



ASTROCHALLENGE 2023 SENIOR DATA ANALYSIS ROUND

Monday 13th March 2023

PLEASE READ THESE INSTRUCTIONS CAREFULLY.

In this part of **ASTROCHALLENGE 2023**, you will be given a dataset to analyse, observe trends, and draw conclusions from. You will be marked mainly on the methods of your analysis and reasoning rather than the accuracy of your answers.

We **strongly** recommend you use industry-standard tools like Microsoft Excel™, RStudio or various Python libraries to process the data, where applicable.

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1 An Introduction to Data Analysis

Astronomy and Data

Astronomy has always been a data-driven discipline. From the earliest civilisations to the very bleeding edge of 21st-century humanity, data has been the core of the matter. Humans have **obtained** and **processed** data; we have **analysed** and **made conclusions** from said data to learn more about the world and the universe we live in.

In the modern era of data-driven astronomy, no observation method has transformed the field as much as **imaging**. Needless to say, our astronomy knowledge is highly dependent on the **availability and quality** of data we can gather about the night sky; breakthroughs in modern astronomy often follow novel, eye-opening data. Imaging is at the core of data collection in astronomy, so much of the information we can gather about our universe comes in the form of **electromagnetic radiation and photons**.

But why limit us to what we can **see**? With different filters and imaging devices, we can look at the universe through a totally different set of eyes. **False Colour** images of objects representing wavelengths **outside the visible spectrum** allow us to see what we cannot see.

To help us explore the various images taken by various telescopes and sky surveys, we will be using a tool called **SAOImageDS9**, download the software [here](#).

You are highly encouraged to learn more about controls in **SAOImageDS9** in the **Appendix** before you proceed with the question.

About the Data Analysis Question

A question completely dedicated to data analysis in this form was introduced since **ASTROCHALLENGE 2020**. In the continued spirit of learning, you might find some parts to be rather guided—this is intentional. However, others will require you to think out of the box, and be resourceful with the data source.

This question is meant to replace one of the five questions in the Team Round, so the maximum number of marks in this entire round will be **20**. Exact mark allocations will be given within the right margin next to each part or sub-part, in boldface and in square brackets, like such: **[2]**.

You are allowed to reference external sources to help you in answering the questions. However, note that copying from sources without apparent synthesis or evaluation will be penalised. Every item that you submit must be of your own work; cite any external references as needed. **Failure to do so will be penalised.**

Deliverables

This section outlines the deliverables to be submitted for the data analysis question. **Everything** in the following list is to be submitted—any omissions will lead to your team losing marks.

- A `.fits` file containing your response to Question 1.d) `<Your school abbreviation>_T<your team number>_1d.fits` (In other words, if you are in Team 1 from Astro Challenge Secondary School, please label your response as `ACSS_T1_1d.fits`);
- A *type-written* report in `.pdf` format named `<Your school abbreviation>_T<your team number>_Report.pdf`, which should include:
 - Your team’s attempts for all questions;
 - A bibliography, if any external sources were used and cited;
 - An appendix, with all your graphs and images

2 X

1. Open up SAOImageDS9. Under Analysis in the menu bar, select Virtual Observatory. Check Rutgers X-ray Analysis Server #2, as shown in Fig. 1.

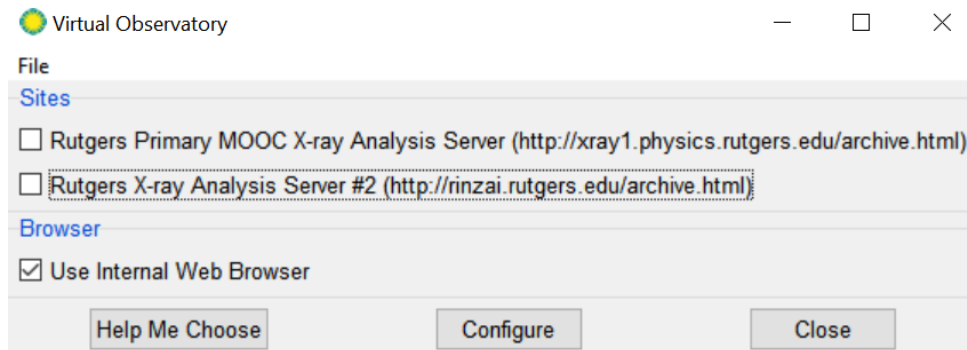


Figure 1: Virtual Observatory pop-up window

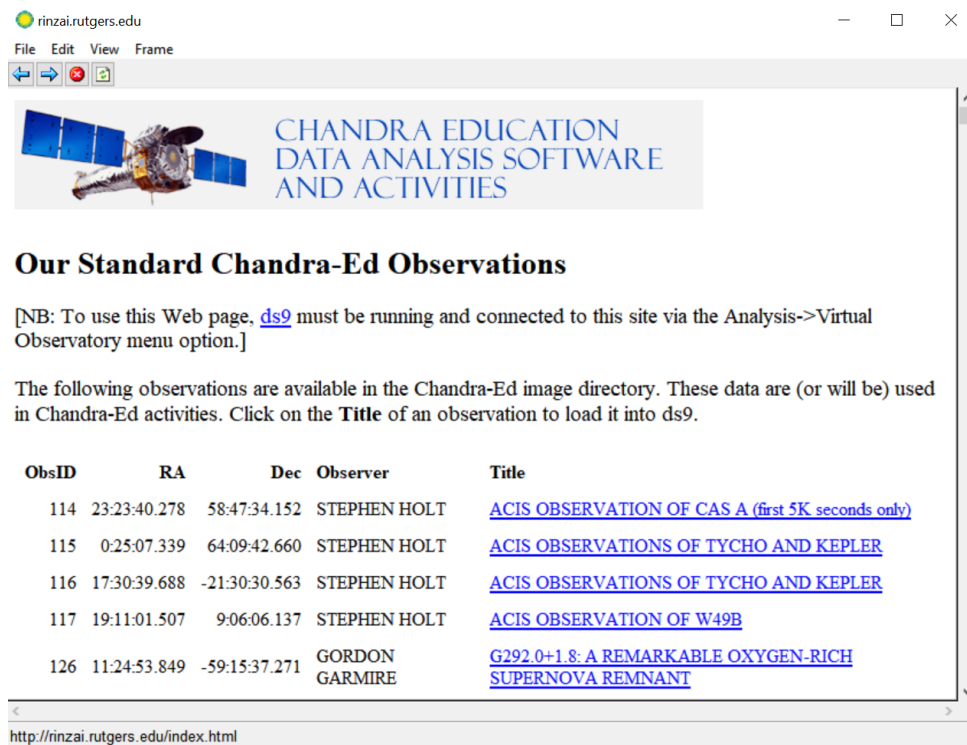


Figure 2: Rutgers X-ray Analysis Server #2 page

Once the page loads (Fig. 2), click on the first link **ACIS OBSERVATION OF CAS A (first 5K seconds only)**. This will load the image from the observation into your main window in DS9. Once we have the image, we can also change its colour. Let's increase the contrast by changing the colour from grey to bb under Color in the buttons bar. You should see something like this (Fig. 3).

Change the scale by going to the Scale menu or scale button and select sqrt (square root).

- (a) **What do you observe about the image? Explain how the change in scale caused this change.** [2]

Actually, the image you see does not do the data justice. This detector on the Chandra Telescope (ACIS) is capable of identifying the energy level of the X-ray photons it collects. To see the spectrum of energy levels of X-ray photons from Cassiopeia A, select edit → region in the buttons bar and create a circular region that encompasses Cassiopeia A¹. Next go to Analysis in the menu bar, select Chandra-Ed Analysis Tools in the

¹Ensure that the shape is Circle under Region in the menu bar, the region button under edit will draw any shape set in the menu.

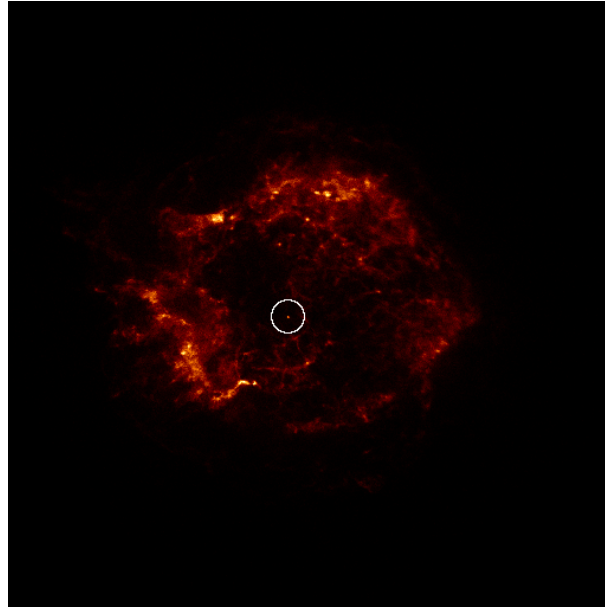


Figure 3: X-ray image of the Cassiopeia A (central Neutron Star circled)

dropdown menu and then Quick Energy Spectrum Plot] in the submenu (Fig. 9).

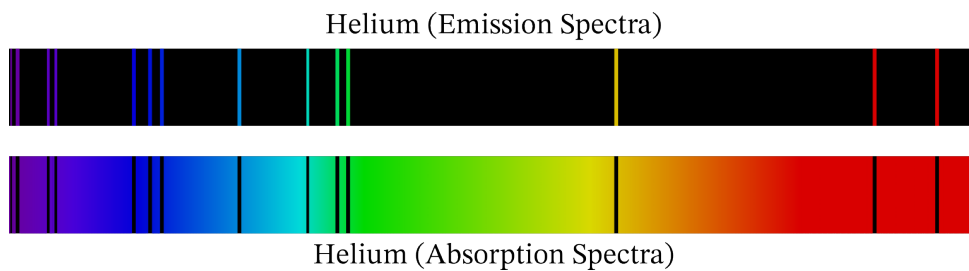


Figure 4: Emission and Absorption Spectra of Helium atoms. Credit: Nagwa, 2023

You may be aware that atoms of an element absorb and emit light characteristic to the element itself. Emission lines are associated with the specific wavelengths of light emitted by the transitions of excited electrons from higher to lower energy states in the atoms while absorption lines are the specific wavelengths of light absorbed by the transitions of electrons being excited from lower to higher energy states in the atoms of an element. The emission lines of an element's atoms can be identified by providing a source of energy to excite electrons in the atoms to higher energy states and recording the light emitted when these unstable electrons trickle back down to their stable energy states; on the other hand, absorption lines are identified by providing a background source of light in a range of continuous wavelengths and recording the light that pass through the unexcited atoms of the element, resulting in certain wavelengths appearing dark in the spectrum as they are absorbed to excite electrons in the atom to higher energy states (Fig. 4).

- (b) **The Quick Energy Spectrum Plot plots the number of photons detected within regular intervals of energies over the entire range of energies of the photons collected (i.e., a histogram of photon energies). How does this allow us to capture the emission and absorption lines of elements from Cassiopeia A?** [1]
- (c) **Based on your answer in part b, identify two emission lines and their energies in the Quick Energy Spectrum Plot. Show your working clearly.** [1]

After you have analysed your energy spectrum plot and without removing the circular region, choose Energy Filter from the same submenu under Chandra-Ed Analysis Tools. This tool allows you to only show detected photons whose energies fall in the chosen range (Fig 5). Note that the energy values are in keV and the lowest reasonable value is 0.1 since that marks the start of the spectrum for X-rays). You may choose an arbitrary energy range at this point².

²Note that you should choose an energy range which has a significant photon count according to your energy spectrum plot.

Upon choosing an energy range, the program will generate a new frame for your image, showing the photons detected in the energy range. Select this new frame and select `frame → single` in the buttons bar, you can now save this image as a FITS file under `File → Save` in the menu bar. After saving, you can delete this frame (`frame → delete` in the buttons bar) to avoid confusing yourself. You may repeat the process of generating for two more frames with different energy filter ranges. The goal here is to create three frames of three distinctive energy ranges to represent the three different colours in an RGB Image.

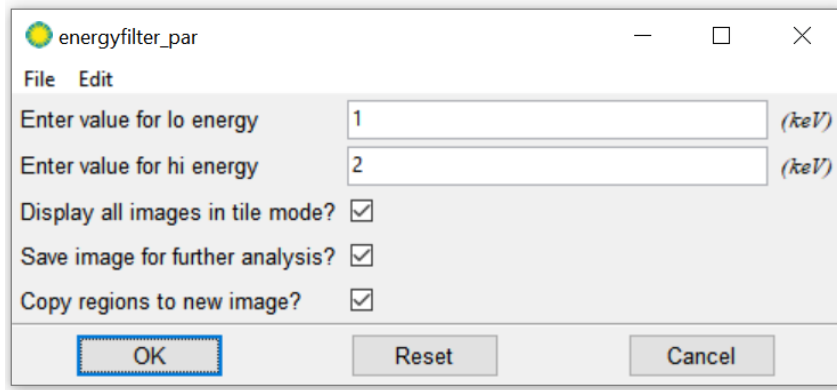


Figure 5: The Energy Filter tool window

Next, we will create a composite image from the three frames that we have created. Go to `Frame` in the menu bar and select `New Frame RGB`. A pop-up window will open, as shown in Fig. 6. The radio buttons under `Current` represents the frame that is active. Choose `Red` and open an image frame you saved (`File → Open` in the menu or buttons bar). You will see that the image that shows up is coloured red. You can adjust the bias and contrast before moving on to highlight the features of the image. Next, select `Green` under `Current` and repeat the process for the next image. Finally, do the same for `Blue`. If you would like to synchronise the changes to the bias and contrast of all three images, go to the `Lock` dropdown menu and lock `Colorbar`, you can also lock other aspects like `Scale`. If you would like to modify your image after you have closed the window, you can find it under `Frame → RGB...` in the menu bar.

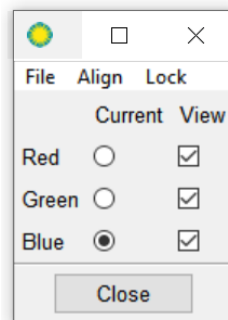


Figure 6: RGB Frame pop-up window

- (d) Identify three elements from the Quick Energy Spectrum Plot of Cassiopeia A and create an RGB composite image of Cassiopeia A with each colour representing an element you have chosen. Mark out the elements you have identified on the energy spectrum plot and present it as working to this part of the question. Save your created image in SAO as an RGB Image (.fits) under `File → Save As` in the menu bar. Also, save the colour image as PNG and attach it to your report (`File → Save Image → PNG...`). [2]

The observation of Cassiopeia A that we have just explored was made in 2000. It has been a long time and we have newer observational data now. Let's see if we can notice some changes about Cassiopeia A with time. Search for and download observation ID 19606 from Chandra X-ray Center [here](#). Follow the steps in the Appendix B to download the data.

Extract the folder within the .tar package file using any archive manager (like WinRAR).

Delete all but the original bb color frame of Cassiopeia A in SAOImage9, now create a new frame and open the `acisf19606N002_evt2.fits.gz` file in the extracted folder `19606/primary`. Set `color` to `bb` and apply the appropriate scaling to make the two images look as close as possible. Set your frame to `tile` mode in your buttons bar so you can look at both images simultaneously. Find a significant feature in both images that bear resemblance. You can use the `edit` → `cross` (crosshair) in the buttons bar to help you determine the proximity of features.

- (e) **Take a screenshot of the feature you have identified in each image, label them, and include your screenshots in the report. Take the angular distance of these features from the centre star of the Cassiopeia A (circled in Fig. 3) by drawing a Ruler region³ (take screenshots of your working). What is the difference in angular distance from the neutron star to the feature in each image? What does this tell you about Cassiopeia A?** [2]
- (f) **Given that the shell of Cassiopeia A is expanding at around 5000km s^{-1} . Approximate the size of Cassiopeia A in terms of light years across.** [2]

³Change the shape of the region to `Ruler` in the menu bar and user a region tool under `edit` in the buttons bar.

3 Cosmic Rolex

2. Pulsars are rapidly rotating neutron stars that have a strong magnetic field misaligned with their axes of rotation. The rotating magnetic fields can generate beams of electromagnetic radiation pointing in the directions of the magnetic poles of the neutron star. If these beams of radiations point towards Earth as the neutron stars rotate, we can detect it as a pseudo-star, but with a regular period of brightness variation. These periods are often very accurate, making the pulsars seem like cosmic clocks that can tell time. X-ray pulsars are similar but emit most of its radiation in X-rays. X-ray pulsars are usually in binary systems with a star, siphoning material from their companion into an accretion disk around themselves. When these stellar materials get funnelled into the magnetic poles of the X-ray pulsar, they heat up immensely and release radiation in the X-ray spectrum. Cen X-3 is an X-ray pulsar in Centaurus and our next object of interest.

You can save your file from the previous section as a FITS file, close your DS9, and reopen it. From the Virtual Observatory database which we accessed previously, find and open **Obs Id 1943**⁴.

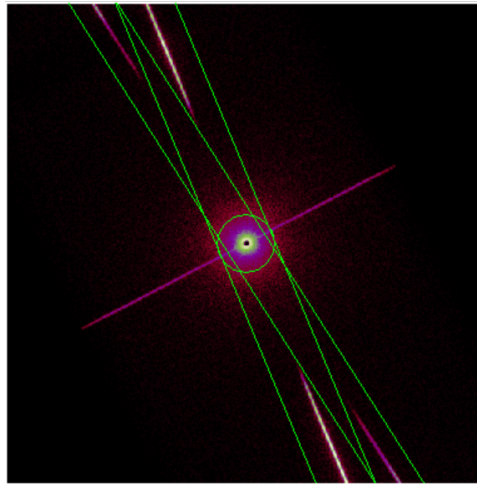


Figure 7: Image of Cen-X3

Change the color to He and the scale to min max and linear. You should get something like what is shown in Fig. 8. Do not delete any regions in the image. If you do, reload the data from the Virtual Observatory. These streaks are not features of the object itself but diffraction spikes due to the gratings used to analyse the spectroscopic frequencies of the target object in the Chandra Telescope. Hence, we need to include these streaks as regions in our analysis.

Without adding or deleting any regions, conduct a Quick Energy Spectrum Analysis under Chandra-Ed Analysis Tools in the Analysis menu. In the pop-up graph plot, save the plot data under File → List Data and save as .txt format (Make sure to save it as a “filename.txt”, and not just “filename”).

In your listed data, you will see three columns. The first is the energy of the photon received, the second is the number of photons received, and the third is the uncertainty of the measurement.

Import the data into Excel, sum up the total energy from X-ray photons received by the telescope in this exposure and the total number of photons received. Refer to Appendix C if you need help with import .txt data into Excel.

- (a) Calculate the average energy of a photon that the detector received. [0.5]
- (b) Given that the average photon count when the X-ray beam from Cen X-3 is facing us is 78.8596 per second and the effective aperture of the Chandra X-ray Observatory has an area of 353 cm^2 , calculate the apparent bolometric magnitude of Cen X-3 when it is the brightest, assuming Cen X-3 emits most of its energy in X-ray. You may reference the intensity of radiation from a celestial source with a known apparent magnitude. [1.5]

⁴Please make sure that after clicking on the link to download the data, you can see all the printouts in Fig. 10. and that the file you have downloaded is cenx3.fits and not 1943.fits. You can search for “1943” using CTRL-F (make sure you have clicked on the internal browser page so that the page is recording your inputs) and CTRL-G after the text is highlighted to cycle to the first search result at the top of the page.

Without adding or deleting any regions, create a light curve with FTTOOLS/Light Curve under Chandra-Ed Analysis Tools (Analysis menu bar, Fig. 9). Zoom in on the plot generated by drawing a rectangle with your mouse around the area to zoom in to. Do so until you can see the clear periodic variations in the X-ray brightness of the object.

- (c) **Take a screenshot of your plot and measure the period of brightness oscillation. Show your working on your screenshot.** [1]
- (d) **Based on information from the light curve only, do you expect the radiation received to be from a small, concentrated source (e.g., a small star), or a large extended one (e.g., a nebula/gas cloud)? Explain.** [1]

Now open another tool: FTTOOLS/Power Spectrum under Chandra-Ed Analysis Tools. The peaks in this plot show the frequencies that best fit the time variations in the data. Zoom in on the peak, what do you notice, does the frequency correspond to the period you have calculated in part c)?

You may have noticed that there is not just a singular dominant frequency, but several, and the peak tapers off on both sides. This is due to the orbital motion of Cen-X3 around its companion, which results in doppler shift of the X-ray pulses we receive from the pulsar.

- (e) **Explain how doppler shift results in this distribution of the observed frequencies of the pulsar's rotation.** [1]
- (f) **With information from the power spectrum plot, find the maximum and minimum doppler-shifted frequency of the rotation of the Cen-X3. Hence, find the maximum radial velocity of Cen-X3. Include your working on a screenshot of the power spectrum plot.** [2]

By observing the change in the doppler-shifted rotational period of Cen-X3 and the periodic dimming of the pulsar when it is eclipsed by its companion star, we can determine the orbital period of Cen X-3 to be 2.1 days. Since Cen-X3's companion is an optical supergiant star, we can measure its radial velocity through spectroscopy and find its maximum radial velocity to be 26 kms^{-1} . Furthermore, by observing the eclipse of Cen-X3 by its supergiant companion, we have obtained the orbital inclination of the binary pair to be 70 degrees⁵.

- (g) **Hence, calculate the mass of the binary system of Cen-X3, give your answer in solar masses. HINT: Use Kepler's third law for binary systems.** [2]
- (h) **What is the mass of the Cen-X3 and its companion star respectively?** [1]

⁵An edge-on orbit has an orbital inclination of 90 degrees with respect to us.

A Using SAOImageDS9

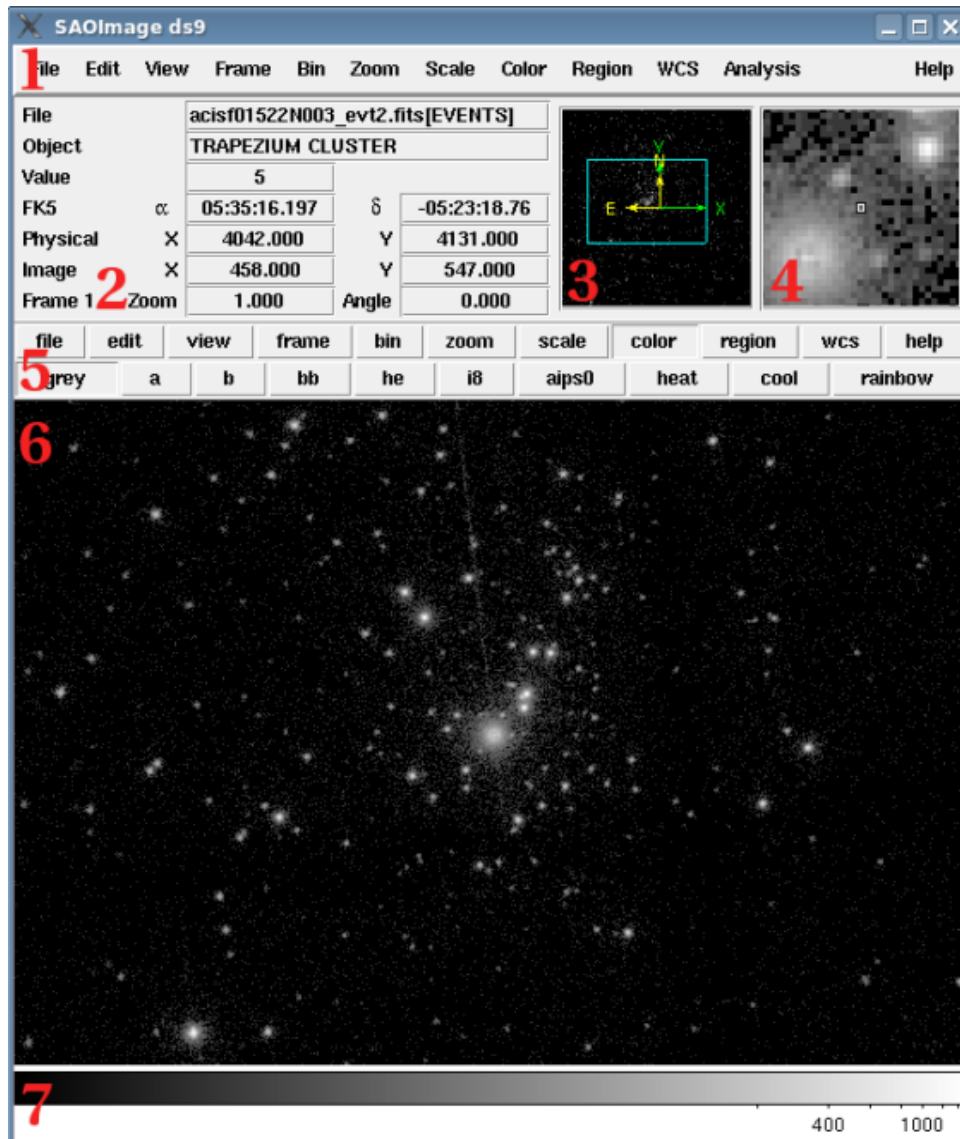


Figure 8: The SAOImage 9 interface

1. **Menu bar:** Provides access to all ds9's features.
2. **Information panel:** Displays information about the values at the cursor position and the data file.
 - (a) **Object:** Object name loaded from the header of the data file
 - (b) **Value:** Number of photons that hit the sensor at that pixel, i.e., brightness of the pixel.
 - (c) **FK5:** Celestial Coordinates of the cursor position according to the reference stars of the Fifth Fundamental Catalogue. RA and Dec values are in hours:minutes:seconds
 - (d) **Physical:** Pixel coordinate with respect to the CCD camera (different from "Image" coordinates if the image shown is part of a larger image)
 - (e) **Image:** Pixel coordinate with respect to the image, the coordinates are with respect to the centre of each pixels. Bottom-left of the bottom-left pixel of an unrotated image is assigned a coordinate of (0.5,0.5).
3. **Panner:** A cyan rectangle that can be dragged around the image to view its parts. Also shows the cardinal directions and image axes.
4. **Magnifier:** Shows a magnified view of what the cursor is hovering over.

5. **Buttons:** Duplicates many of the options found in the menu bar. Choose a category from the top row to view the options on the bottom row in that category. In Fig. 1, the “color” category is chosen and “grey” is selected from the options.
6. **Display frame:** Area where the FITS image is shown. A single frame is shown in Fig. 1. Multiple frames can be opened, more operations and options with frames are shown under the drop-down menu for “Frame” in the menu bar and under “frame” in the buttons bar.
7. **Colorbar:** Displays the colormap, bias, and contrast settings. To change the colormap, use the “Color” menu or button. The contrast and bias can be adjusted by holding down right-click and dragging on the ds9 display (up-down and left-right respectively). The Color → Colormap Parameters dialog box can also be used to change the contrast and bias.

You can save all your settings and preferences by opening Edit → Preferences dialog box.

Navigation Tips

1. Zoom button → Zoom Fit when you are out of frame
2. When using the Pan tool (Edit button → Pan), click towards where you want to go, not drag.
3. Use the arrow keys on your keyboard to move the mouse one pixel in the specified direction.

Chandra-Ed Analysis Tools

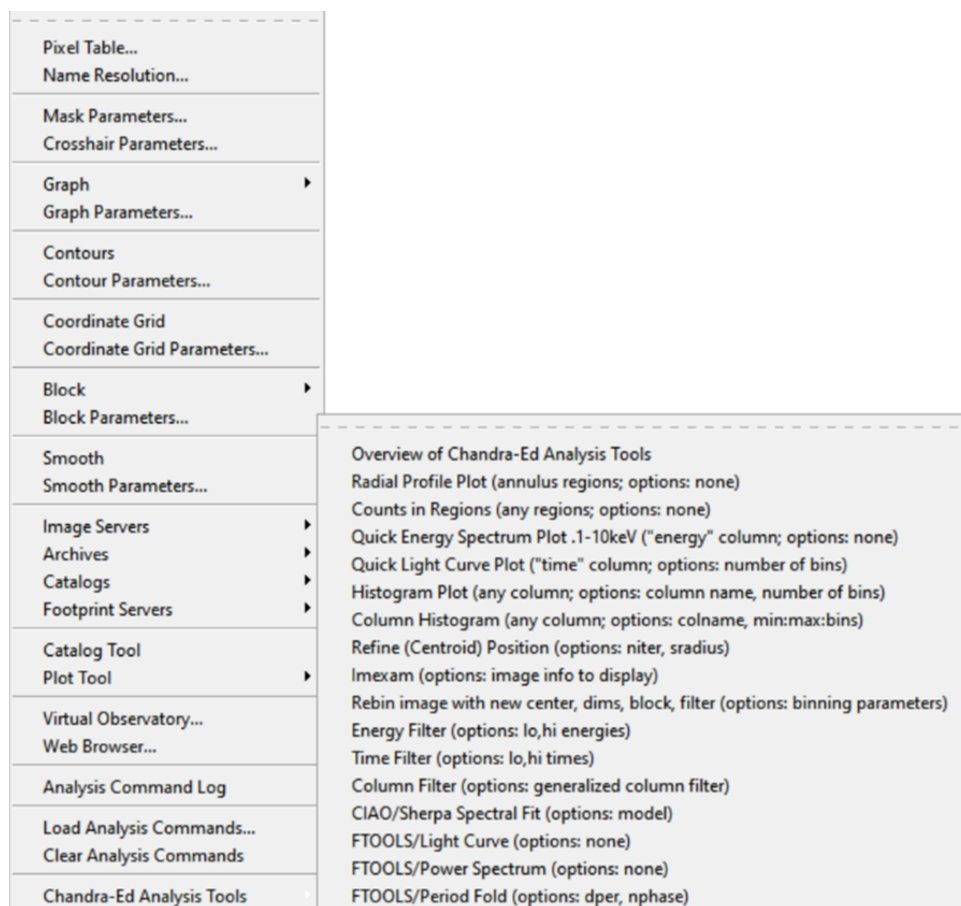


Figure 9: Submenu of Chandra-Ed Analysis Tools. Credit: SAOImageDS9, 2009

Frames

Frames allow DS9 to display multiple images at once and also allow you to work with multiple images at once. To create a new frame, click on either Frame in the menu bar and New Frame, or the frame button and new. You may

not be able to see your frame at first, that's because you are in the single frame mode. Change your mode in the buttons bar under frame or under Frame in the menu. The available modes and their functionalities are listed below:

Single Frame: shows one frame in the window at one time, you can move to the next frame by pressing tab on your keyboard or next and back in the buttons bar under frame.

Tile Frames: shows you all the available frames in a tiled format, the frame in which you are working will be highlighted with a blue border. To change between frames, press "tab" on your keyboard or click on the frame you would like to go to.

Blink Frames: switches between the frames periodically, showing only one frame at a time in the window.

B Downloading data from Chandra X-ray Center

1. Enter the desired Observation ID into the search field, followed by pressing the search button.

2. Make sure the result that you would like to download is selected with the blue check mark. We will only be using the primary data package for our analysis, uncheck "Secondary package". Click the "Add Products to Retrieval List" button.

Select	Row	Seq Num	Obs ID	Instrument	Grating	Appr Exp	Exposure	Target Name	PI Name	RA	Dec	Status	Data Mode	Exp Mode	Avg Cnt Rate	Evt Cnt
<input checked="" type="checkbox"/>	1	502954	19606	ACIS-S	NONE	50.0	49.41	Cassiopeia A	Patnaude	23 23 26.70	+58 49 03.00	archived	GRADED	TE	209.15	10334576

3. Click "Retrieve Products".

Row	Seq Num	Obs ID	Instrument	Target Name	PI Name	Status	Public Release Date	Package	Product(s)	Description	Remove
1	502954	19606	ACIS-S	Cassiopeia A	Patnaude	archived	2020-05-14 08:40:14	primary	all	---	Remove

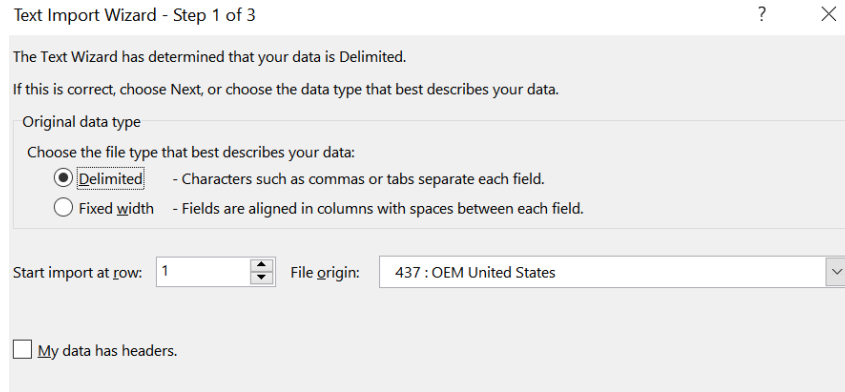
4. Follow the instructions of the page to retrieve your downloadable file. You may need to refresh the page provided by the given link a few times before your file shows up. The file you would have downloaded should be in the .tar format; this is an archive format, similar to .zip or .rar.

For online support please contact the [CXC Helpdesk](#).

C Importing txt file into Excel

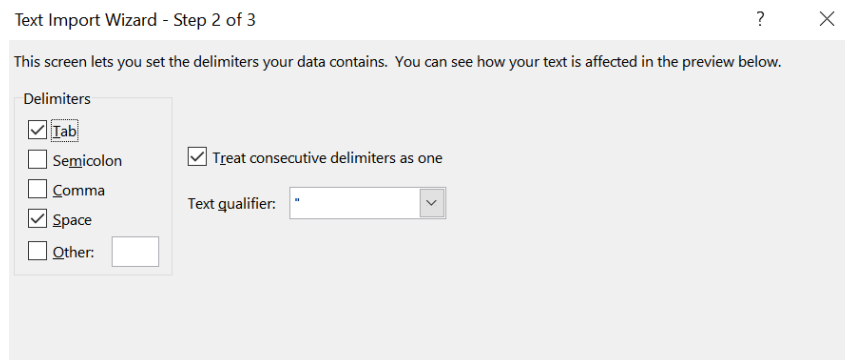
When you open a .txt file that contains a table like format, Excel will try to interpret it as one. You will be met with the Text Import Wizard. Follow the following steps.

1. Select "Delimited".



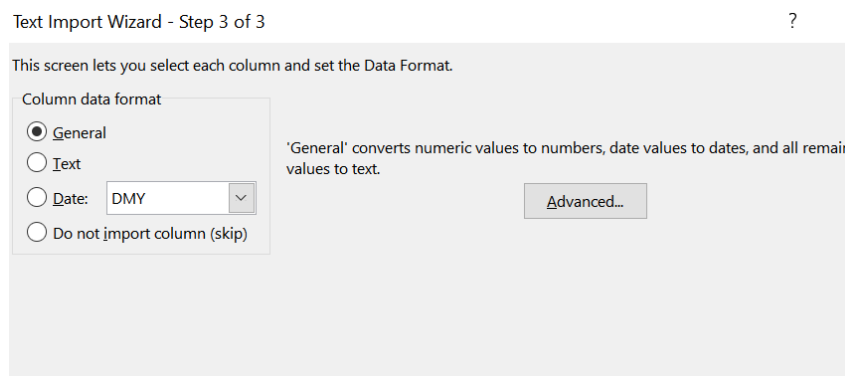
2. Next.

3. Check "Space".



4. Next.

5. Select "General".



6. Finish.

Cen X-3 Virtual Observatory printouts

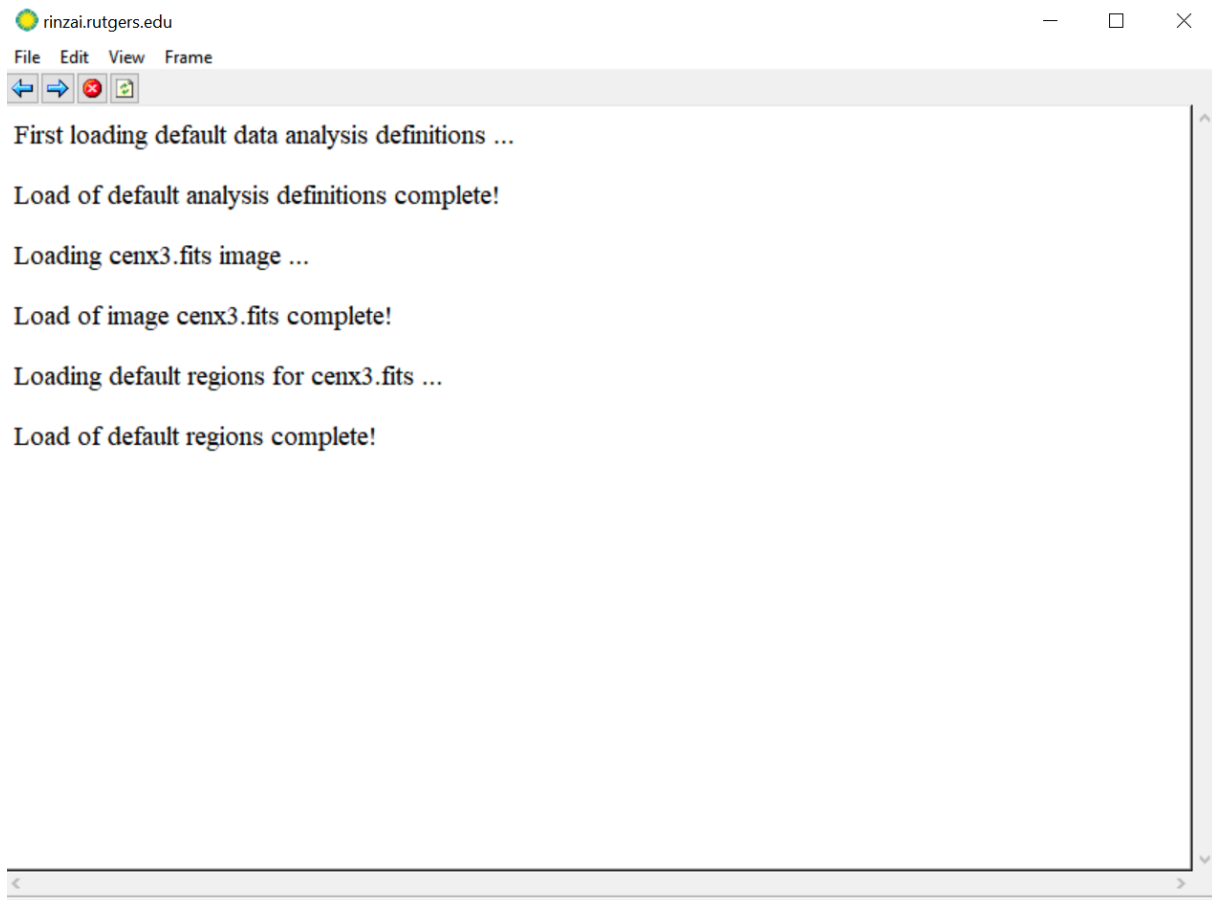


Figure 10: Correct printouts after downloading the observation data for Question 2