SCUBA-2 Photometry of X-ray Binary Jets

1 Objectives

Analyze SCUBA-2 observations of the relativistic jet launched from the black hole within the X-ray binary system V404 Cygni. You will also combine your SCUBA-2 data with an array of simultaneous multi-wavelength data to construct one of the most powerful tools we have to probe jet properties in these systems, the broad-band spectrum.

2 Background Reading

Read the introduction section of the papers linked below (click the arXiv pre-print link to get free access to the papers).
`http://adsabs.harvard.edu/abs/2016ApJS..222...15T`
`http://adsabs.harvard.edu/abs/2019MNRAS.482.2950T`

3 Introduction

Astrophysical jets are ubiquitous phenomena in our universe, linked to a wide range of objects, from young stars to black holes. These powerful, highly collimated outflows deposit significant amounts of energy and matter into the surrounding medium, affecting star formation, galaxy evolution, and even the distribution of matter in the universe.

Of all the systems that launch jets, X-ray binaries (XBs; binary systems containing a stellar mass compact object, such as a black hole or neutron star, accreting matter from a companion star) are particularly excellent testbeds for studying jet phenomena. These systems are typically transient in nature, evolving from periods of inactivity into a bright out-bursting state on timescales of days to months, in turn providing a real time view of how jets evolve and interact with their environment.

To study XB jets, one of the tools we can employ is the broad-band spectrum, characterizing how the brightness of the jet emission changes with frequency. XB jets display a broad-band spectrum consisting of optically thick synchrotron emission (modelled as a power-law) extending from radio up to sub-mm or infrared frequencies, which breaks to optically thin synchrotron emission at higher frequencies. The spectral break is a key observational tracer of jet physics, as this portion of the spectrum probes emission from the most compact region of the jet, where particles are first accelerated up to high energies. The exact spectral shape (i.e., spectral index, location of the spectral break) depends on jet properties such as geometry, magnetic field structure, and particle density profiles, as well as the plasma conditions in the region where the jet is first accelerated.

In this lab, you will reduce JCMT SCUBA-2 sub-mm observations of the XB V404 Cygni, taken during its 2015 outburst. Through combining your sub-mm flux measurement with other multi-wavelength data you will create a broad-band spectrum, and fit different models to the spectrum to estimate jet properties in this system.

4 Procedure

4.1 PART 1:

1. Download the data for this lab from the CADC. You will need to download both the target data and the calibrator data. To find the target data, you can search the archive for the project code: M15AI54 (you should find 3 epochs of data, but you only need to download the July 02 data). To find the calibrator data, type JCMTCAL into the target box, and 2015-07-02 into the date box (you will find multiple calibrator observations, make an educated choice as to which one you want to use). You ONLY need the 850μm data, not the 450μm data! HINT: I suggest creating separate "raw_data" and "results" directories on your machine to store you data and data products.

2. Navigate into the directory where you have stored your raw data, and initialize the Starlink software by sourcing the startup script, and loading in the packages you will need. In the bash shell, this can be done with the following commands.

   `cd ./file_dir`
   `source $STARLINK_DIR/etc/profile` or `starlink`
   `kappa`
   `smurf`

3. Make a list of the raw data files of the target source and save them to a text file. This file will tell the reduction software what raw data you would like to reduce. Note that DATA_DIR should point to the directory where you saved the raw data, DATE takes the form yyyymmdd (e.g., 20190102), and SCAN should be a set of 5 numbers (e.g., 00008 or 00034).

   You will notice that there is data from multiple scans, taken at different times throughout the night, of the target source present (8 scans on July 02). We want to analyze data from each scan separately (to be combined later), so we need a list file for each scan.

   ```
   ls DATA_DIR/s8*DATE_SCAN*.sdf > OUTPUT_FILE_DATE_SCAN.lst
   ```

4. Repeat step 3 for the calibrator data. You will only have a single calibrator scan, and thus a single list file.

5. The task that does all the heavy lifting in the reduction process is called the mapmaker. This task uses a configuration file, which defines the parameters that the mapmaker will use to reduce the data. Make a copy of this file (that is stored in the starlink directories), save it to your local directory, then view with your favorite text editor. We will be using the bright, compact recipe, as our target source will be a bright point source (this configuration file also works for our calibrator!).

   ```
   cp -r $STARLINK_DIR/share/smurf/dimmconfig_bright_compact.lis YOUR_DIR
   sublime YOUR_DIR/dimmconfig_bright_compact.lis
   ```

6. Run the mapmaker using the bright compact recipe for each target scan, and the calibrator scan. Pay attention to the info output to the screen.

   ```
   makemap in=^OUTPUT_FILE_DATE_SCAN.lst out=OUTPUT_MAP_DATE_SCAN
   config=^YOUR_DIR/dimmconfig_bright_compact.lis
   ```

7. Run a picard recipe, SCUBA2_CHECK_CAL, on the calibrator map output from the mapmaker. This will allow you to calculate the flux conversion factor (FCF), that will be used to convert raw current units (pW) to fluxes (Jy). In the text output to the screen, make sure to record the FCF number (the peak FCF not the arcsec one!).

   ```
   picard -log sf SCUBA2_CHECK_CAL CAL_MAP_DATE
   ```

8. Scale the output maps of all the target scans to flux units using your FCF from the previous step.

   ```
   cmult in=OUTPUT_MAP_DATE_SCAN out=OUTPUT_MAP_DATE_SCAN_cal.sdf scalar=FCF_VAL
   ```

9. Once you have a reduced and flux calibrated a map for each target scan on July02, you can combine all the data together, and then crop the noisy edges off the map. Note that the cropping recipe needs you to provide a parameter file (par.lst) that will define how much to crop off the map (create and save this file according to instructions below).

```
ls DATA_DIR/OUTPUT_MAP_DATE_*_cal.sdf > FILES_reduced_DATE.lst
wcsmosaic in=^FILES_reduced_DATE.lst out=OUTPUT_MAP_DATE_allscans_cal.sdf
picard -log sf -recpars par.lst CROP_SCUBA2_IMAGES OUTPUT_MAP_DATE_allscans_cal.sdf
```

The contents of par.lst should be as follows (this leaves the inner 200 arcsec of your map):

```
[CROP_SCUBA2_IMAGES]
MAP_RADIUS=200
CROP_METHOD=200
```

10. Estimate the rms noise in your final combined map (HINT: the value you want is the mean, since you are looking at the error component of the data).

```
stats comp=err OUTPUT_MAP_DATE_allscans_cal_crop.sdf
```

11. View your final combined map with the Gaia tool. You can determine the peak flux of the source by using the object detection tool in Gaia. To do this, go to Image Analysis/Object Detection, and hit the "detect objects" button. The FLUX_MAX value in the pop up table is the value you want to record.

```
gaia OUTPUT_MAP_DATE_allscans_cal_crop.sdf
```

4.2 PART 2:

Now we will combine our SCUBA-2 data point with other multi-wavelength data (seen in the table below). This multi-wavelength data was taken simultaneously with the JCMT SCUBA-2 data you reduced in Part 1. The analysis for Part 2 of this lab will involve some coding in python, and a jupyter notebook has been provided to assist you with this.

Table 1: Flux Densities of V404 Cygni

Telescope/ Band	Freq. (GHz)	Flux Density (mJy)
VLA	5.25	3.9 ± 0.04
VLA	7.45	3.9 ± 0.03
VLA	20.8	5.1 ± 0.03
VLA	25.9	4.9 ± 0.02
SMA	220.3	8.9 ± 2.2
SMA	230.3	5.5 ± 2.5
J	371950.9	42.5 ± 4.0
H	245731.5	29.8 ± 2.4
K	183921.8	32.7 ± 3.1
I	136891.5	24.7 ± 2.1
V	548267.1	19.5 ± 2.0
B	682587.6	18.8 ± 2.5
U	865201.9	14.3 ± 3.1
UV1	1153047.9	7.4 ± 9.0

1. First we will examine the longer wavelength part of the broad-band spectrum, which will be dominated by jet emission. Follow the provided jupyter notebook to plot a broad-band spectrum with your SCUBA-2 data point and the other multi-wavelength data.
2. Fit a power law (representing optically thick synchrotron jet emission) to your radio through sub-mm data using the following functional form,

$$F_\nu = A\left(\frac{\nu}{\nu_0}\right)^\alpha$$

3. Plot your best fit model on the broad-band spectrum.
4. Second, we will consider shorter wavelength part of the broad-band spectrum, which will contain contributions from the synchrotron jet and the companion star. Write a model function that contains 2 components; a broken power-law (representing both the optically thin and thick parts of the jet) and a blackbody (representing the companion star).

$$F_{\nu,\mathrm{jet}} = \begin{cases} f_{\mathrm{br}}(\nu/\nu_{\mathrm{br}})^{\alpha_{\mathrm{thick}}} & , \nu < \nu_{\mathrm{br}} \\ f_{\mathrm{br}}(\nu/\nu_{\mathrm{br}})^{\alpha_{\mathrm{thin}}} & , \nu > \nu_{\mathrm{br}} \end{cases}$$

$$F_{\nu,\mathrm{bb}} = \left(\frac{\pi R^2}{D^2}\right)\left(\frac{2h\nu^3}{c^2}\right)\left(\frac{1}{e^{\frac{h\nu}{kT}}-1}\right)$$

5. Using the best fit parameters provided in the notebook for this 2 component model, plot this new model on your broadband spectrum.
6. Calculate the radiative jet power by integrating over the jet component of your broad-band spectrum.

$$L_{jet} = 4\pi D^2 \int_{\nu_1}^{\nu_2} \nu F_\nu d_\nu$$

7. Assuming a single zone synchrotron model, and your best fit parameters, calculate the radius (in units of gravitational radii; $r_g = GM/c^2$) and magnetic field strength (in units of Gauss) of the jet acceleration zone.

$$R_F = \nu_{\mathrm{br}}^{-1} S_{\mathrm{br}}^{\frac{p+6}{2p+13}}$$

$$B_F = \nu_{\mathrm{br}} S_{\mathrm{br}}^{\frac{-2}{2p+13}}$$

Here $p = 1 - 2\alpha_{\mathrm{thin}}$

5 Analysis Questions

- What is the flux density and RMS noise you measured from the SCUBA-2 data? Have you significantly detected the target source in this observation? Why or why not?
- What is the value of the spectral index you fit in Part 2 step 1? What does this value tell you about the type of synchrotron emission you are observing at these frequencies?
- Given your two component model, in what frequency range does the jet dominate the emission we observe? Where does the companion star dominate the emission? Can you think of another emission source that we have not included in our model, but that may be contributing to the observed emission as well?

- What limits did you choose for your jet power integral? Why?
- Compare your radiative jet power to the radiative output of the sun.
- What is the radius of the event horizon for the black hole in V404 Cygni (HINT: You will need to look up the mass of the black hole in this system)? How does the acceleration zone radius compare to the event horizon radius?
- In reality, the broad-band spectrum of these jets is dynamic, where the break frequency can change by over several orders of magnitude. If the break frequency was located at a lower frequency, what happens to the acceleration zone properties?