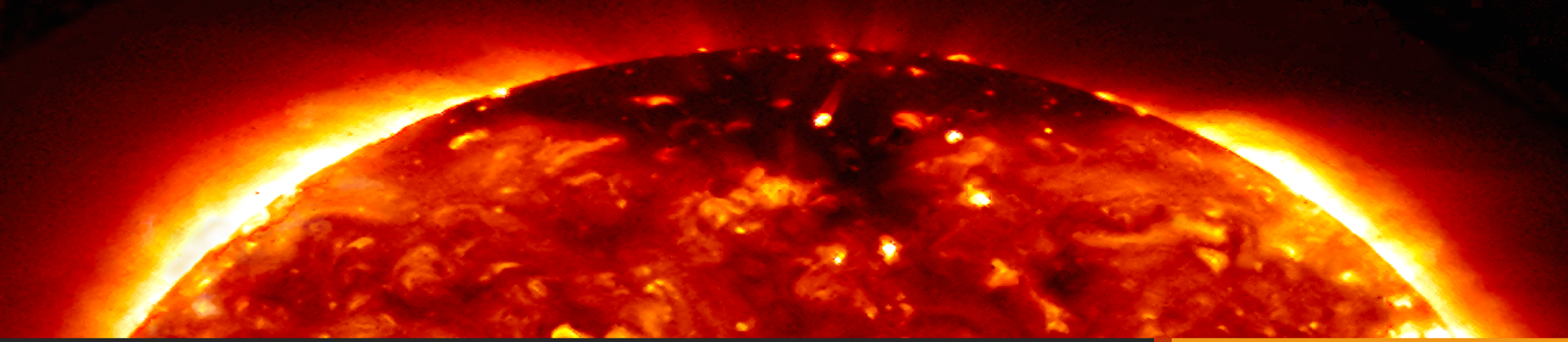
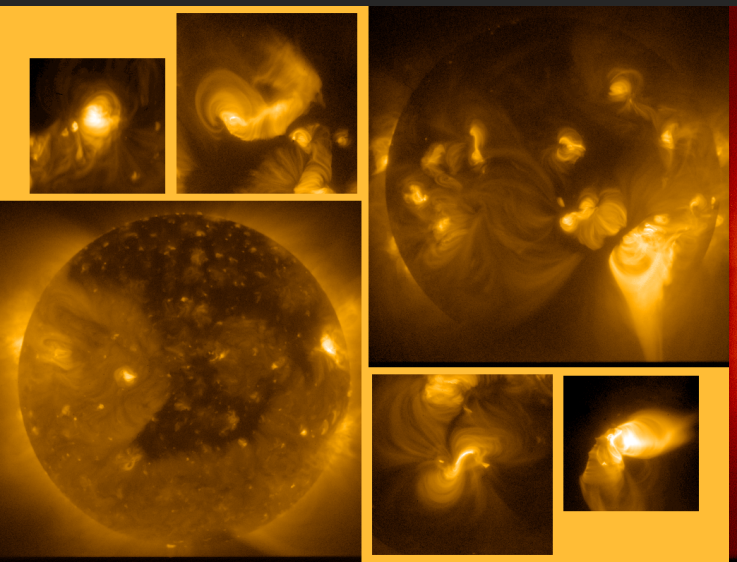
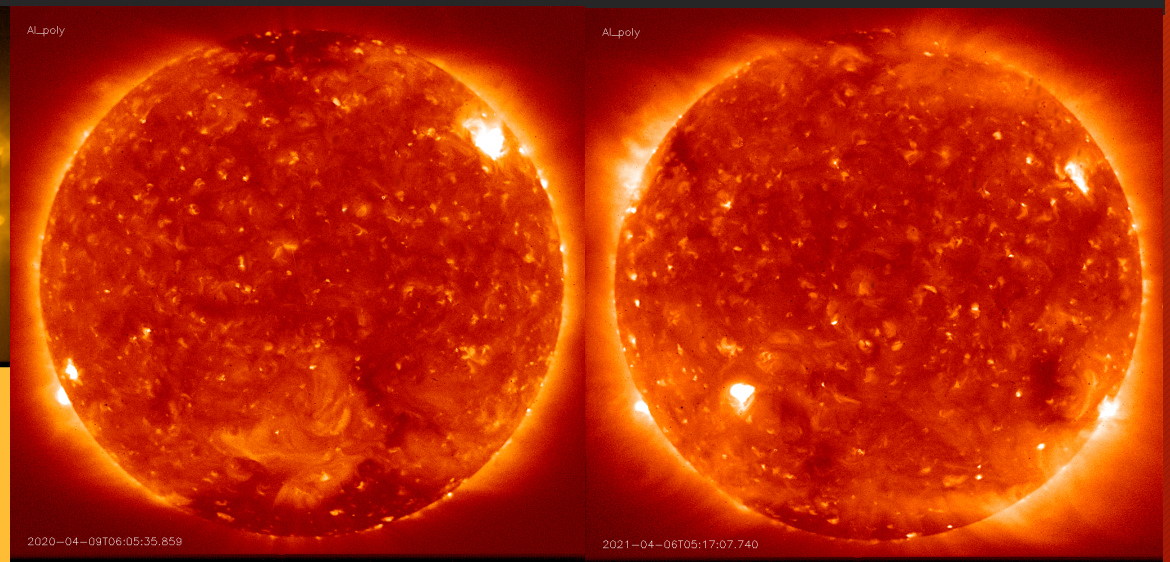


Introduction to X-Ray Telescope Data Analysis

XRT

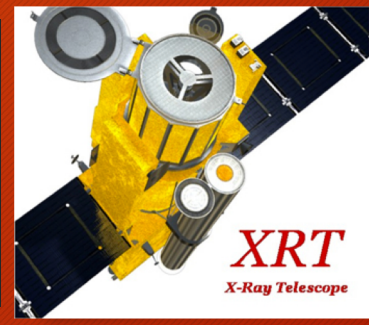




Created by
Lucas Guliano

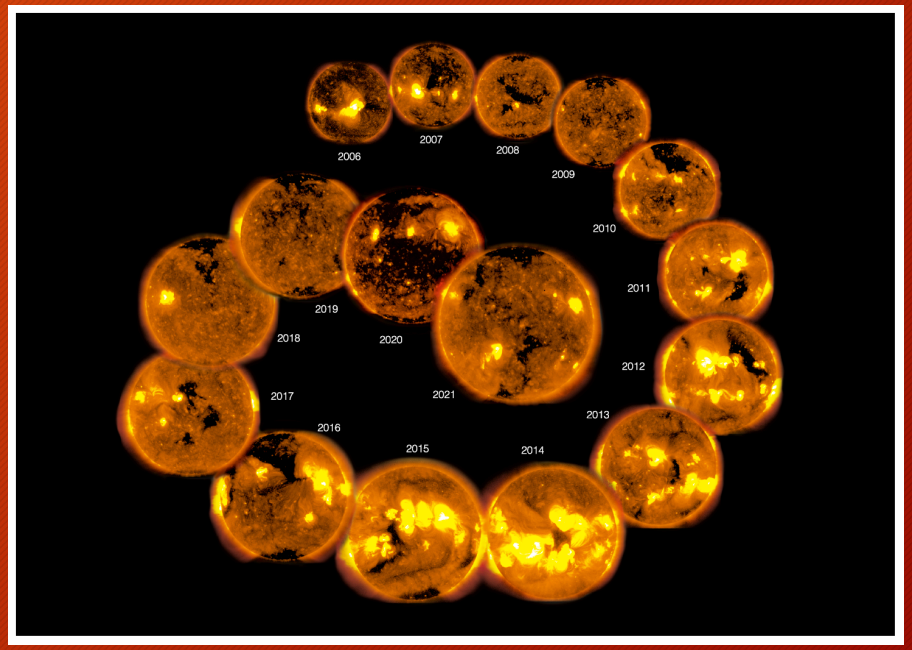
2022/07/07

Introduction/XRT Analysis Guide



- The goal of this presentation is to provide a simplified overview of the XRT data analysis process covering:
  - Basics of XRT and XRT Data data
  - XRT data access and downloading
  - XRT Catalog use and Filtering XRT data
  - Reading and Preparing XRT data
  - XRT movie generation
  - Upcoming XRT data processing projects
- Primarily done with Solar Soft IDL pack (SSWIDL)
  - Future move towards Python (XRTpy)
- A more detailed guide to the analysis process can be found at:

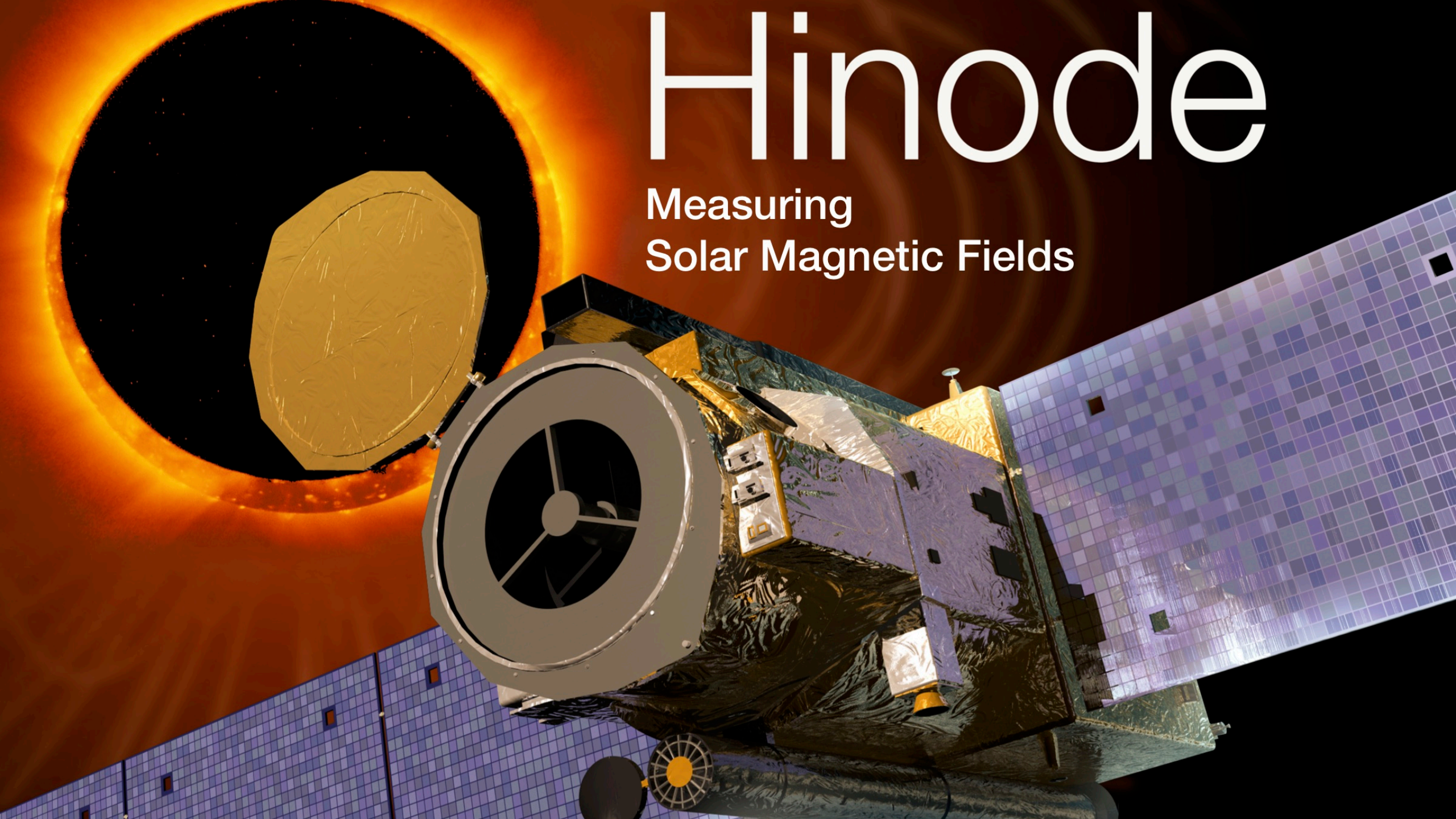
  https://xrt.cfa.harvard.edu/resources/documents/XAG/XAG.pdf



Aki Takeda (MSU)

Hinode

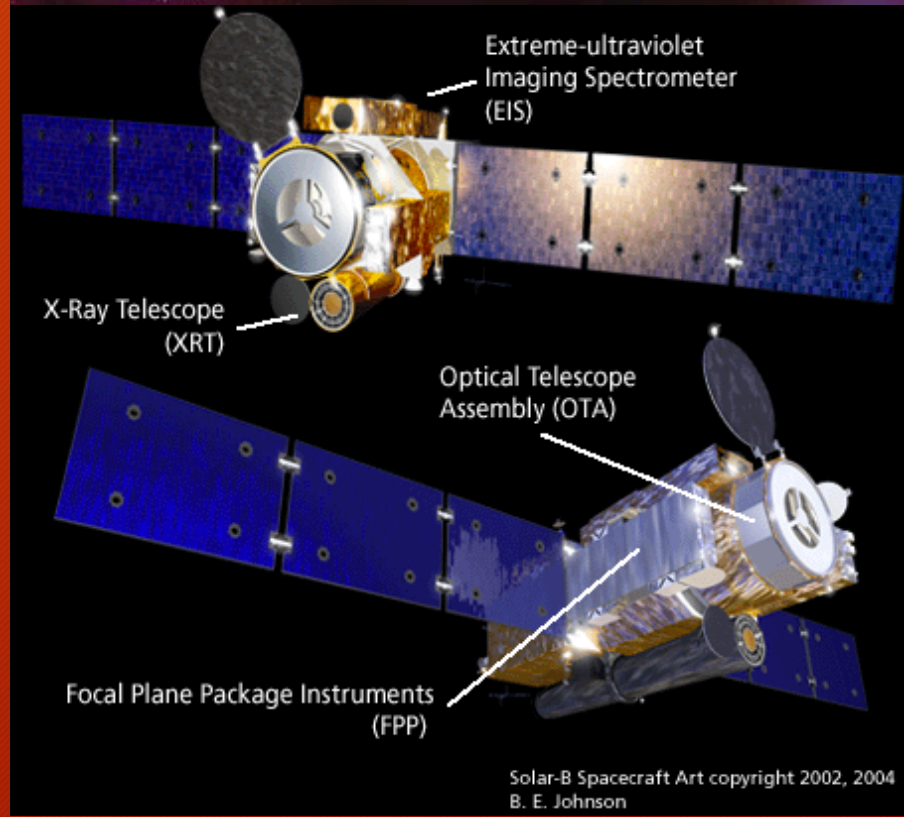
Measuring Solar Magnetic Fields



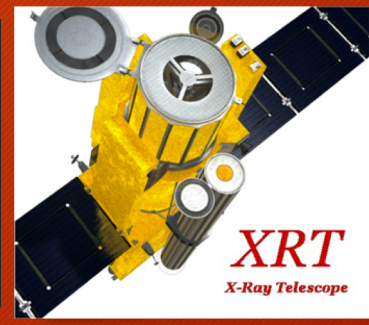
X-Ray Telescope (XRT)

https://xrt.cfa.harvard.edu/

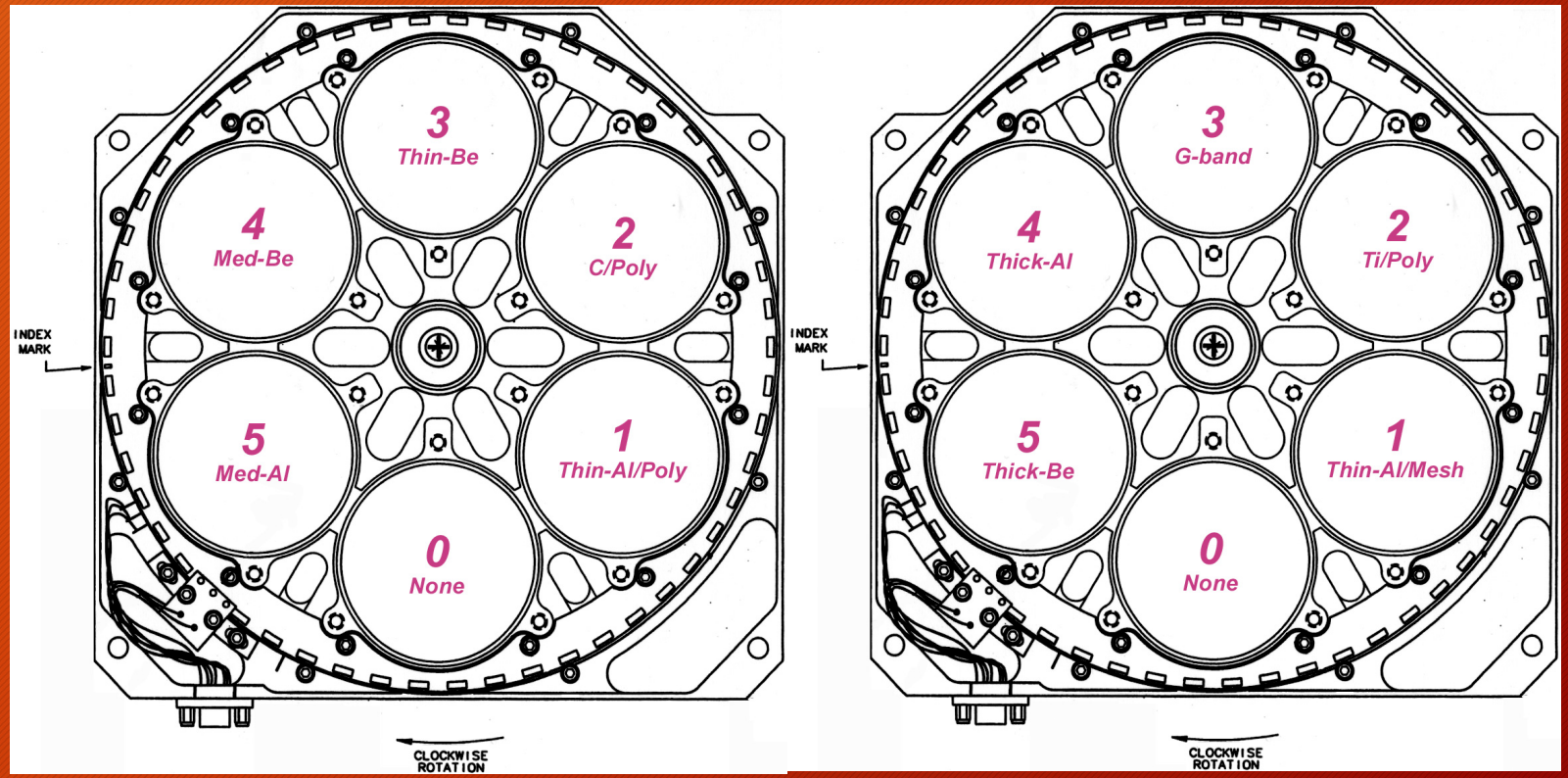
- Three instruments on Hinode:
  - X-Ray Telescope (XRT)
  - Extreme-Ultraviolet Imaging Spectrometer (EIS)
  - Solar Optical Telescope (SOT)
- First light in 2006
  - Full continuous operations (small gaps)
- High-resolution grazing-incidence telescope
  - Soft X-ray images
- Wide temperature coverage to see all the coronal features
- XRT consists of:
  - X-ray and visible light optics
  - Focal plane mechanisms (filters and shutter)
  - 2k x 2k CCD camera
- Full sun images (synoptics) or subframe images



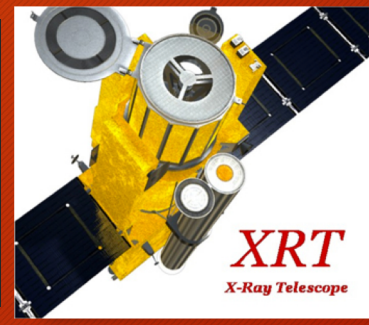
XRT Data: CCD and Filters



- CCD size: 2048×2048 pixels
- 35’× 35’ field of view
  - Possible sub-frame readouts
- Approximately 1” per pixel
- Two filters wheels
  - Creates filter pairs
  - Filter ratios
- Twice daily synoptics
  - Full disk, sun center images
  - Short and long images
- Frequently focuses on ARs
- Generates ~0.7 GB daily



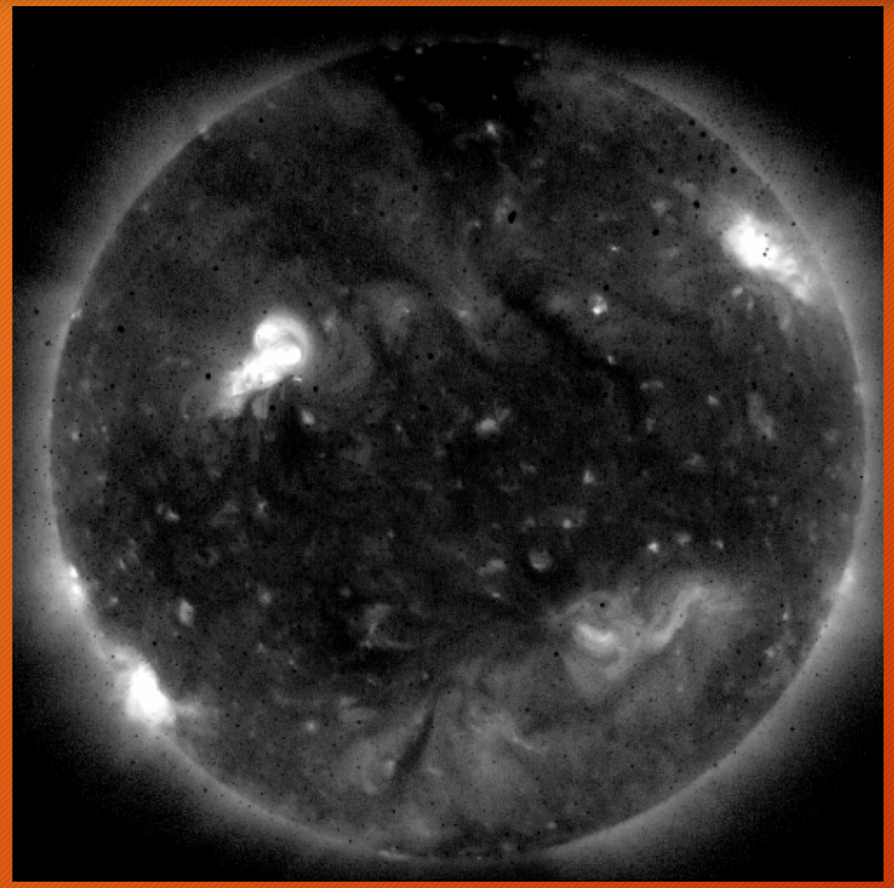
XRT Data Levels



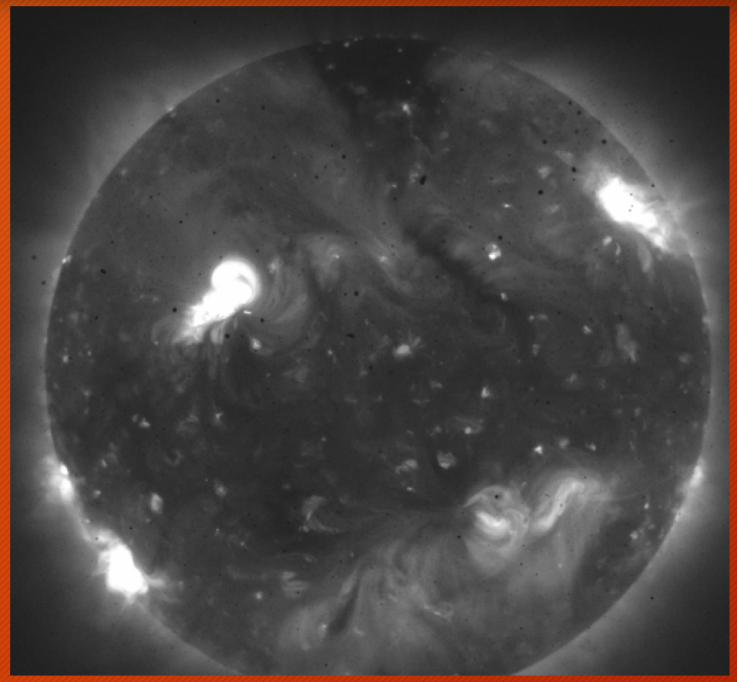
- Data is stored in levels of processing
- Each data level serves specific functions and usability

Level	Pixel values	File format	Purpose
QuickLook	Data Number (DN)	FITS	Operations, Data Verification, QuickLook movies
0	DN	FITS	Basic science
1	DN/sec	FITS	Calibrated images
2	Physical units	Any	Short and long exposures summed into one image; Differential Emission Measure; Temperature Maps

XRT Data Examples

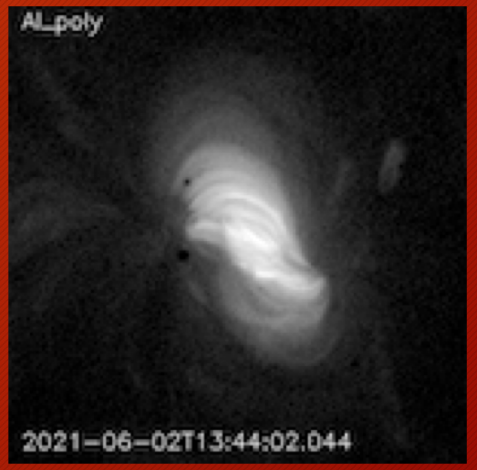


Level 1

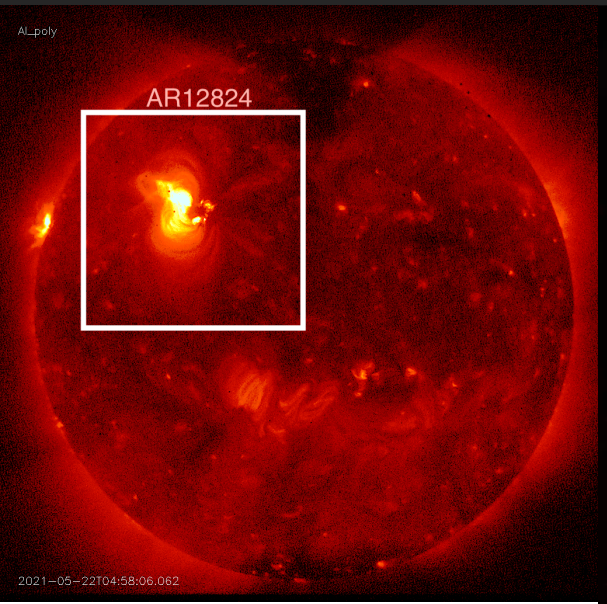


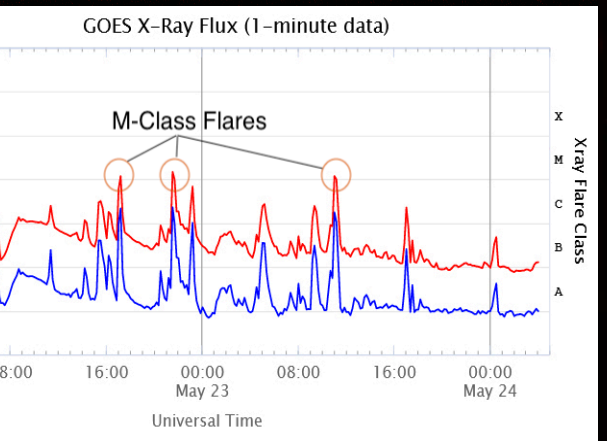
Level 0

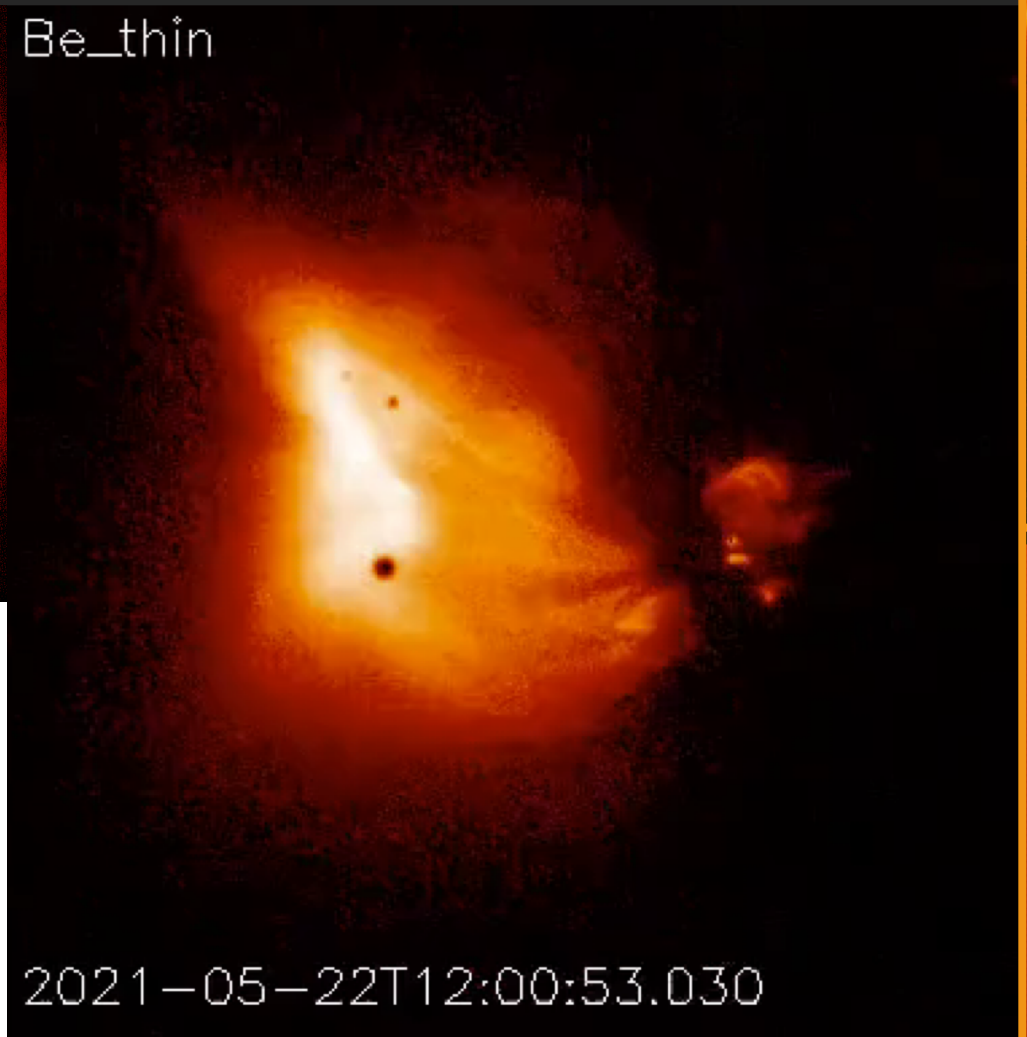
Subframe AR images

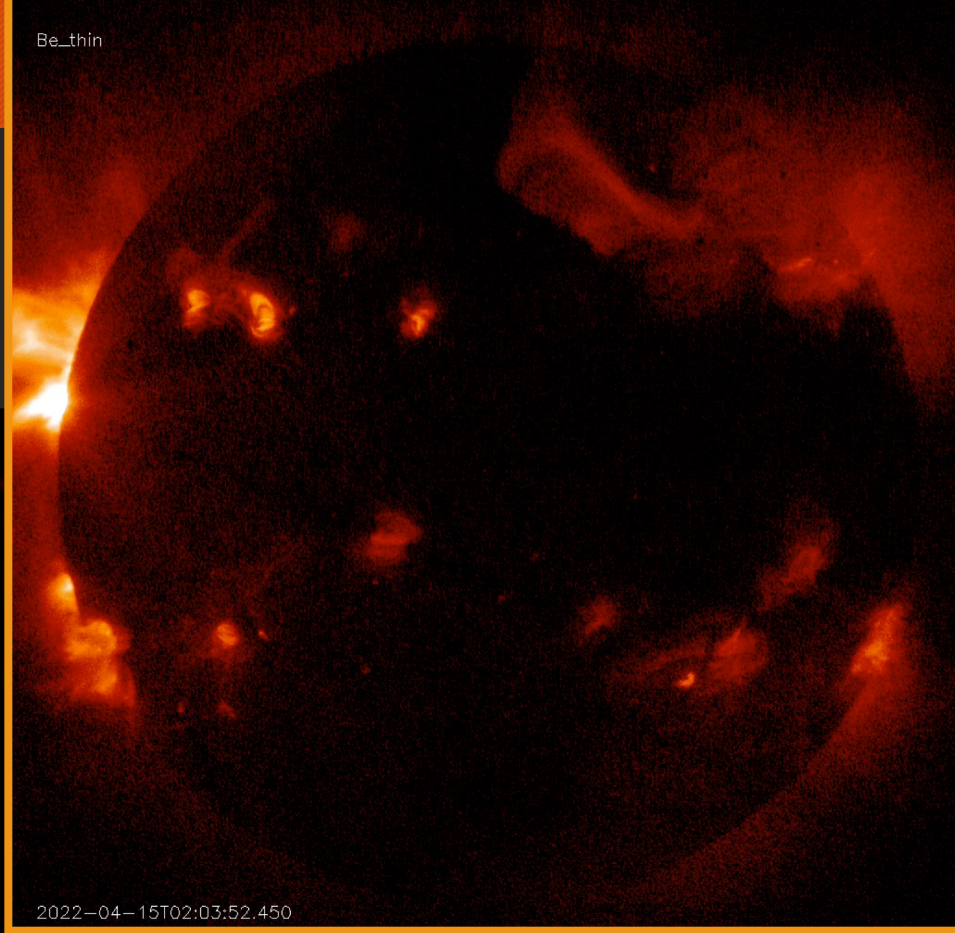


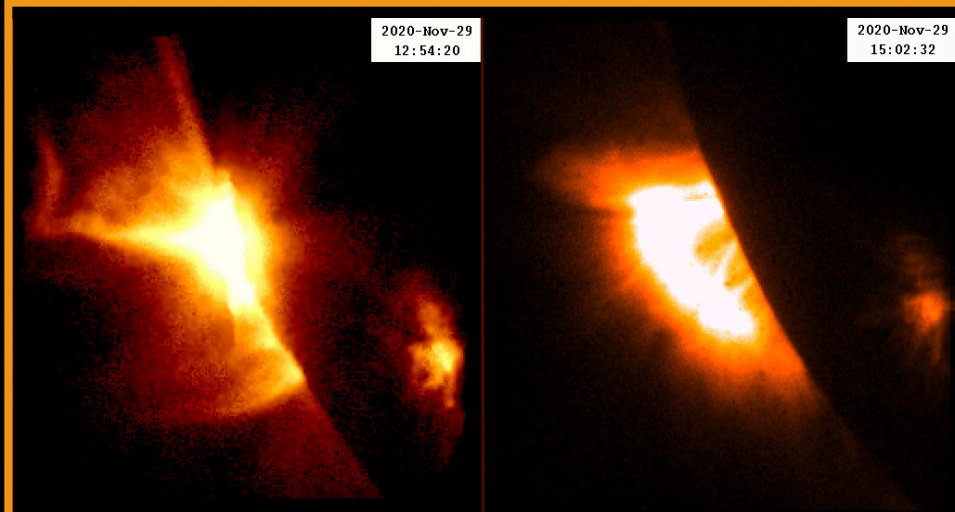
XRT Data Examples





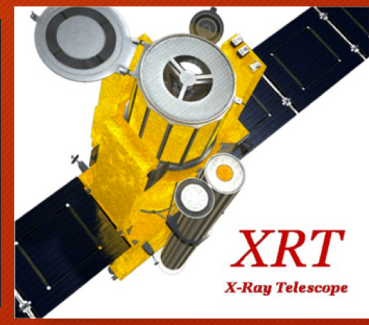






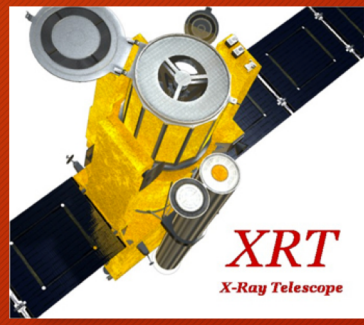
Finding and Getting XRT Data

Quick Browsing XRT Data Products

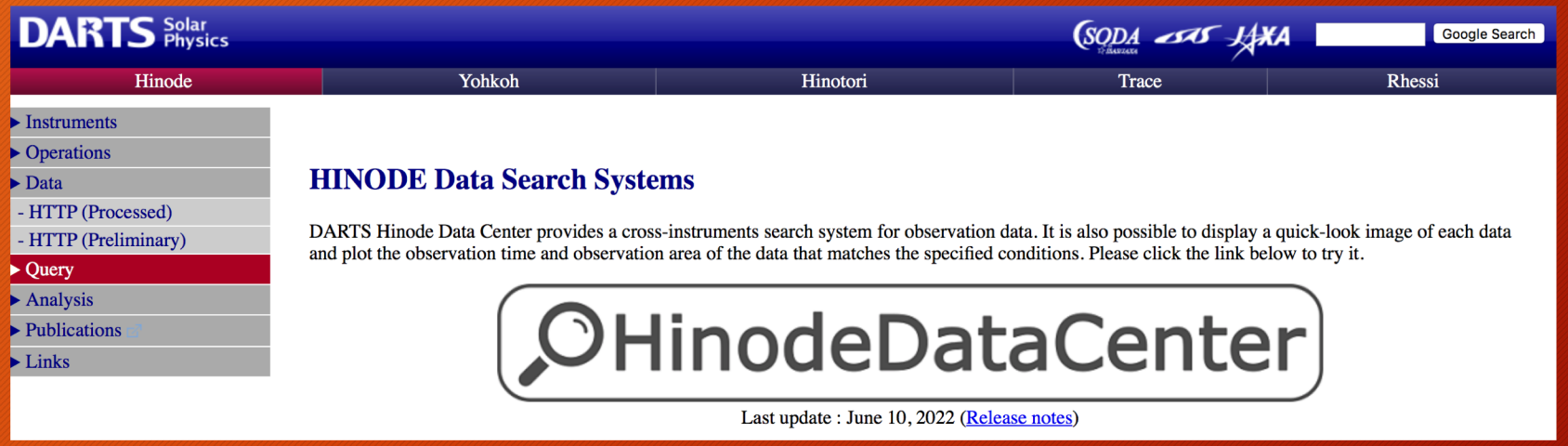


- Daily Synoptic Gallery:
  - Image gallery of processed daily XRT synoptic images
- SnapView Files:
  - Summary images for each day displaying the type and location of observations from that day along with a GOES X-ray flux plot
- XRT Flare Catalog:
  - Catalog with an entry for each flare observed by XRT. Aligns with Hinode flare catalog. Contains a movie and a summary plot for each entry
- Focused Mode Catalog:
  - Catalog with an entry for each focused mode with a a summary movie and plot showing what the primary observation was during each period
- Level0 Mpeg Archive:
  - Automatically generated monthly summary movies sorted by filter
- Carrington Map Archive:
  - Images generated from XRT data showing full solar rotations

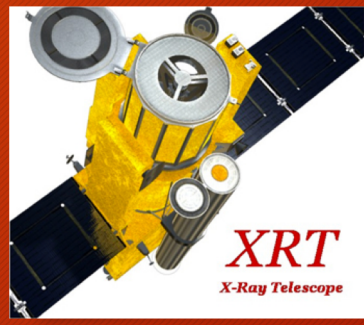
Getting Data: DARTS
https://darts.isas.jaxa.jp/solar/hinode/



- Contains data and information for all 3 Hinode instruments; including XRT
- Full Level0 archive: https://data.darts.isas.jaxa.jp/pub/hinode/xrt/level0/
  - Access to all level0 (raw data) fits files
- Hinode Data Query Link: https://darts.isas.jaxa.jp/solar/hinode/query.php?A01=Go%20to%20Search
  - Query data on various serach terms
  - Quick look and download individual or bulk data files

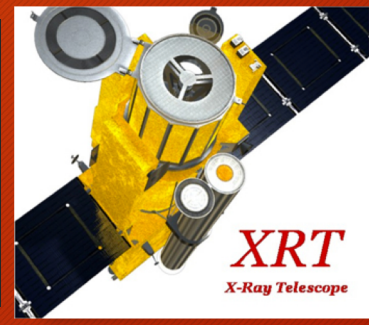


Getting Data: VSO
http://sdac.virtualsolar.org/cgi-bin/search

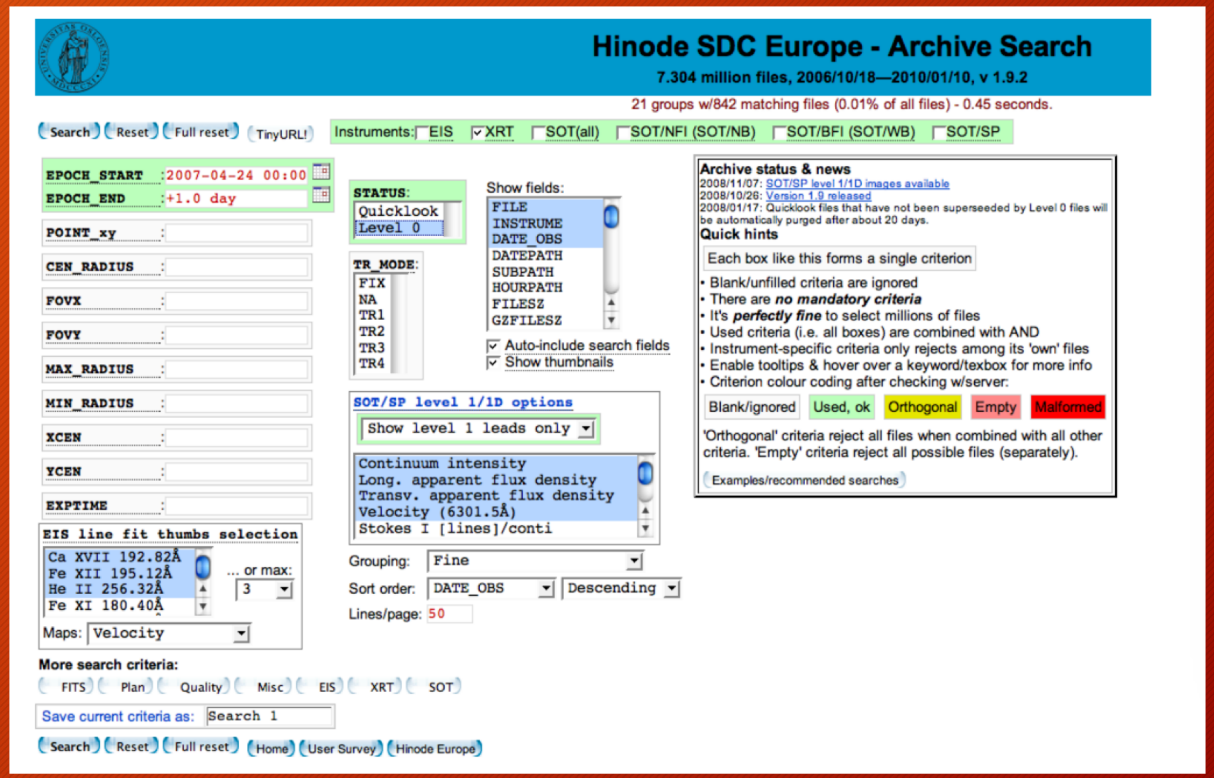


- Useful tool for searching for datasets across multiple solar observatories
- Uses search parameters to filter through XRT level 1 datasets
- Create desired dataset and download through a variety of methods

Getting Data: Science Center Archive
http://sdc.uio.no/search/



- Select XRT data from list of current instrument data at top of the webpage
- Query on multiple data types
- Download through the retrieve feature
- Instructions for data download will be send to email



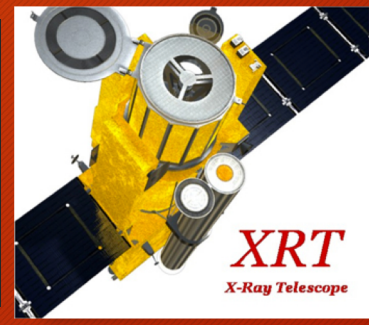
Using XRT Data

with Solar Soft IDL

XRT Solar Soft (SSWIDL) Set Up

- Installation and SolarSoft information can be found at:
  - https://www.lmsal.com/solarsoft/
- Utilizes scripts written in the Interactive Data Language (IDL) format
- Include Hinode/XRT libraries during installation process
  - In order to use the code provided here, some ancillary XRT files are necessary and can be installed by running sswdb upgrade from within SSWIDL and adding the hinode/xrt branch of the SSWDB tree (if not done at initial installation)

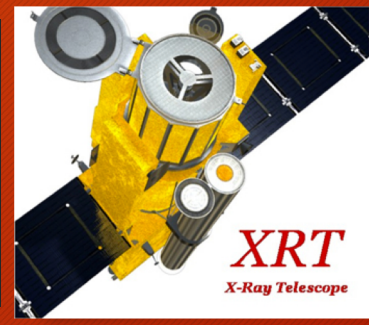
XRT Data Catalog Search



- The XRT catalog contains a subset of XRT FITS header keywords, (FOV, filters, size, etc…) for each XRT observation
- Returns XRT catalog records suitable for selecting data as a structure array
- Runs in IDL/SSWIDL
  - Same structure as https://www.lmsal.com/solarsoft/xrt_cat.html

```
IDL> t0='2007-04-18T02:30:00'
IDL> t1='2007-04-18T12:30:00'
IDL> xrt_cat, t0, t1, catx, ofiles
IDL> help, catx
    CATX     STRUCT    = ->  <Anonymous> Array[311]
IDL> help, ofiles
    OFILES    STRING    = Array[311]
```

XRT Data Filtering



- Filter of XRT with the IDL command line using FITS keywords
  - All FITS keywords can be utilized
  - Keywords can be found in each FITS file header
- Basic filter example:
  - Normal image types
  - X axis size of 512

>filt=where(catx.ec_imty eq ‘normal’ and catx.naxis1 eq 512)

EC_IMTY_: Image type; input string values of ‘dark’ or ‘normal’.

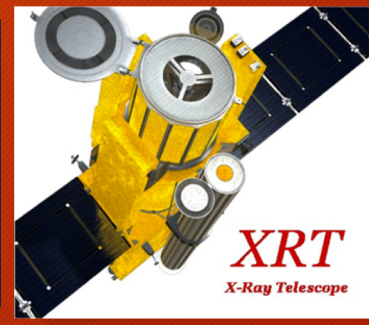
EC_FW1_: Filter Wheel 1 position; input string values of ‘Open’, ‘Al_poly’, ‘C_poly’, ‘Be_thin’, ‘Be_med’, ‘Al_med’

EC_FW2_: Filter Wheel 2 position; input string values of ‘Open’, ‘Al_mesh’, ‘Ti_poly’, ‘Gband’, ‘Al_thick’, ‘Be_thick’

EC_VL_: Visible light shutter position; input string values of ‘open’ or ‘closed’.

NAXIS1: General FITS keyword for pixel length in the *x*-direction; input integer value. XRT images are generally 384×384, 512×512 or 1024×1024; though any given area of the CCD can be read out.

Reading XRT Data

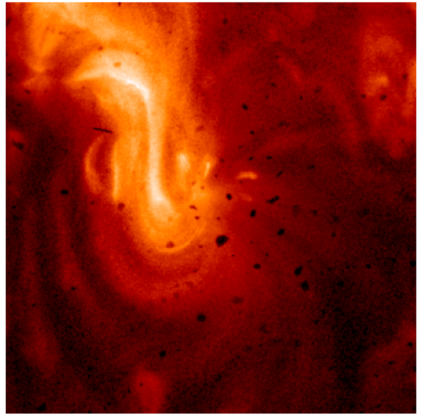


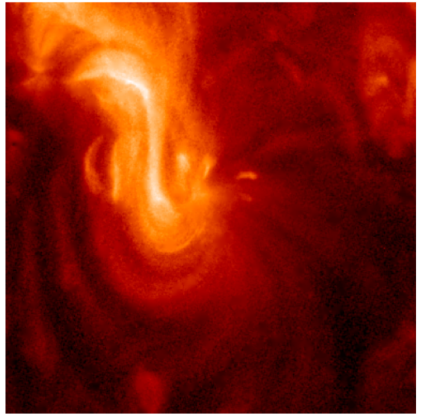
- XRT image headers and data can be read using the IDL routine read xrt.pro
- Data read into arrays storing pixel information and header values

Basic call, to read headers and data:

```
IDL> ss=where(catx.ec_imty_ eq 'normal' and catx.naxis1 eq 2048)
IDL> read_xrt, ofiles[ss], index, data
IDL> help, ofiles[ss]
    <Expression>    STRING    = Array[5]
IDL> help, index
    INDEX           STRUCT    = ->   <Anonymous>  Array[5]
IDL> help, data
    DATA            INT       = Array[2048, 2048, 5]}
```

Calibrating XRT Data





- Utilizes routine **xrt_prep.pro** to convert level 0 to level 1
- Basic call: IDL> xrt_prep, input1, input2, index out, data out

Read in raw FITS image(s) from a filelist or read in a datacube and structure.

Fill pixels of value = 0 (missing data) with a "missing data value" = -999.

Replace near-saturated pixels for values greater than some threshold (default: 2500 DN).

Option to remove radiation-belt/cosmic-ray hits and streaks.

Calibrate for read-out signals.

Locate missing pixels and replaces their values with a linear patch to improve Fourier filter performance.

Remove the CCD bias (pedestal), and dark current (using the subroutine xrt clean ro.pro which also calibrates the read-out signals).

Remove vignetting.

Option to normalize each image for exposure time.

Option to compute map of calibration uncertainties.

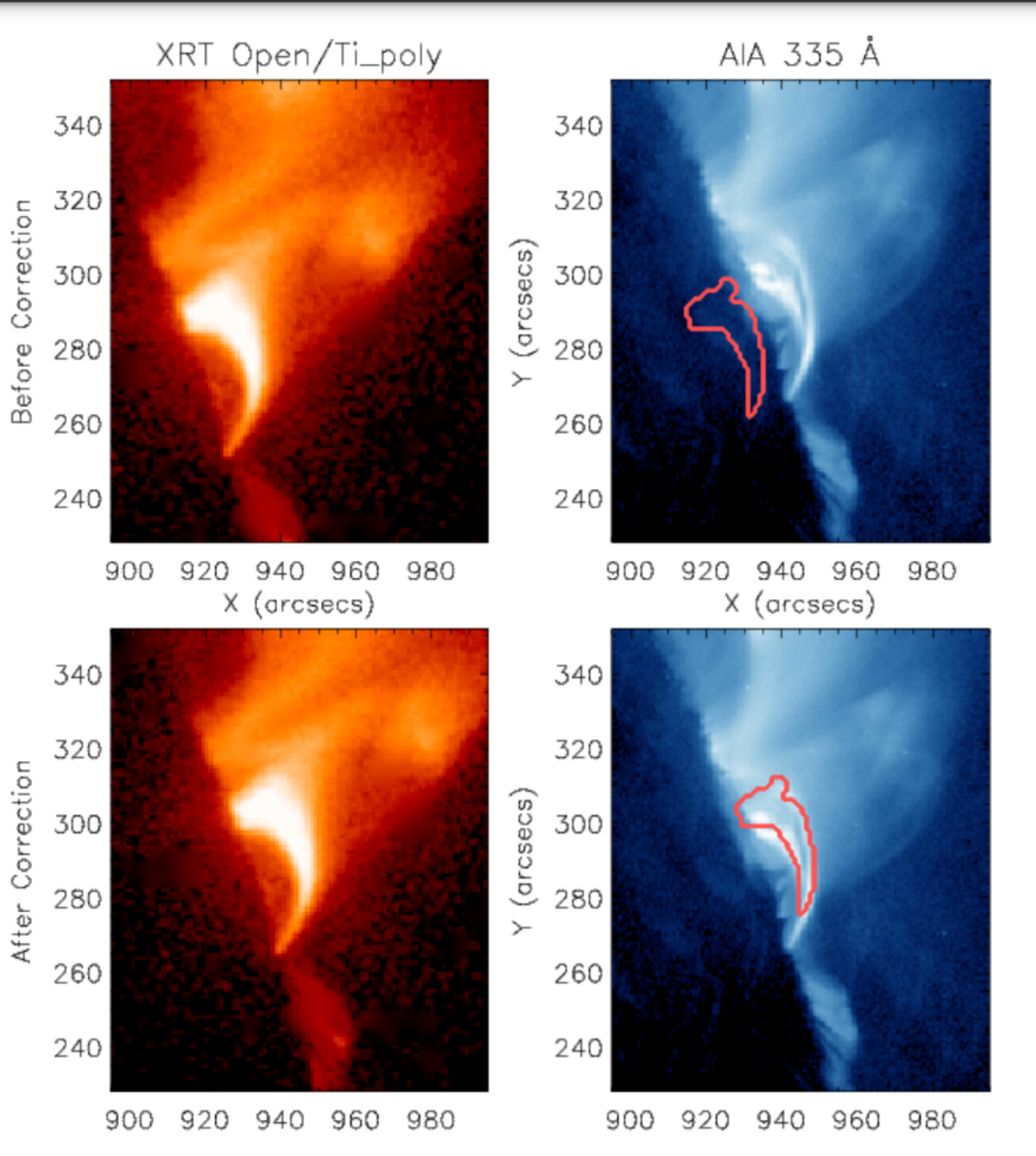
Option to cosmetically correct for contamination spots or dust.

Output the corrected image(s) in an updated structure and data cube.

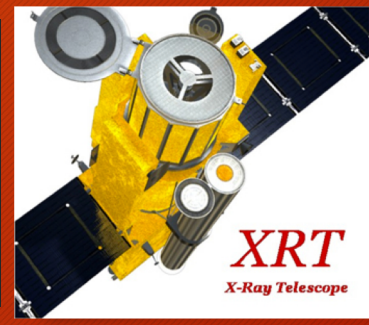
Option to coalign XRT data using xrt read coaldb.pro.

Co-aligning XRT Data

- Updates the alignment of XRT data
  - Useful for comparing between instruments
- Called as part of the data prep routine
- Does not alter XRT data and only updates FITS keywords
- Users can determine what type of co-alignment calibration was performed by reading the image history keyword
- Basic Call: IDL> new_index = xrt_read_coaldb(index)



Making Composite Images



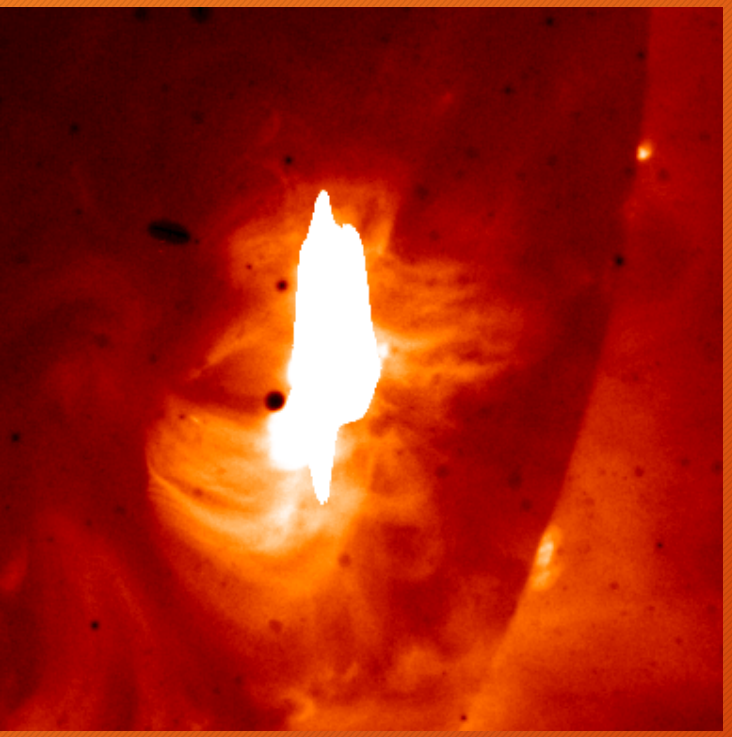
- Two routines available for making composite images
- **Mk_xrt_composite** combines a single long and short exposure pair of images to increase the dynamic range and to replace saturation with unsaturated data:

IDL> mk_xrt_composite, l_idx, l_da, s_idx, s_da, c_idx, c_da

- Can be done in batches with the **xrt_batch_composite** routine

IDL> xrt_batch_composite, l_idx, l_da, s_idx, s_da, index_out, data_out

Example of Composite Images

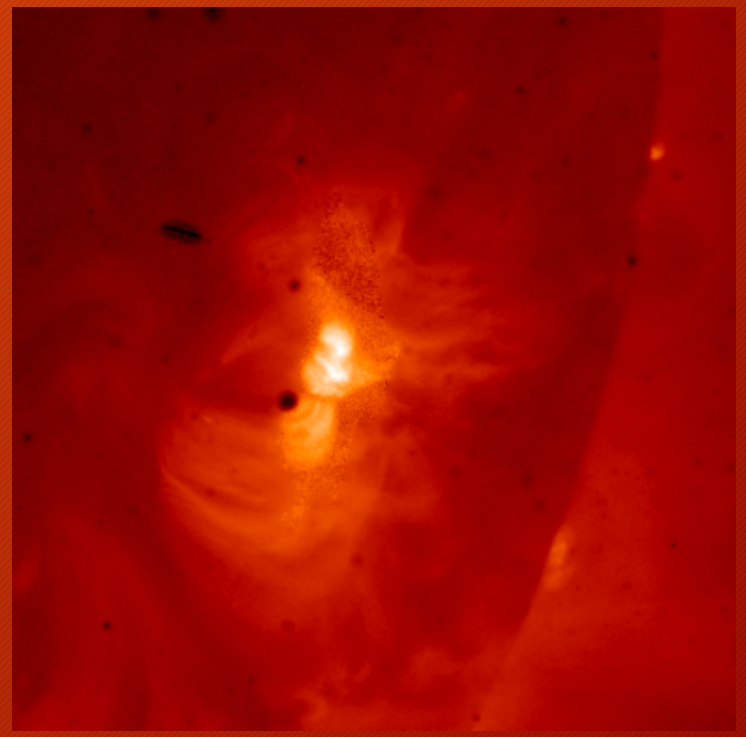


Al_poly long image
5.8 second exposure time

+

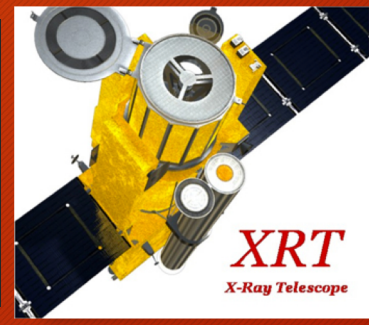
Al_poly short image
0.2 second exposure time

=



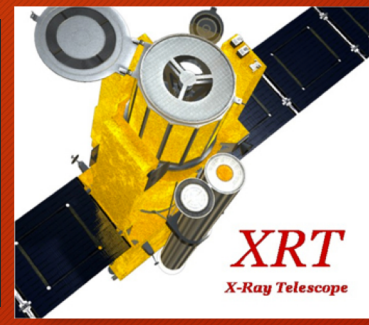
Composite image

Deconvolving the Point Spread Function



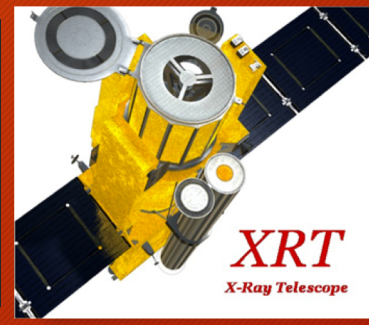
- A point spread function (PSF) was developed for XRT
- Can be deconvovled to improve quality using **XRT_deconvolve**
- IDL>xrt_deconvolve,in,da,new_in,new_da
- Improves image clarity and decreases blurring effects

Instrument Responses and Inferring Physical Quantities



- Please refer to section 2.11 of the Analysis Guide for detailed summary
- XRT data analysis requires understanding the physical units of the relevant values and functions
- Information regarding details of these properties is well summarized in the analysis guide
  - Somewhat complicated and nuanced procedure

XRT Movie Generation (Gather Data)



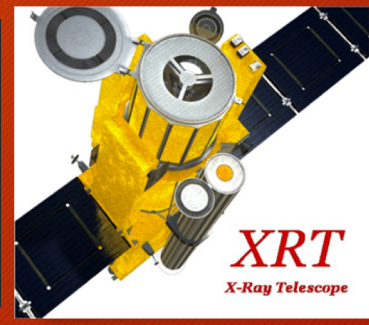
Read Dataset from file

```
file = DIALOG_PICKFILE(FILTER='*.txt')
OPENR, lun, file, /GET_LUN
flist1 = ''
line = ''
WHILE NOT EOF(lun) DO BEGIN & $
  READF, lun, line & $
  flist1 = [flist1, line] & $
ENDWHILE
FREE_LUN, lun
```

Read from Catalog

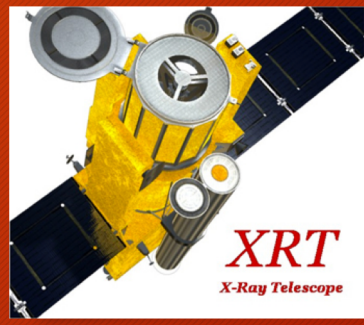
```
tt0 = ‘2021-10-08T10:45:00'
tt1 = ‘2021-10-08T11:15:00'
xrt_cat, tt0, tt1, catx1, ofiles1
filt1 = where(catx1.ec_fw1_ eq ‘Be_Thin' and
catx1.naxis1 eq 256)
flist1 = ofiles1[filt1]
```

XRT Movie Generation (Prepare Data)



- Read in the XRT data from flist1 array
  - read_xrt, flist1, index1, data1
- Prepare data using xrt_prep commands
  - Explicitly call despike_despot
  - xrt_prep, index1, data1, index_out1, data_out1, /despike_despot
- Create an array to hold rescaled data:
  - xy = size(data_out1, /dimensions)
  - image_set = make_array(xy[0], xy[1], xy[2]
- Get number of files
  - numf = xy[2]

XRT Movie Generation (Scale)



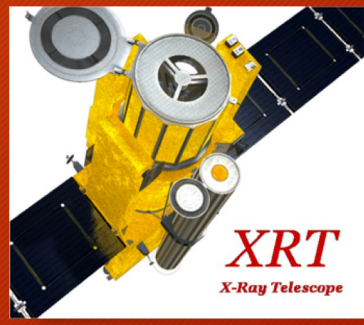

```
loadct, 3

for i = 0, numf do begin $
        image=sigrange(data_out1[*,*,i], frac=.9999, range=range) &$
        if range[0] gt 0 then imin=alog10(range[0]) else imin=alog10(20.0) &$
        imax = alog10(range[1]) &$
        image=alog10(image > 1.0^imin) &$
        image = image <imax &$
        image_set[*,*,i] = image &$
        stretch, 0, 255, 1.1 &$
        wdef, 0, xy[1] &$
        tvscl,rebin(image,xy[0],xy[1]) &$
        xyouts, 0.03, 0.03, index1[i].date_obs, /normal, size=2.0 &$
        if index1[i].EC_FW1_ eq 'Open' then xyouts, 0.03, 0.95, index1[I].EC_FW2_, /normal, size=2.0 &$
        if index1[i].EC_FW2_ eq 'Open' then xyouts, 0.03, 0.95, index1[I].EC_FW1_, /normal, size=2.0 &$
        wait, 0.0
```

Load red temperature color table

Rescale logarithmically

Write the time and filter to each image

XRT Movie Generation (Save)



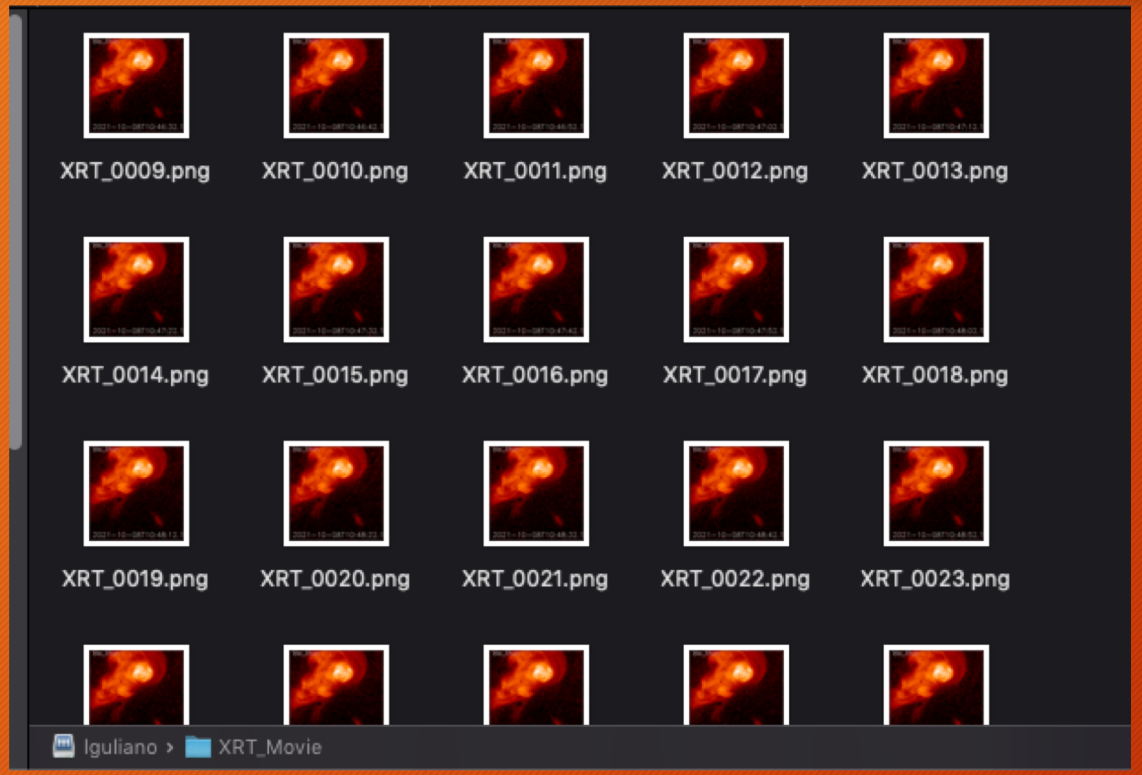

```
for i = 0, numf do begin $
        DEVICE, GET_DECOMPOSED=old_decomposed &$
        DEVICE, DECOMPOSED=0 &$
        LOADCT, 3 &$
        WINDOW, 1, XSIZE=XY[0], YSIZE=XY[1] &$
        stretch, 0, 255, 1.1 &$
        wdef, 0, xy[1] &$
        tvscl,rebin(image_set[*,*,i], xy[0],xy[1]) &$
        xyouts, 0.03, 0.03, index1[i].date_obs, /normal, size=2.0 &$ &$
        if index1[i].EC_FW1_ eq 'Open' then xyouts, 0.03, 0.95, index1[I].EC_FW2_, /normal, size=2.0 &$
        if index1[i].EC_FW2_ eq 'Open' then xyouts, 0.03, 0.95, index1[I].EC_FW1_, /normal, size=2.0 &$
        filename = 'XRT_'+strtrim(string(i,format='(I04)'),2)+'.png' &$
        WRITE_PNG, filename, TVRD(/TRUE)
```

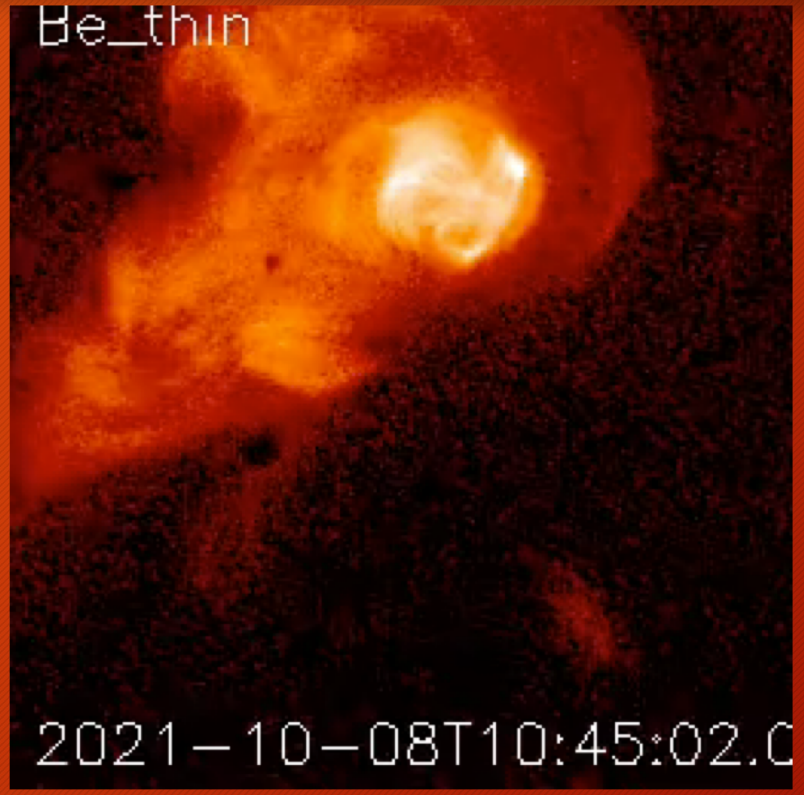
Display each image

Write time and filter info

Save to image format

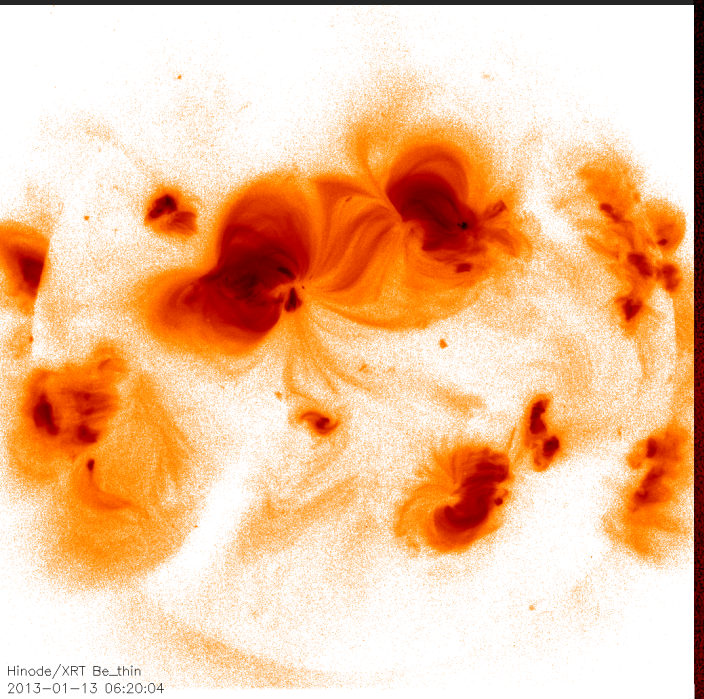
XRT Movie Generation

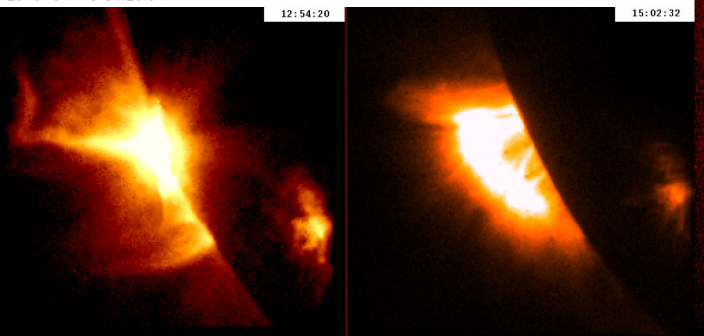


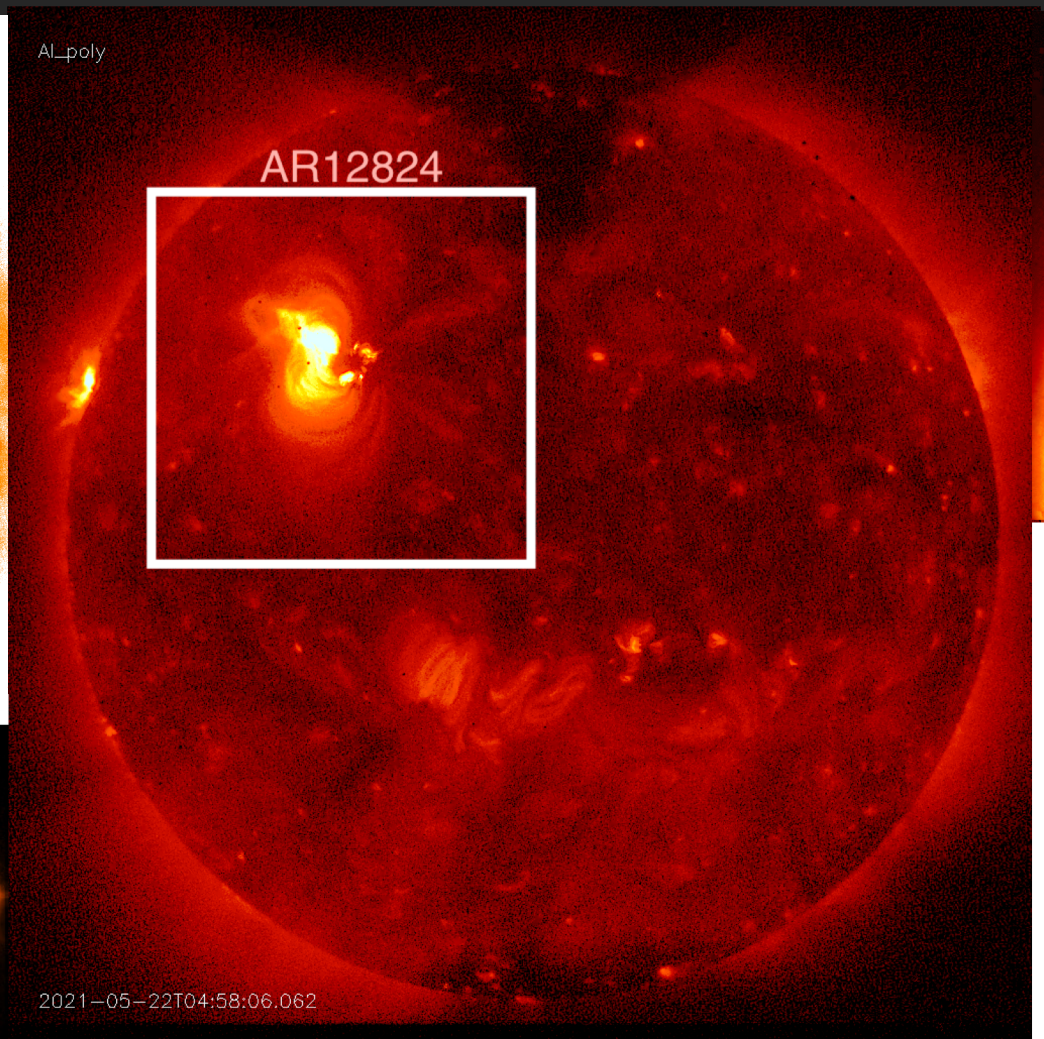


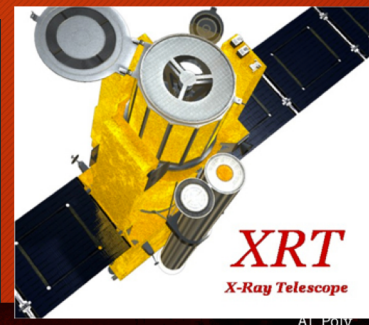

```
ffmpeg -framerate 10 -pattern_type glob -i '*.png' -c:v libx264 -r 30
-pix_fmt yuv420p 20211008_High_Cad.mp4
```

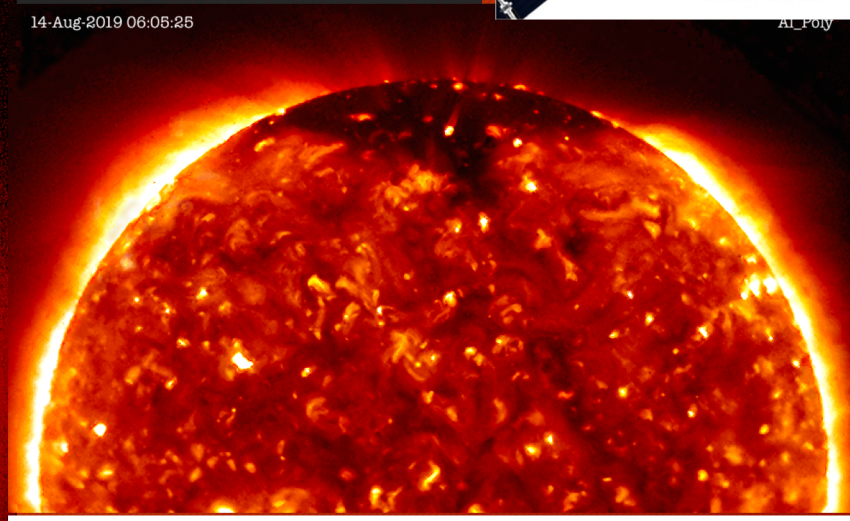
End

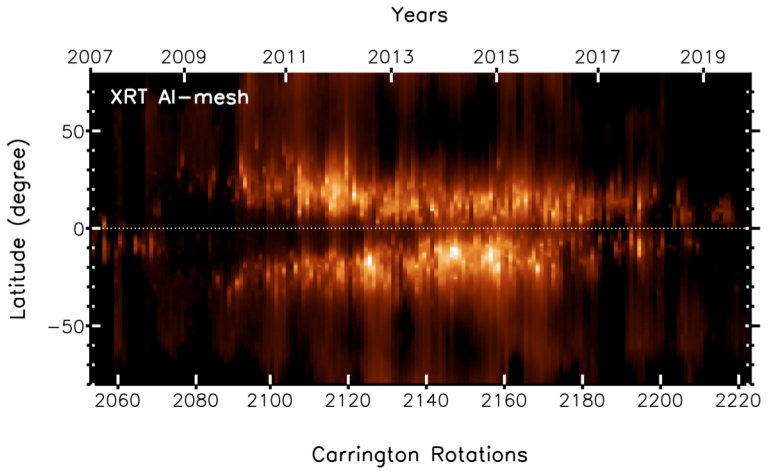

Hinode/XRT Be_thin
2013-01-13 06:20:04


12:54:20
15:02:32


Al_poly
AR12824
2021-05-22T04:58:06.062


XRT
X-Ray Telescope


14-Aug-2019 06:05:25
Al_Poly


Years
2007
2009
2011
2013
2015
2017
2019
XRT Al-mesh
Latitude (degree)
50
0
-50
2060
2080
2100
2120
2140
2160
2180
2200
2220
Carrington Rotations