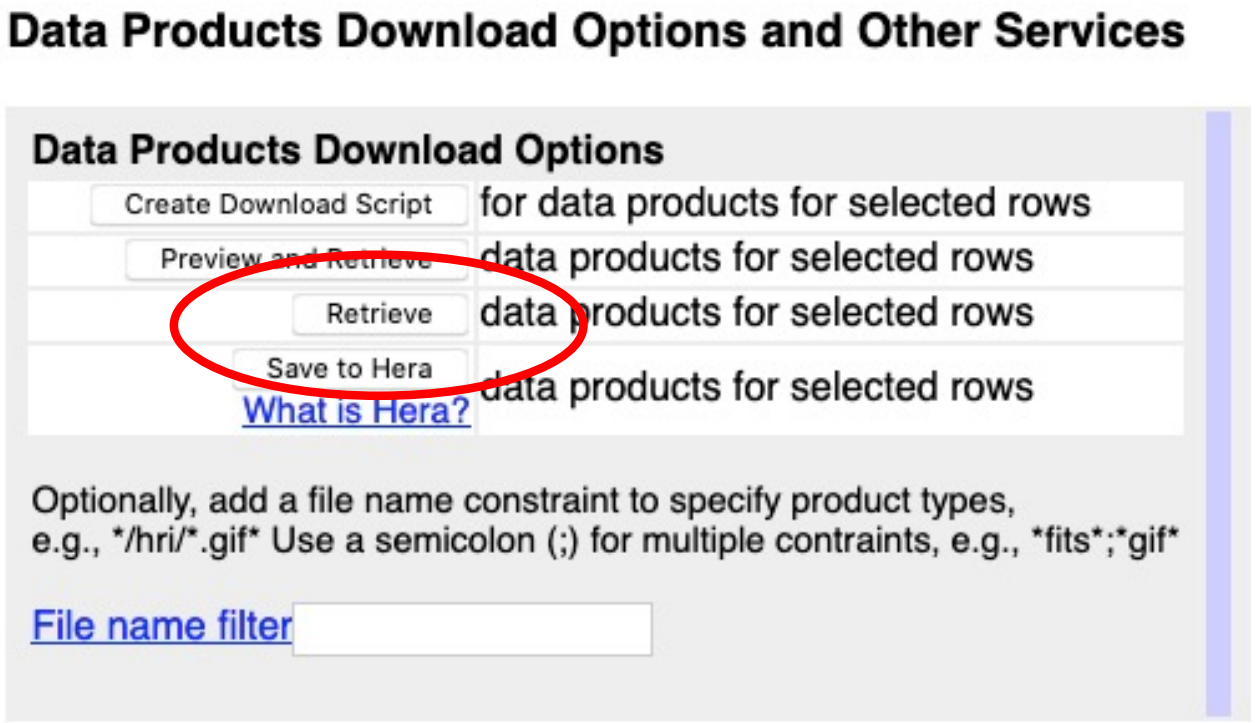
Retrieve Data Products for selected rows

Further Actions:

Do you want to Cross-correlate you

- There are many available data sets, and we will select the first one
- Click “Retrieve Data Products for selected rows”

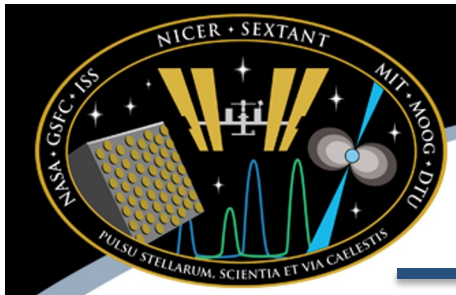
Initiating Download



- Click “Retrieve”
- Wait until TAR Complete message appears before clicking the download link

Advanced Usage

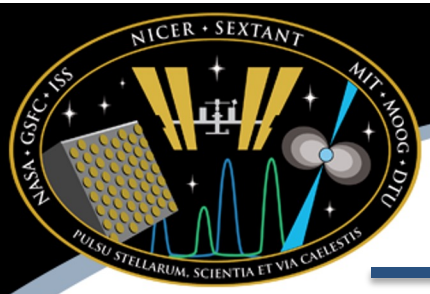
- You can use “Preview and Retrieve” to look at data sets before downloading them
- ”Create Download Script” will create a script using “wget” that you can use on your own computer
- Use the “download_wget.pl” script to download multiple data sets to your computer
  https://heasarc.gsfc.nasa.gov/docs/nicer/archive/nicer_archivestart.html



Extracting the Archive

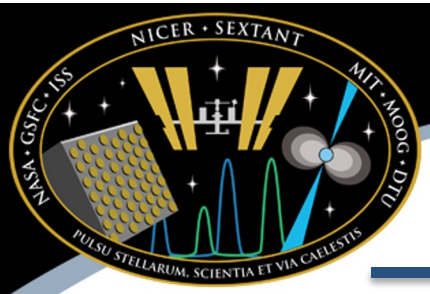
- Data are delivered in a “tar” archive, which needs to be expanded
- Place the .tar file you downloaded in the directory you plan to work in
- Extract the archive

```
tar xvpf filename.tar
```



Concept of NICER Observations

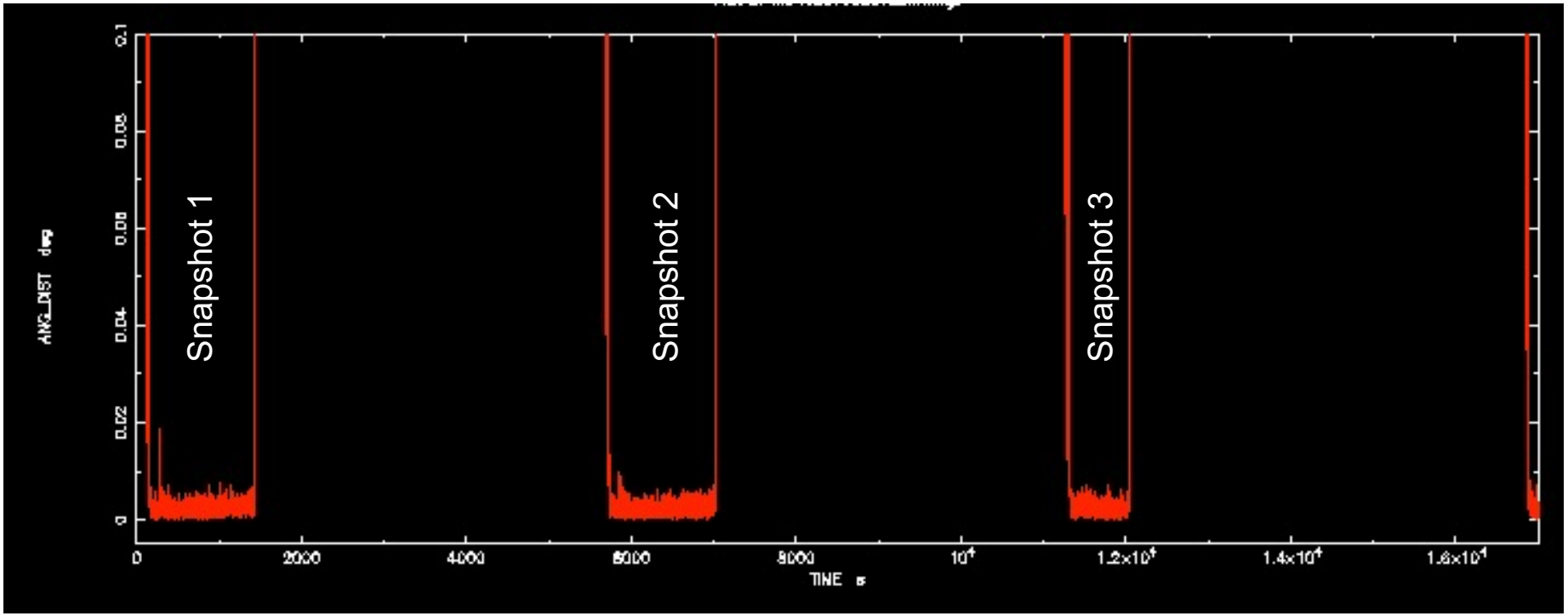
- NICER Observations are archived with an observation ID called an OBS_ID. Example 3010080128
- 3010 – **proposal** number
- 08 – **target number** listed in proposal
- 01 – **visit number** listed in proposal
- 28 – **segment number** (visits are broken into daily segments)
  - This is what you download!
- Proposal, target, and visit are driven by the science of the proposal
- The segment number is driven by the convenience of the data processing pipeline



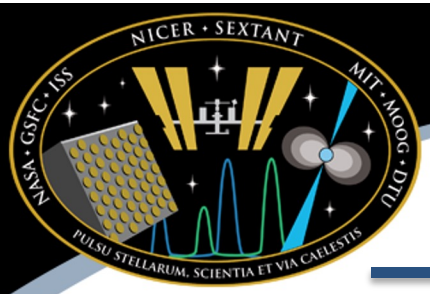
Segments and Snapshots

- A single observation segment is what you download from the archive
  - Should contain no more than a ~day's worth of data (broken at UTC midnight)
- A segment may contain more than one contiguous pointing at the target. Each is known as a snapshot. Example:
  - 01:31-01:55 – snapshot 1
  - 03:57-04:15 – snapshot 2
  - 23:49-00:07 – snapshot 3 (spans midnight)
- The data set you download only has data corresponding to the target of interest, not snapshots of other targets observed on the same day

Snapshots Example



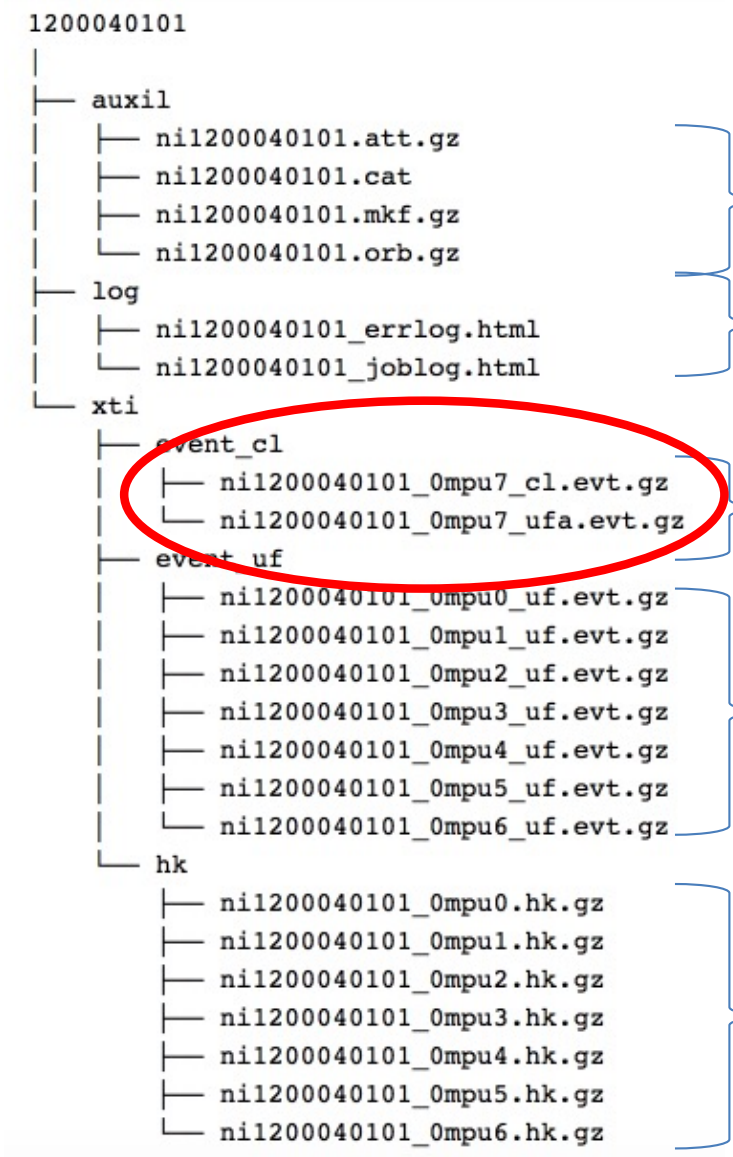
- Snapshots are primarily driven by International Space Station orbit and visibility constraints
- Command used:
  `fplot 3010080128/auxil/ni3010080128.mkf.gz  offset=yes`
  X axis: TIME
  Y axis: ANG_DIST



Visits, Segments, Snapshots Summary

- The summary to this discussion is that your "science" observation will almost always be broken into smaller pieces called segments (daily) and snapshots (multiples of ~90 minute cadence)

NICER Observation Layout



NNNNNNNNNN – observation segment directory

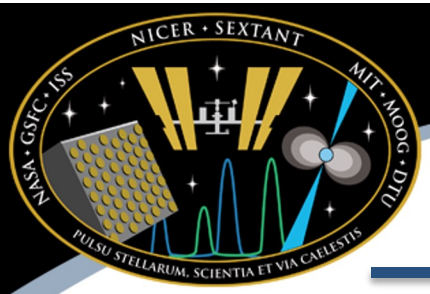
auxil – data "about" the observation
filter (mkf) orbit (orb) attitude (att)

log – pipeline processing logs

event_cl – cleaned events (good science data)

event_uf – raw unfiltered event data

hk – instrument housekeeping



Important NICER Files

- niNNNNNNNNNN_cl.evt – ”cleaned” and calibrated event file contains every event that passes the screening criteria
  - This is the file you will most often use for science
- niNNNNNNNNNN_ufa.evt – calibrated but unfiltered event list
- niNNNNNNNNNN.mkf – filter file (.mkf) which contains quantities to screen on
- Note that by default these files are gzip-compressed when you retrieve them from the archive. In the case of very large files, this may interfere with data processing and you will need to uncompress them before processing

FITS Event Files ("ufa" and "cl")

HDU 2 EVENTS BinTable 9 cols x 16744802 rows

Col	Name	Format[Units](Range)	Comment
1	**TIME**	**1D [s]**	**Time of events**
2	RAWX	1B [pixel] (0:7)	Event X position RAW coordinates
3	RAWY	1B [pixel] (0:6)	Event Y position RAW coordinates
4	PHA	1I [chan] (0:4095)	Slow Pulse Height Analyzer
5	PHA_FAST	1I [chan] (0:4095)	Fast Pulse Height Analyzer
6	DET_ID	1B	Detector ID number - 10*MPU+FPM
7	DEADTIME	1B [s]	Event dead time
8	EVENT_FLAGS	8X	MPU Event Flags
9	TICK	1K	MPU tick count of event
10	**PI**	**1I**	**Slow Pulse Invariant**
11	**PI_FAST**	**1I**	**Fast Pulse Invariant**
12	**MPU_A_TEMP**	**1E**	**MPU Analog Temperature**
13	**MPU_UNDER_COUNT**	**1J**	**MPU undershoot rate**
14	**PI_RATIO**	**1E**	**Ratio PI/PI_FAST**

Events

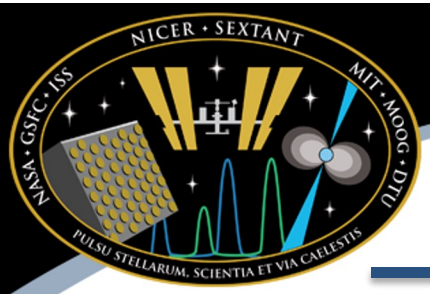
GREEN = Calibration Additions

HDU 3 GTI BinTable 2 cols x 13 rows

Col	Name	Format[Units](Range)	Comment
1	START	1D [s]	GTI start time
2	STOP	1D [s]	GTI stop time

GTI – Good Time Intervals

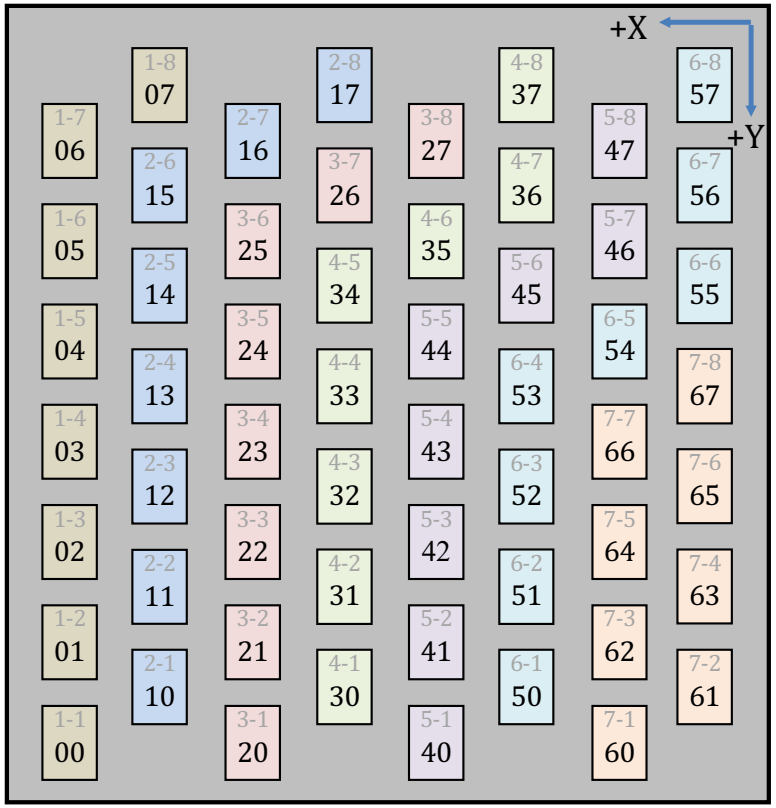
Command used: `ftlist 3010080128/xti/event_cl/ni3010080128_0mpu7_cl.evt.gz HC`

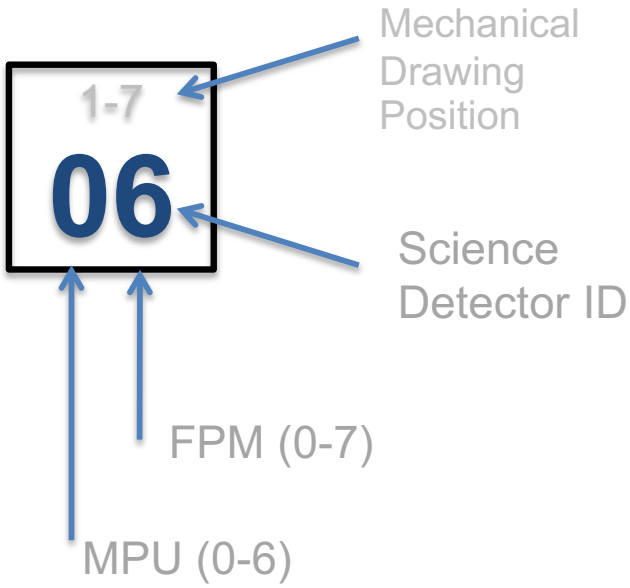


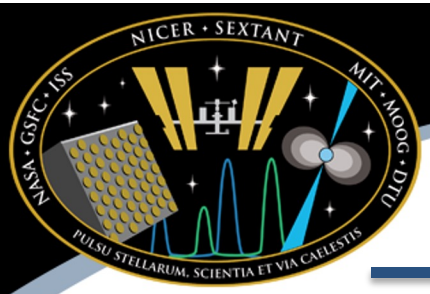
Detector Identification

- There are 56 modules arranged as follows (see following page):
  - seven MPUs labeled 0-6
  - eight FPMs per MPU, labeled 0-7
- The modules are labeled with a single integer DET_ID in the event list:
  - DET_ID = 10 x MPU + 1 x FPM
  - Example: 27 means MPU2, FPM7

Detector Layout

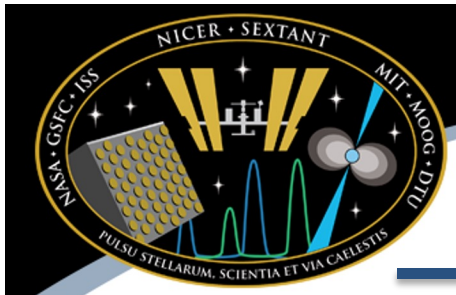






Running Standard NICER Pipeline Processing

- The next section discusses how to run standard NICER pipeline processing for yourself
- Why would you want to do this?
  - New software may be available
  - New calibration data may be available
  - Applying screening is a scientific judgement; you may need to alter the defaults
- The standard pipeline processing tool is called: nicerl2
- See https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/nicerl2/ for more information



What Does nicerl2 do?

- Applies standard processing to a single observation segment data set
  - Standard calibration ("nicercal" task)
  - Merges per-MPU event files into single "ufa" file
  - Generates filter file (.mkf file)
  - Applies screening ("nimaketime" and "nicerclean" tasks)
- End result is a cleaned event list in xti/event_cl/niNNNNNNNNNN_0mpu7_cl.evt
- Note that any existing cleaned event file may be clobbered if you set clobber=YES!

Running nicerl2

- Basic command:

```
cd /path/to/data
nicerl2 indir=3010080128 clobber=YES
```

- What does it do
  - Change working directory to your work area
  - Run nicerl2 with the observation directory 3010080128 to be processed
  - clobber=YES means to overwrite existing .mkf and .evt files
    (Note that if you set clobber=NO, you will need to rename or move the changed files before running nicerl2)

Things You May Want to Change

- Consider background modeling
  - You may need to add additional columns in order to make the background models work properly. See the “nicerl2” thread for more information. Example for 3C50 model:

```
nicerl2 … niprefilter2_coltypes=base,3c50
```

- Consider if the screening is too conservative, and most of your data disappeared
  - See next talk for tips on how to improve this

What Is Next?

- The key output of nicerl2 is a cleaned event file.
- This is the key product you can use to
  - Extract light curves
  - Extract spectra
- Next section discusses these tasks

Xselect

- NICER is compatible with the HEASoft environment called xselect.
- xselect is an interactive console environment that allows you to perform various selection operations, and extract products

Starting and Initiazing xselect

- In this example we will start xselect and read our cleaned event file
- Start xselect

```
cd 3010080128/xti/event_cl
xselect
```

  - Change to directory with cleaned events
  - Run xselect
- Read events

```
read events ni3010080128_0mpu7_cl.evt
Event Directory:      .
Reset the Mission?    Y
```

  - The file name is the cleaned event file produced by nicerl2

Extracting Light Curve

- In this example we will extract a light curve with 16 second time bins and plot it
- Extract light curve

```
set binsize 16.0
extract curve
```

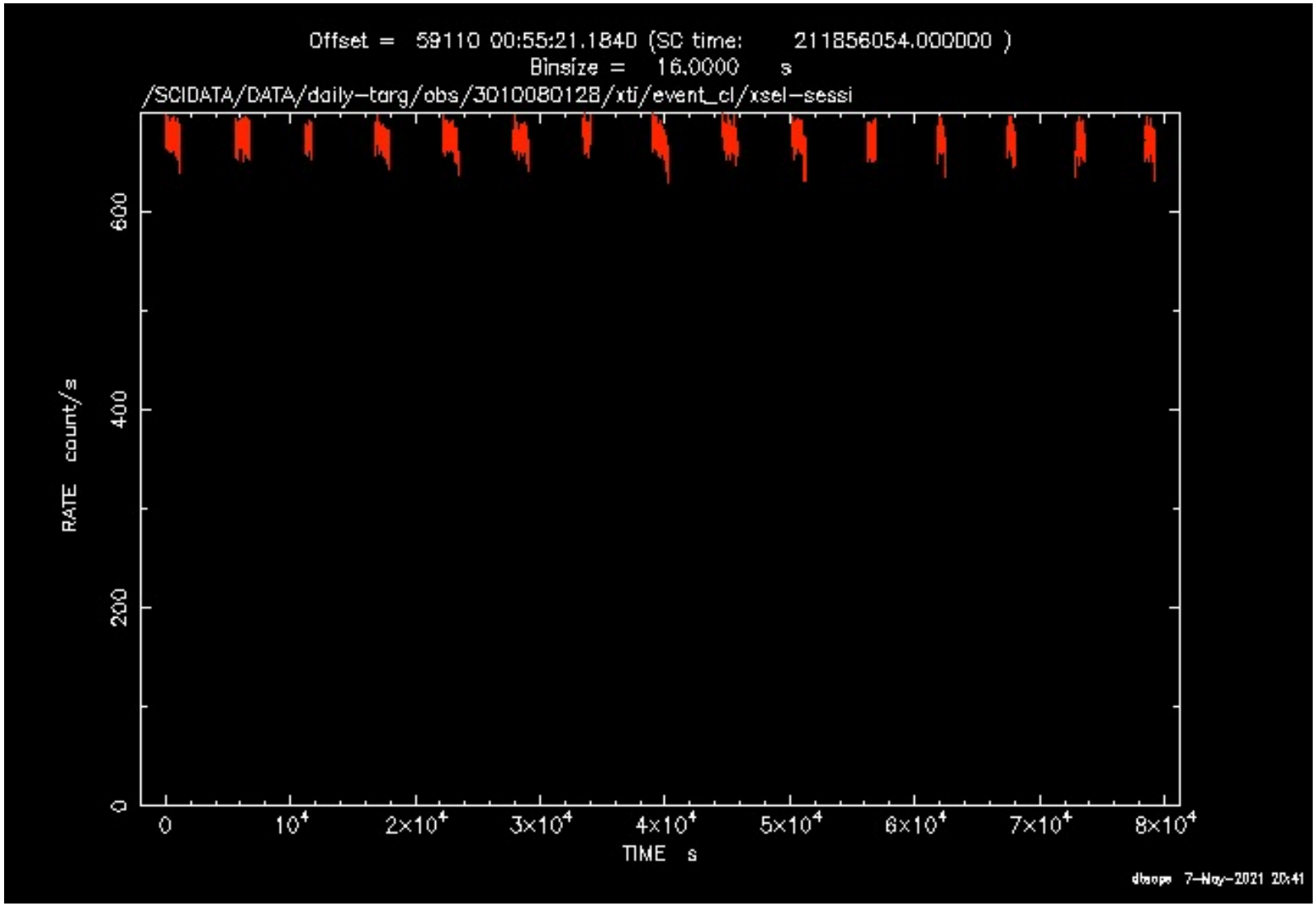
  - Set time bin size to 16 seconds
  - Extract light curve
- Plot the light curve

```
plot curve
```

- Save the light curve for future use

```
save curve mylightcurve.lc
```

Example Light Curve



Extracting Spectrum

- In this example we will extract a spectrum and plot it
- Extract spectrum

```
extract spectrum
```

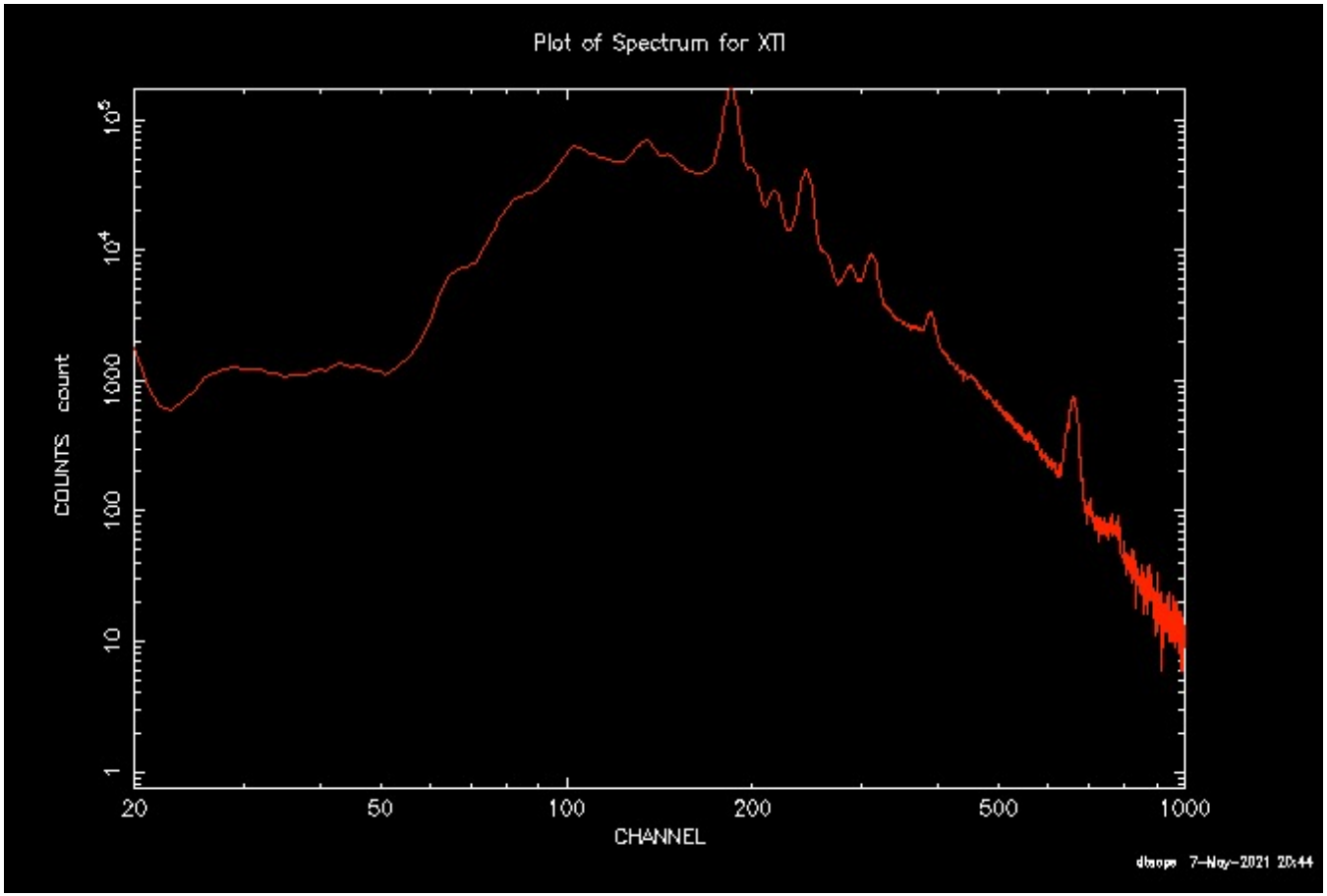
  - Set time bin size to 16 seconds
  - Extract light curve
- Plot the spectrum

```
plot spectrum
log y on
log x on
r x 20 1000
```

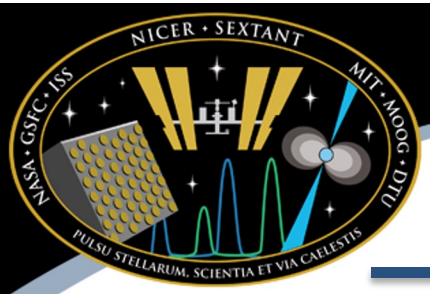
- Save the spectrum for future use

```
save curve myspectrum.pha
```

Example Spectrum



- Note PI Channel = (Energy/10 eV). Example PI=150 is the same as E=1.5 keV



What is the Next Step?

- The next step can be spectral analysis
- You will need response data for your observation
- NICER responses are composed of
  - ARF – "Ancillary Response File" – total detector throughput information
  - RMF – "Redistribution Matrix File" – detector resolution and redistribution information
- Both files are required for analysis

Where to Get ARFs and RMFs

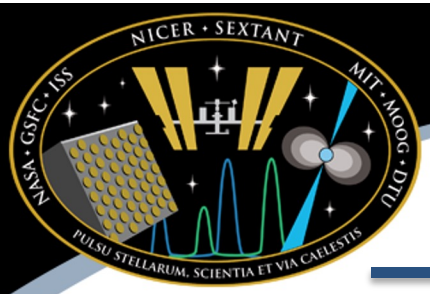
- NICER has an analysis thread describing how to do this in more detail:
  https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/arf-rmf/
- You will be required to download additional data, and extract the tar file as described
- Then you can use the included nicer-add-arfs and nicer-avg-rmfs scripts to generate response files for your data
- Please note that if you use the default 52-detector array, you do not have to edit any of the files.

How to Load NICER Data in XSPEC

- XSPEC is the supported spectral fitting package for NICER data
- To load NICER data:

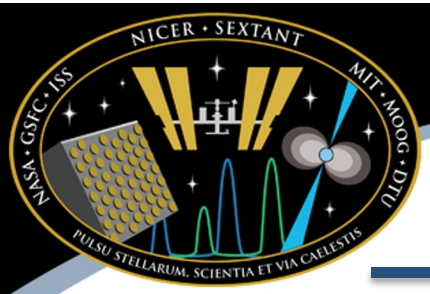
```
data 1:1 myspectrum.pha
arf 1:1 nixtiaveonaxis20170601v003.arf
rmf 1:1 nixtiref20170601v001.rmf
ignore **-0.25,10.-**
```

  - Read spectrum, ARF and RMF
  - Set default energy range to 0.25-10 keV by ignoring <0.25 and >10.0 (may depend on signal to noise and science needs)



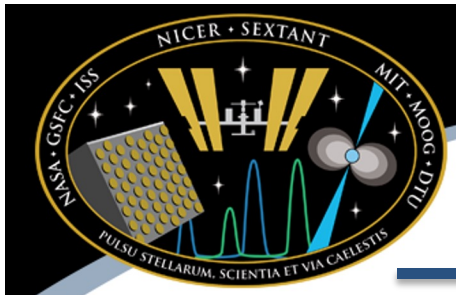
What about Background?

- Unlike an imaging detector NICER does not have a way to select a different background region.
- NICER provides two different background modeling approaches
  - The “3C50” model (Remillard et al.)
  - The “space weather” model (Gendreau et al.)
- More will be discussed in future presentations



Conclusion

- We have taken NICER analysis from beginning to end
  - Software, Calibration data
  - Archive searching
  - Download and extraction of observation data
  - Running standard processing
  - Extracting high level products
    - Spectra
    - Light curves



Future Presentations

- Future presentations will give more information about finer points, tips and caveats of NICER analysis
  - Changing screening criteria to retrieve “more” data
  - New NICER software changes expected shortly
  - NICER calibration status
  - NICER timing and barycentering
  - Background modeling
  - Spectral fitting best practices