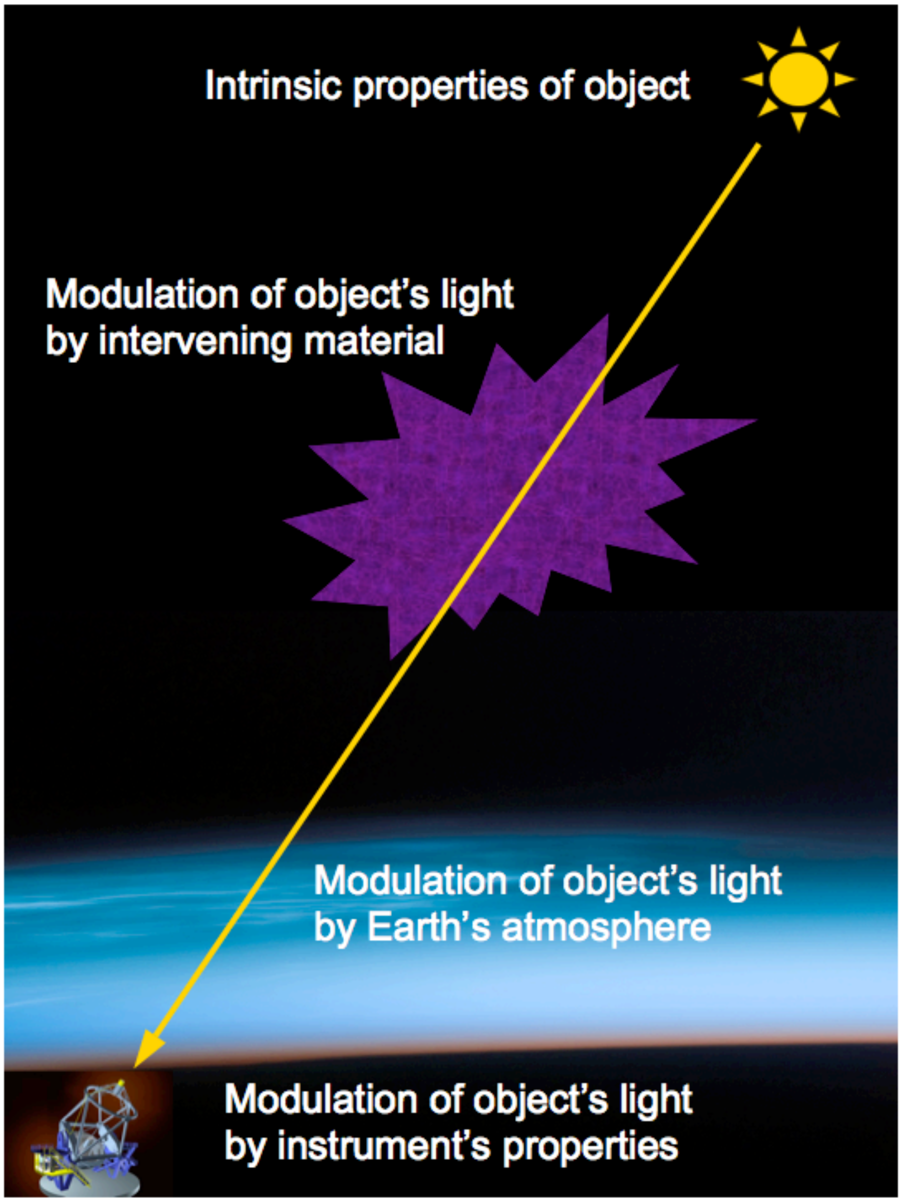
ASTR 288C – Lecture 5

Monday, 5 October 2009

Data and Error Analysis

Introduction

The goal in observational astronomy is to learn about the **intrinsic** properties of objects in our observable universe through observations. However, this is not an easy task as all you have are **observables**, such as an apparent magnitude or brightness, an observed spectrum, an observed light curve, etc.

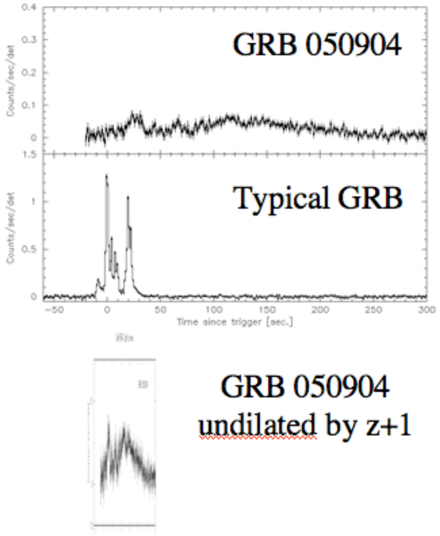


In order to measure *intrinsic* properties of objects in the universe, you have to have some knowledge about how the light traveling to your instrument has been modulated on it’s way through the universe to your detector. These are:

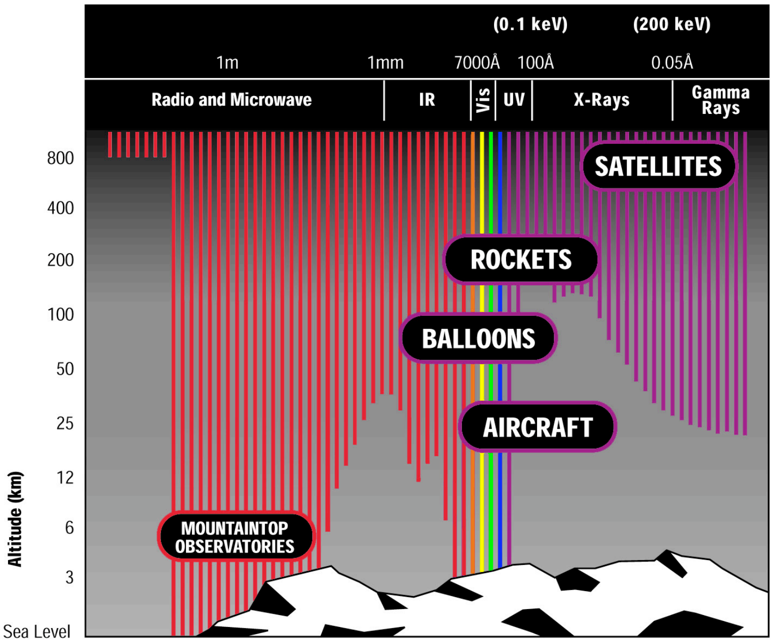
- **Environment of the object**: The immediate environment of the object can modulate the light emitted by the objects. Example: If a star is in a molecular cloud, the emitted light can be absorbed and it’s spectral energy distribution changed.

- **Intervening material along the line of sight**: The light of the object will pass through material along the line of sight. Example: If a supernova is located inside a nearby galaxy, the light might be absorbed by clouds of gas and dust in the host galaxy, intra-galactic material (such as hot gas inside clusters of galaxies), and material in our own galaxy. The Galactic extinction has been mapped in various bands and is available in electronic form (through NED, for example).

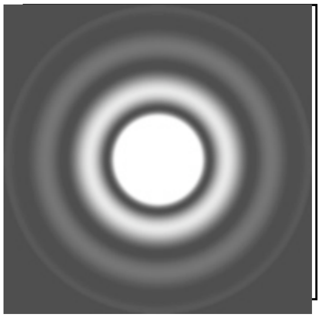
- **Space**: Space itself can change the appearance of light curves and spectra. Example: When you observe a very distant object (such as a Gamma-Ray Burst from the edges of the visible universe), the expansion of the universe while the light was traveling to the detector has to be taken into account. This can lead to a redshift of the spectrum and time dilation of the light curve and temporal behavior of the light (the correction goes as 1+*z* where *z* is the redshift).

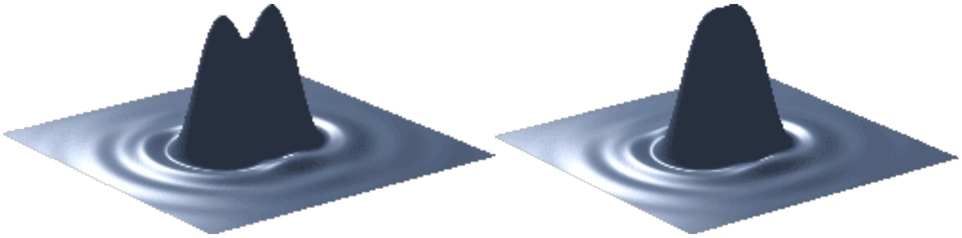


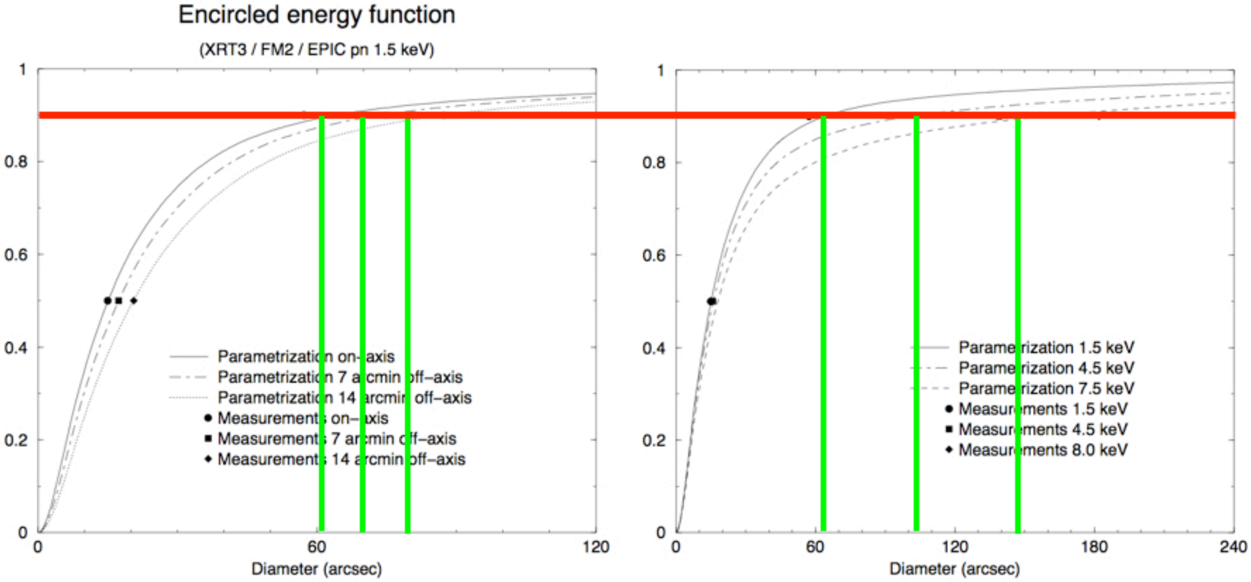
- **Earth’s atmosphere**: The Earth’s atmosphere is not completely transparent for most parts of the electromagnetic spectrum. There are only a few “windows” to the universe where light is not completely blocked (mostly in the optical and radio). At all other wavelengths, light will be obscured. The atmosphere also moves and the air mass might limit the “seeing” in the absence of adaptive optics.



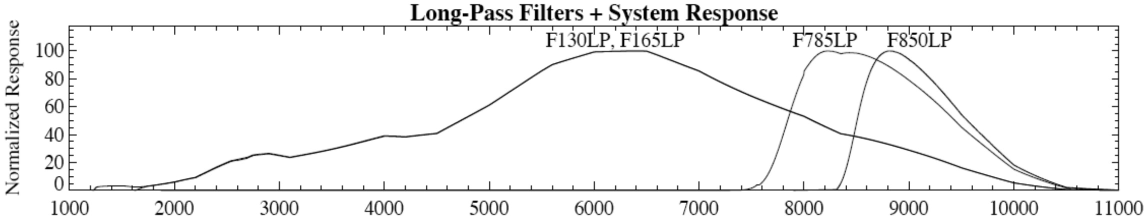
- **Characteristics of your telescope+instrument**: Every telescope and instrument attached to a telescope modulates the incident light. A careful calibration is essential in getting reliable results on the intrinsic properties of an astronomical object. Recorded data is affected, among others, by:
    - **Spatial resolution** of telescope optics (mirrors, masks, etc) and detector (number of pixel). Nearby objects might blend into one object if the spatial resolution is not high enough. Other non-imaging telescope designs use masks to cast a shadow from which the position of an object in the sky can be reconstructed. The spatial resolution is often measured as the “90% encircled energy radius” and is a function position on the detector and energy.



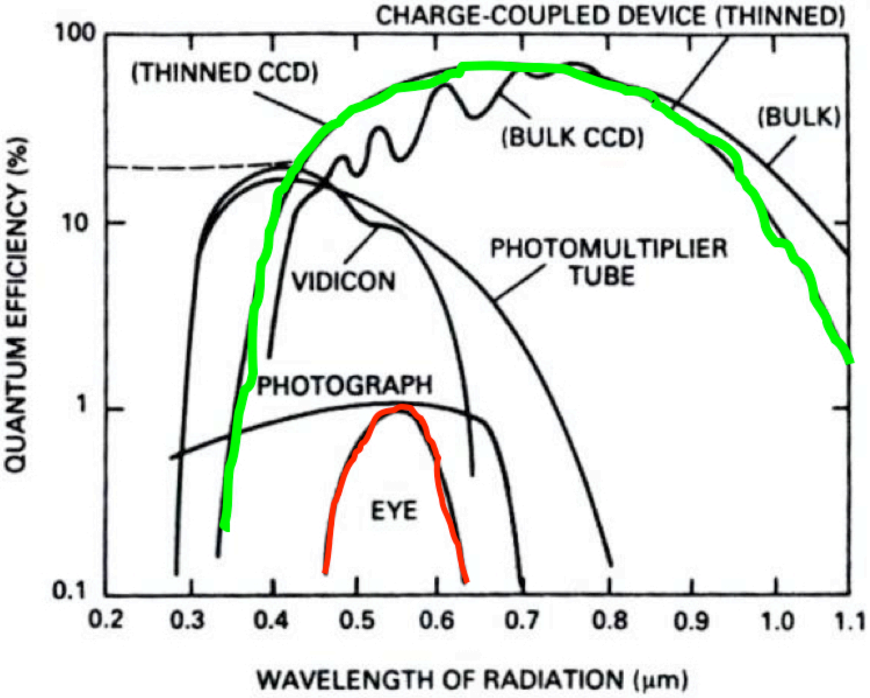




- **Wavelength transmission**: Every instrument has a certain wavelength-dependent throughput. This throughput needs to be well calibrated to allow conversion of apparent magnitudes to absolute magnitudes and fluxes.

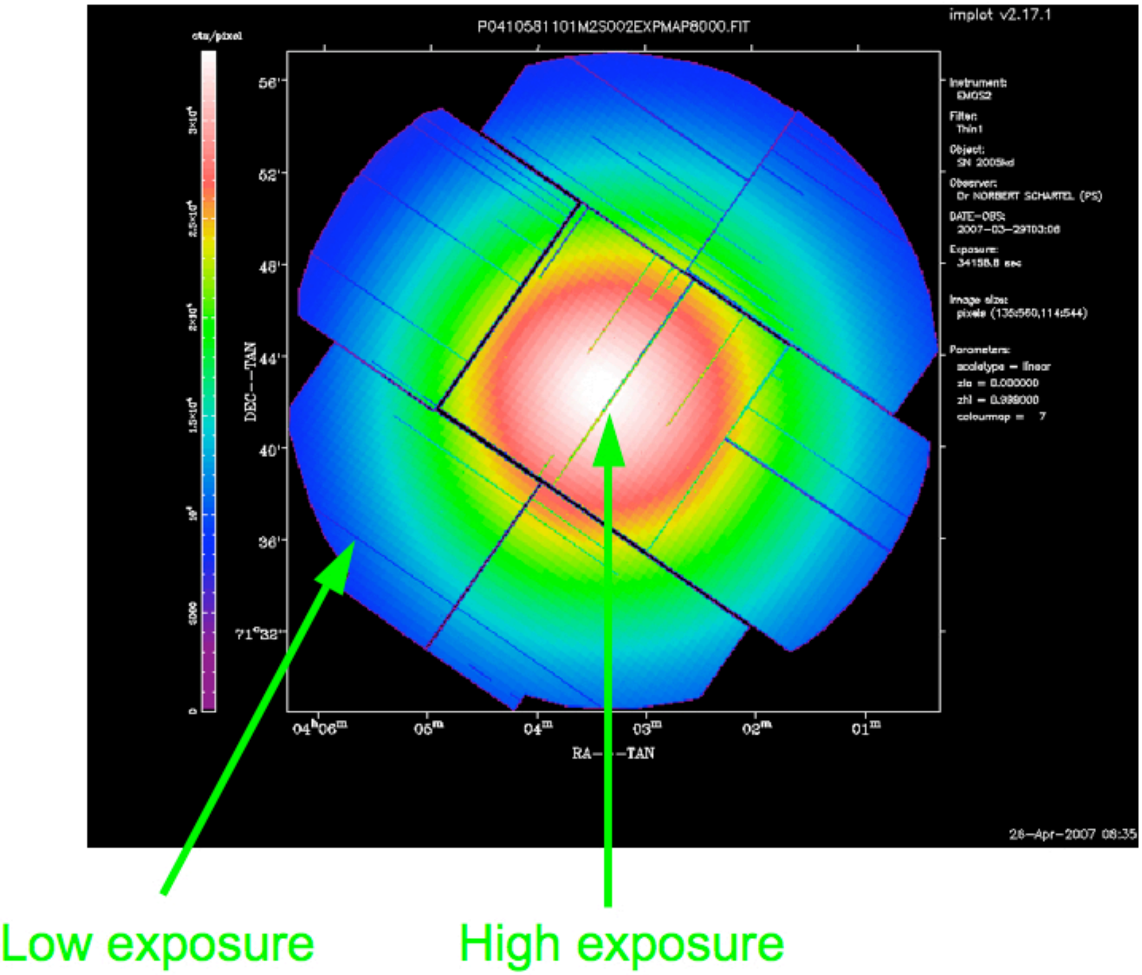


- **Quantum efficiency** of the detector. Each pixel on CCD detectors has a different quantum efficiency for incident radiation at certain wavelengths. The human eye has a quantum efficiency of less than 10% (90% of all incident light does not get detected). Modern CCD detectors have a quantum efficiency of >90%.

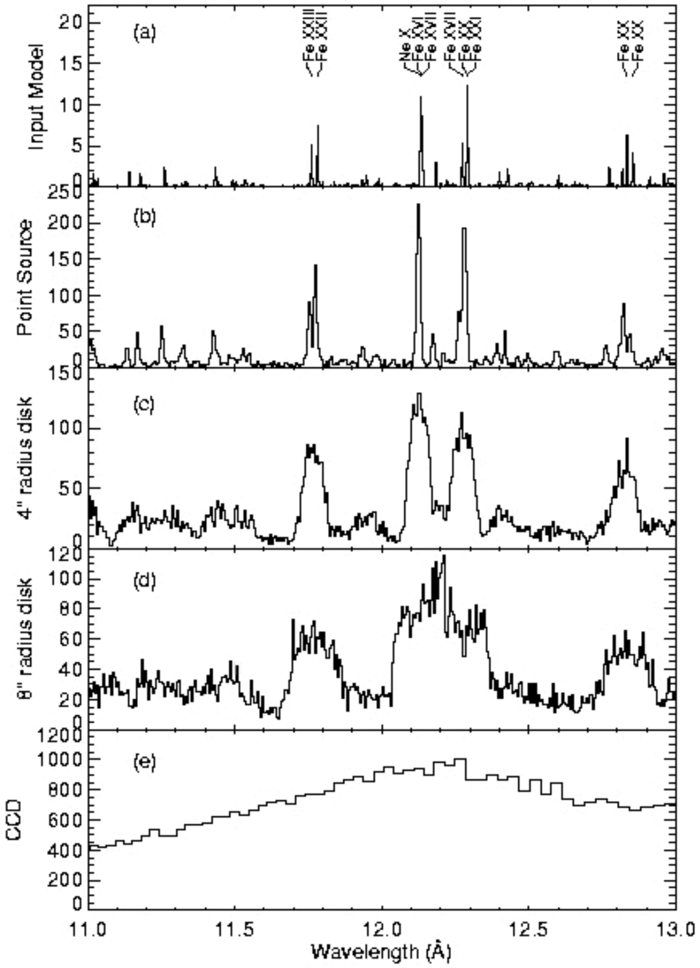


- **Gain Correction:** This correction converts the pulse height of the electronic signal that is read out of the detector into photon energies. The gain correction is a function of the position on the detector. Therefore, a “gain map” needs to be created for each intrument.

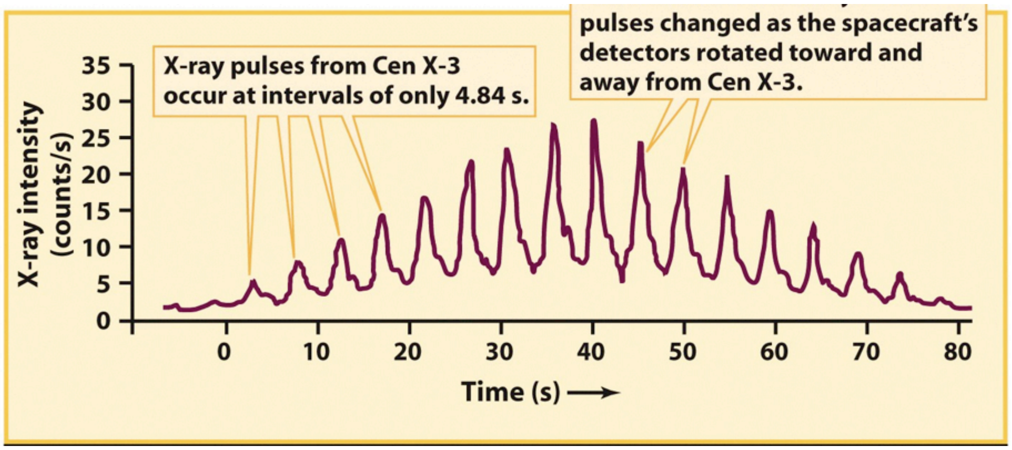
- **Vignetting:** Telescopse are not perfect and have less photon collecting area in the corners (at larger off-axis angles). Unless an instrument has very little vignetting (<10%), an exposure map should be constructed that gives the sensitivity of the instrument (mirror+detector) for each position on the detector in sky coordinates. The unit of an exposure map is “seconds”, which is the effective exposure time at each pixel location.



- **Energy resolution**: Each detector has a different ability to record the energy of incident photons. Also, grating instruments have a higher energy resolution than CCD detectors.



- **Time resolution**: The ability to count photons fast enough might limit the detection of fast-changing states of your objects (e.g., pulses that change their energy output on millisecond scales).



All of the above are a **function of time**. While some changes occur on long-term time scales and can be ignored (e.g., the environment of an object or intervening material along the line of sight), others are subject to intermediate time scales changes (e.g., sensitivity of a detector and its energy resolution can deteriorate over the mission life span of a space-based observatory due to deposits on the surface of detector, or the drift of a spacecraft clock).

During the data **analysis process**, the instrumental properties are corrected for by applying **calibration products** that are part of the data analysis package. These are sometimes called the “CALDB products”. Other corrections are applied during the high-level data analysis (such as correcting the measured flux for Galactic absorption).

Example of a simple Swift X-Ray Telescope data analysis session:

We want to determine the count rate and flux of an X-ray source. Load the image into “ds9” and create two region files, one for the source, and one for the background:

```
> ds9 xrt_image &
```

Next, start the “ximage” software:

```
>  ximage
```

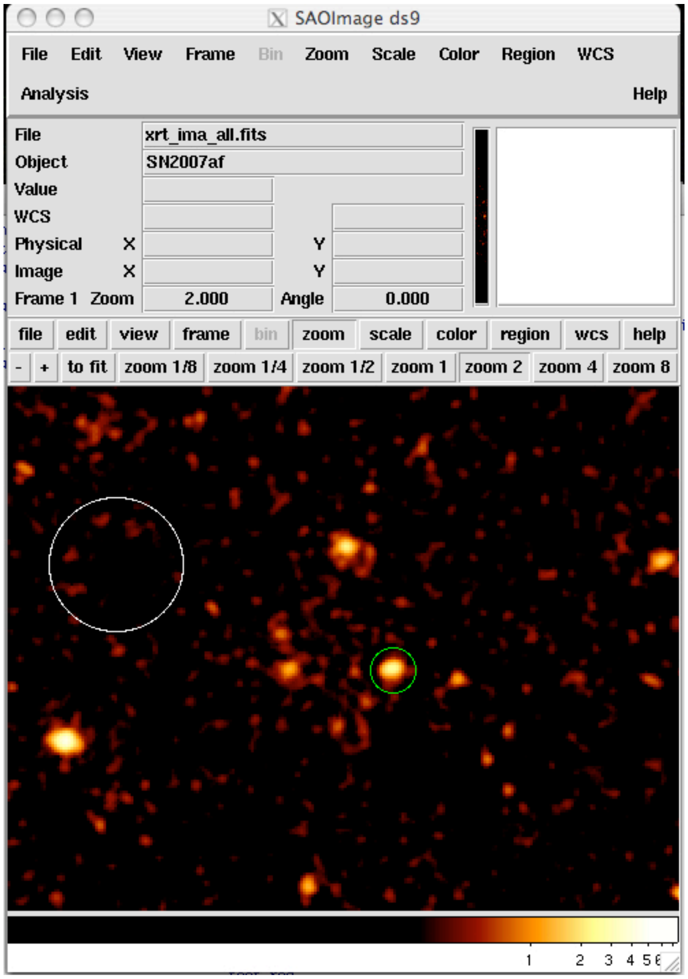
Load the image:

```
XIMAGE> read xrt_image.fits
 Telescope SWIFT XRT
```

The software recognized that this is a Swift satellite X-Ray Telescope data set and loaded the calibration package.

```
XIMAGE> display
```

Show the image on the screen.



File xrt_ima_all.fits
Object SN2007af
Frame 1 Zoom 2.000 Angle 0.000

Next, do a simple “sliding box” source detection:

```
XIMAGE> sosta/srcregion=on.reg/bgregion=off.reg

 Using background defined by region...
 Calculate psf for optimum half-box...
 Using average energy for PSF:  1.
 Total # of counts 128.00000 (in 217 elemental sq pixels)
 Background/elemental sq pixel :          1.246E-01 +/- 9.5E-03 cts
 Background/elemental sq pixel/sec :      1.032E-06 +/- 7.8E-08 cts/s

 Source counts :                          1.010E+02 +/- 1.1E+01 cts
 s.c. corrected for PSF :                 1.306E+02 +/- 1.5E+01 cts
 s.c. corrected for PSF + sampling dead time
                    + vignetting          1.323E+02 +/- 1.5E+01 cts
 Source intensity :                       8.364E-04 +/- 9.5E-05 c/sec
 s.i. corrected for PSF                   1.082E-03 +/- 1.2E-04 c/sec
 s.i. corrected for PSF + sampling dead time
                    + vignetting ->       1.096E-03 +/- 1.2E-04 c/sec <-
 Signal to Noise Ratio          :         8.781E+00


   Exposure time              :           120727.249 s
   Vignetting correction        :         1.013
   Sampling dead time correction :        1.000
   PSF correction             :           1.293
   Optimum half box size is      :        6.5000000 orig pixels

exit
```

The background-corrected net count rate of the source, corrected for the point-spread-function (PSF), telescope vignetting, and deadtime correction, is 1.1±0.1 x 10^{-3} cts/s, and the source was detected at a signal-to-noise ration of S/N = 8.8 sigma. This is a solid detection because it is higher than 3-sigma which is usually used as a detection threshold.

The above instrument is a “**photon-counting**” instrument that has the ability to detect single photons. These photons hit a CCD detector and the energy of each photon is converted into a charge that can be read out by the electronics of the detector. Each photon is counted individually. We therefore call them “**counts**”.

The above simple analysis converted the observed counts, $C_{\mathrm{obs}}(I)$ into the intrumental counts, $C_{\mathrm{inst}}(I)$ for the sum of all enery channels, I.

We can now use the **Counting Relation** to convert the instrumental counts $C_{\mathrm{inst}}(I)$ for into a more physical unit, the flux $f(E)$ over a certain energy range

$$C_{\mathrm{instr}}(I) = \int_{t_1}^{t_2} \int_{E_1}^{E_2} f(E) dt R(I,E) dE + B(I)$$

where

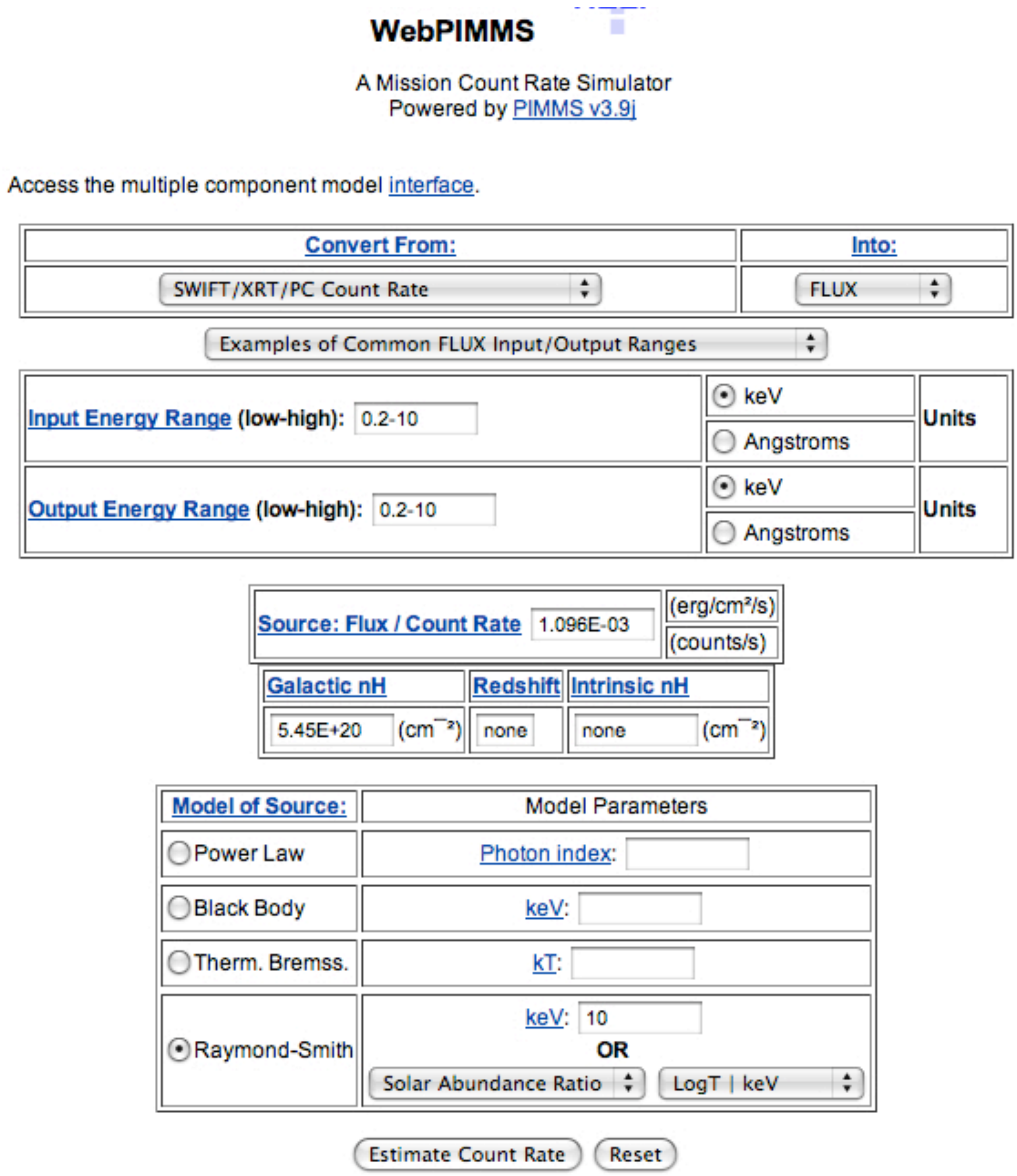
$C_{\mathrm{inst}}(I)$ is the instrumental count in the energy channels I,
$f(E)$ is the flux of the source over the energy range E_1 to E_2,
$R(I,E)$ is the response of the instrument, and
$B(I)$ is the detected number of background counts.

Note that all the **source physics** (the only thing we are really interested in), is in the ***f*(*E*)** term. All other terms only depend on our “experiment” and the details of the observations and the instrument used.

$B(I)$ are the background counts, normalized to the same radius that we used to extract the source counts. We already know the background counts from running Ximage. Therefore, everything in the equation above is known except the source flux.

Solving this equation for $f(E)$ gives the flux of the source over the energy range E_1-E_2 and over the time period (= duration of the observation) t_1-t_2.

Even easier than solving the above equation is to use the PIMMS tool that is available online at http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html. This is the web version of the “portable multi-mission Count Rate Simulator” which is also available as a command-line version.



WebPIMMS

A Mission Count Rate Simulator
Powered by PIMMS v3.9j

Access the multiple component model interface.

Convert From: SWIFT/XRT/PC Count Rate

Into: FLUX

Input Energy Range (low-high): 0.2-10 ● keV ○ Angstroms

Output Energy Range (low-high): 0.2-10 ● keV ○ Angstroms

Source: Flux / Count Rate: 1.096E-03 (erg/cm²/s) (counts/s)

Galactic nH: 5.45E+20 (cm⁻²)

Redshift: none

Intrinsic nH: none (cm⁻²)

Model of Source: ● Raymond-Smith

keV: 10

If you click on “Estimate Count Rate”, you get a “Flux” ($f_{0.2\text{-}10\ \mathrm{keV}} = 5.13 \times 10^{-14}$ erg/cm/cm/s) and an “Unabsorbed Flux” ($f_{0.2\text{-}10\ \mathrm{keV}} = 5.65 \times 10^{-14}$ erg/cm/cm/s). The “Flux” is the measured source flux, the “unabsorbed flux” is the flux before part of it was absorbed by the Galactic foreground column density of 5.45E20 cm^{-2}. This Galactic foreground column density is the number of absorbing neutral hydrogen atoms in our Galaxy along the line of sight. It can be looked up by using the "N_H calculator" http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl and either typing in as input the coordinates of the source or the name of the object.

The unabsorbed source flux can be converted into a luminosity if the distance *d* of the source is know by using the relationship:

$$L_{0.2\text{-}10\ \mathrm{keV}} = 4\pi\, d^2 f$$

Solving for *f* and using a distance of *d* = 21 Mpc (1 Mpc = 3.08×10^{18} cm) gives:

$$L_{0.2\text{-}10\ \mathrm{keV}} = 4\pi\, (21 \times 10^6 \times 3.08 \times 10^{18}\ \mathrm{cm})^2 \ \times\ 5.65 \times 10^{-14}\ \mathrm{erg/cm/cm/s}$$
$$L_{0.2\text{-}10\ \mathrm{keV}} = 3.0 \times 10^{39}\ \mathrm{erg/s}$$

This is the unabsorbed luminosity of the source in the 0.2-10 keV energy band and is an intrinsic source propert. We have no converted an observable (counts) into a physical property of the source.

Background and Errors

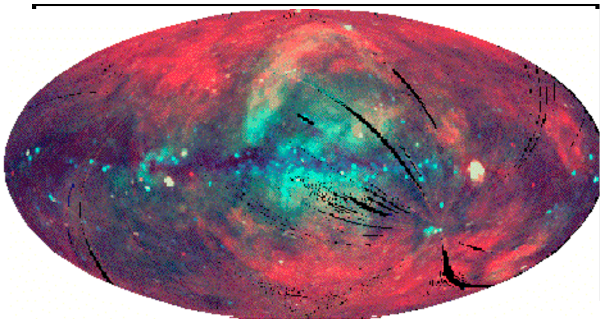
The counting relation includes a background term, *B*(*I*), that is a function of the energy channels of the instrument (*I*):

$$C_{\mathrm{instr}}(I) = \int_{t_1}^{t_2} \int_{E_1}^{E_2} f(E) dt R(I, E) dE + B(I)$$

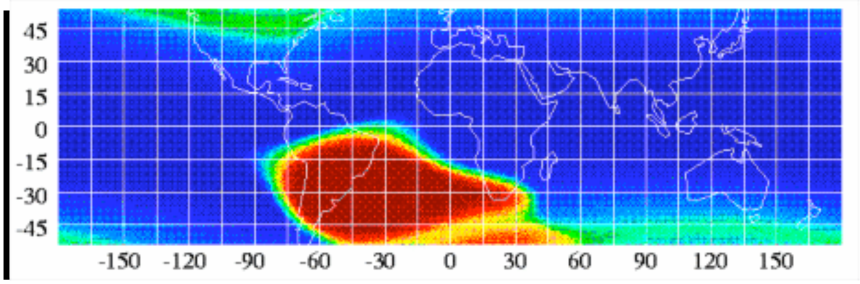
There are two two types of background radiation, **instrumental and sky background**.

The **instrumental background** is detector noise cause by the electronics of the detector and not due to any astronomical sources. For some detectors, this instrumental background can be servere. It is usually corrected for by the data analysis software based on observations where the telescope door was closed.

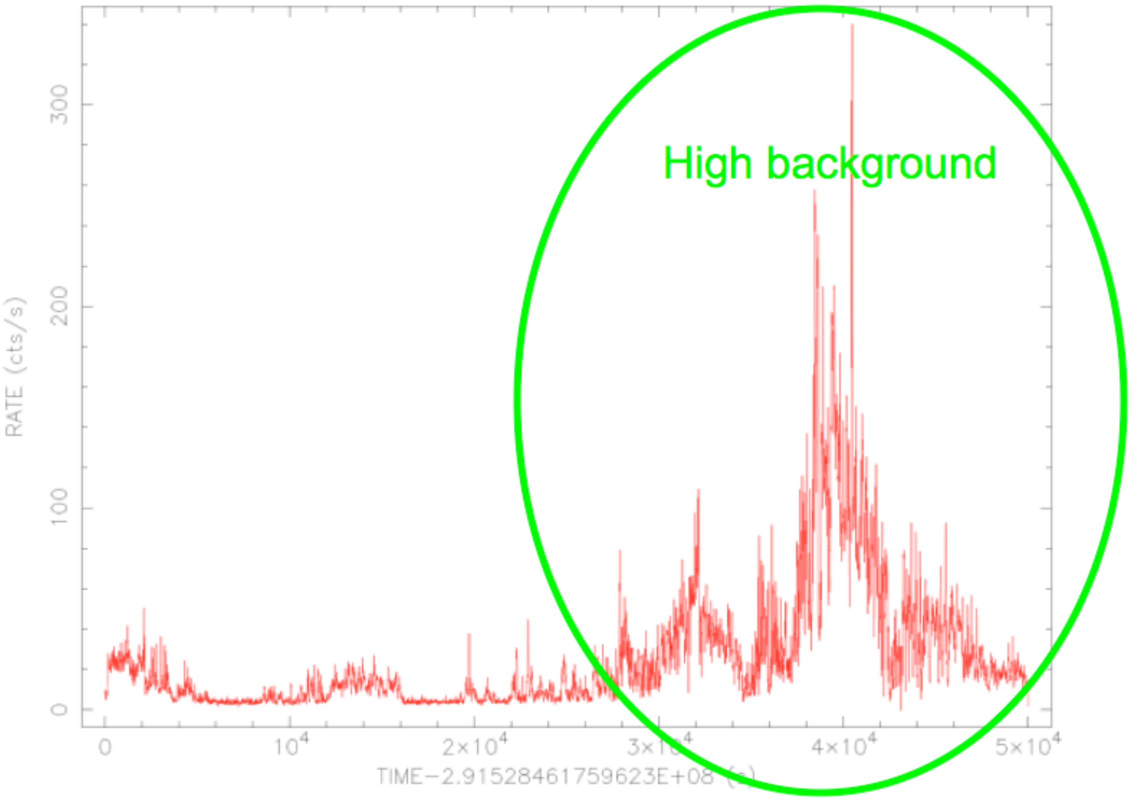
The **sky background** is the combination of spatially unresolved sources that emit a level of light that will contribute to a high background in an image. The image below shows a soft-band X-ray image of the entire sky, obtained by ROSAT, which shows the overall high level of X-radiation in the local universe. The sky background levels is non-uniform and varies across the sky.



Sky background can also arise from energetic particles (such as protons and electrons) that are hitting the instrument. Space-based telescopes are subject to energetic particles in low-earth orbit when flying through the South Atlantic Anomaly, which is a location in the Southern Atlantic where the Earth has a very high magnetic field strength (off the coast of Brazil and Uruguay).



Other sources of sky background are solar flares that can emit large amounts of energetic radiation. The plot below shows the total count rate of an X-ray detector shortly before and during such a solar flare. These times of high background need to be screened out by the analysis software.



In our previous example (Ximage session) we have ignore such flaring period of high particle background. However, by using a large source-free region offset from the source but within the detector borders, we have extracted the sum of instrumental+sky background. The source detection command “sosta” (“source statistics”) has calculated the count rate of the background and has normalized it to the area that was used for the extraction of the source counts, and has subtracted the background from the total counts (source+background), giving us the net source counts.

Lab Work

Today's exercise is to measure the flux from an *X*-ray source. The source is the first observation of the *X*-ray afterglow of the gamma-ray burst GRB 090929B. This burst was discovered by *Swift* on 29 Sep 2009, and has been followed-up over the past week. To analyse this data we will use the HEASOFT tool XImage.

Procedure

- Download the file sw00371050000xpcw3po_cl.evt.gz from <>.
- Move this file to your working directory.
- Uncompress this file using
  - `gunzip -v sw00371050000xpcw3po_cl.evt.gz`

- Load the HEASOFT package
  - `astroload heasoft`
- Start ximage
  - `ximage`

- You should now be running XImage and seeing a prompt that looks like this.

  [XIMAGE>

  You will type all of your XImage commands at this prompt
- Load and display the *X*-ray image.
  - `read sw00371050000xpcw3po_cl.evt`
  - `display`
- Run source detection
  - `detect`
  - This will return all of the detected sources in the image. Identify the *X*-ray afterglow and record the pixel and sky coordinates.
  - Use the cursor to see if these coordinates are reasonable. Pick the best set of coordinates from either the detect command or your examination of the image.
  - *Save these values for your homework.*
- Measure the counts in the source
  - `sosta/xpix=???/ypix=???/optimize`
  - Replace the ???s with your best pixel coordinates.
  - *Save these values for your homework.*
  - The optimize option tells sosta to find the background in a way that optimizes the signal-to-noise ratio when estimating the background.
  - Record
    - the fully-corrected source intensity (in counts per second)
    - the signal-to-noise ratio of the source
    - the background count rate (in counts per sq. pixel per second)
    - *Save these values for your homework.*
- Exit XImage.

  - exit

- Convert the count rate to physical units using WebPIMMS at http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html.
  - Convert from Swift/XRT/PC Count Rate to FLUX.
  - The energy range is 0.2–10 kev for input and output.
  - Enter your source count rate.
  - The Galactic neutral hydrogen column density (nH) is 5.45E+20 cm^{-2}.
  - Gamma-ray burst afterglows have synchrotron spectra, which are power laws. The typical power-law photon index for the *X*-ray afterglow of a gamma-ray burst is 2.
  - Determine the flux from the source.
  - *Save this number for your homework.*
  - Use the uncertainty in the count rate to estimate the uncertainty in the flux.
  - *Save this uncertainty for your homework.*
  - A detailed analysis of this data shows that the photon index is 2.1 ± 0.1, so our estimated value of 2 is reasonable. Compute the flux with a photon index of 2.1.
  - *Save this number for your homework.*
  - Compare the difference in the flux due to the change in the photon index with the uncertainty in the flux assuming a photon index of 2. Is the assumption that the photon index is 2 reasonable? Explain.
  - *Save your answer for the homework.*