Using SCUBA-2 to Probe Variability in X-ray Binary Jets

1 Objectives

Examine time-resolved JCMT SCUBA-2 flux data of V404 Cygni. You will plot time-resolved SCUBA-2 light curves, and use synchrotron theory to calculate the energy, power, and magnetic field in the jet.

2 Background Reading

Read the introduction of the following linked paper (again please use the arXiv link for free access).
`http://adsabs.harvard.edu/abs/2017MNRAS.469.3141T`
As well as, the provided pages from the "Compact Stellar Objects" text.

3 Introduction

Black holes drive the most powerful outflows in the universe, from the kilo-parsec scale jets launched by the most massive black holes in Active Galactic Nuclei (AGN), to the smaller scale jets launched by their stellar mass analogues in black hole X-ray binaries (BHXBs). Within these BHXBs, the black hole accretes matter from a companion star, where a portion of this material is transported back outwards in the form of a jet. Two types of jets have been observed in BHXBs depending on the rate at which mass is accreted onto the black hole; a steady, compact jet (what you observed in the previous lab) at lower accretion rates, and ballistically moving jet ejecta, with apparent proper motions that can exceed the speed of light, at higher accretion rates.

The emission observed from jet ejecta in these systems can be strongly variable over rapid timescales, often showing structured flaring activity. Detecting and characterizing these rapid flux changes can allow us to probe detailed jet properties that are difficult, if not impossible, to measure by other means (e.g., jet geometry, speed, the sequence of events leading to jet launching).

In this lab, you will examine time-resolved light curves of the black hole X-ray binary V404 Cygni taken during its 2015 outburst. In particular, you will work to connect jet ejecta variability properties with internal jet physics.

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 Jun 22 data this time). To find the calibrator data, type JCMTCAL into the target box, and 2015-06-22 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 (7 scans on June 22). 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.

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. In order to make time-resolved maps we need to make a small modification to the configuration file. Make a copy of the configuration file, add the following line to the end of the file, and save it with a new name (dimmconfig_bright_compact_var.lis).

   ```
   shortmap=200
   ```

   This parameter represents the number of time slices you would like in each map (32min scans divided by 200 is 5 sec time bins).

7. Run the mapmaker using the modified bright compact recipe for each target scan.

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

8. Run the following command to make a "cube", with axes RA, Dec, MJD, from your mapmaker output,

   ```
   stackframes OUTPUT_MAP_DATE_SCAN.more.smurf.shortmaps sort=true
   sortby=MJD-AVG OUTPUT_MAP_DATE_SCAN_cube.sdf
   ```

9. Run the mapmaker using the original bright compact recipe for the calibrator scan.

10. 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
    ```

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

```
cmult in=OUTPUT_MAP_DATE_SCAN_cube.sdf out=OUTPUT_MAP_DATE_SCAN_cube_cal.sdf scalar=FCF_VAL
```

12. Once you have a reduced and flux calibrated cube for each target scan on June 22, you can combine all the data together.

```
ls DATA_DIR/OUTPUT_MAP_DATE_*_cube_cal.sdf > CUBES_reduced_DATE.lst
wcsmosaic in=^CUBES_reduced_DATE.lst out=OUTPUT_CUBES_DATE_allscans_cal.sdf
```

13. View your final combined cube with the Gaia tool,

```
gaia OUTPUT_CUBES_DATE_allscans_cal.sdf
```

14. To view the full light curve from the cube, click on central source pixel, and a window will pop up showing the light curve.
15. To make a gif movie of the source with your cube, go to the animation tab in the pop up window, select capture option, and hit play. You will be able to see the dramatic brightness changes first hand!

4.2 PART 2:

The analysis for this lab will involve coding in python, and a jupyter notebook has been provided to assist you with this.

1. The light curve you produced in PART 1 only represents the flux variations for the central pixel in the source. To get a more accurate flux value for each time bin, we can instead fit a Gaussian the size of the JCMT beam to each plane in our cube to extract the flux. You have been provided with a data file of these values. Following the jupyter notebook, read in the time-resolved JCMT SCUBA-2 light curves from the data file provided.
2. Plot the light curve.
3. Quantify the variability amplitude in the light curves using the fractional RMS statistic.

$$F_{\text{var}} = \sqrt{\frac{S^2 - \bar{\sigma}^2_{\text{err}}}{\bar{x}^2}}$$

   Here $\bar{x}$ represents the weighted mean of the flux measurements, the sample variance $S^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$, and the mean square measurement error $\bar{\sigma}^2_{\text{err}} = \frac{1}{N}\sum_{i=1}^{N}\sigma^2_{\text{err,i}}$.
4. Using the largest flare, estimate the energy, power and magnetic field in the ejecta.

$$E_{\min} \sim 3\times10^{33}\eta^{4/7}\left(\frac{\Delta t}{\text{s}}\right)^{9/7}\left(\frac{\nu}{\text{GHz}}\right)^{2/7}\left(\frac{S_\nu}{\text{mJy}}\right)^{4/7}\left(\frac{D}{\text{kpc}}\right)^{8/7}\ \text{erg}$$

$$P_{\min} = \frac{E_{\min}}{\Delta t}\ \text{erg/s}$$

$$B_{\min} \sim 30\eta^{2/7}\left(\frac{S_\nu}{\text{mJy}}\right)^{2/7}\left(\frac{D}{\text{kpc}}\right)^{4/7}\left(\frac{\Delta t}{\text{s}}\right)^{-6/7}\left(\frac{\nu}{\text{GHz}}\right)^{1/7}\ \text{G}$$

   Here $\eta = 1 + \epsilon_p/\epsilon_e$ describes the ratio of energy in protons to electrons, Δt represents the rise time of a flare, D represents distance to the source, S_ν represents peak flux of the flare, and ν represents observing frequency.

5. Include the kinetic energy of the ejecta and redo your calculations.

$$E_{KE} = (\Gamma - 1)E_{\min}$$

Here the bulk Lorentz factor $\Gamma = (1 - \beta^2)^{-1/2}$, and $\beta = v/c$ represents the speed of the jet ejecta in units of the speed of light (use $\beta = 0.4$ for your calculations).

5 Analysis Questions

- What jet properties do you think determine the profile of the flares?
- The light curves you analyzed are taken at 350 GHz ($850\mu m$). What do you think happens to the peak flux and rise/decay times of the flares if we were observing at a lower frequency?
- Does the kinetic energy or radiative energy dominate in the emission from your ejecta?
- Compare you radiative power and magnetic field strength estimates here to those you found for the compact jet in the previous lab.
- Another type of outflow was also detected in V404 Cygni, a powerful wind launched from the accretion disc. If the material in the wind has a mass of $10^{-8} M_\odot$ and a velocity of $1000\,\mathrm{km\,s^{-1}}$, calculate the energy lost in the wind and compare to the energy lost in the jet.
- Here we have assumed the jet is only made of leptons. What happens to the expressions for radiative and kinetic energy if we add baryonic content?