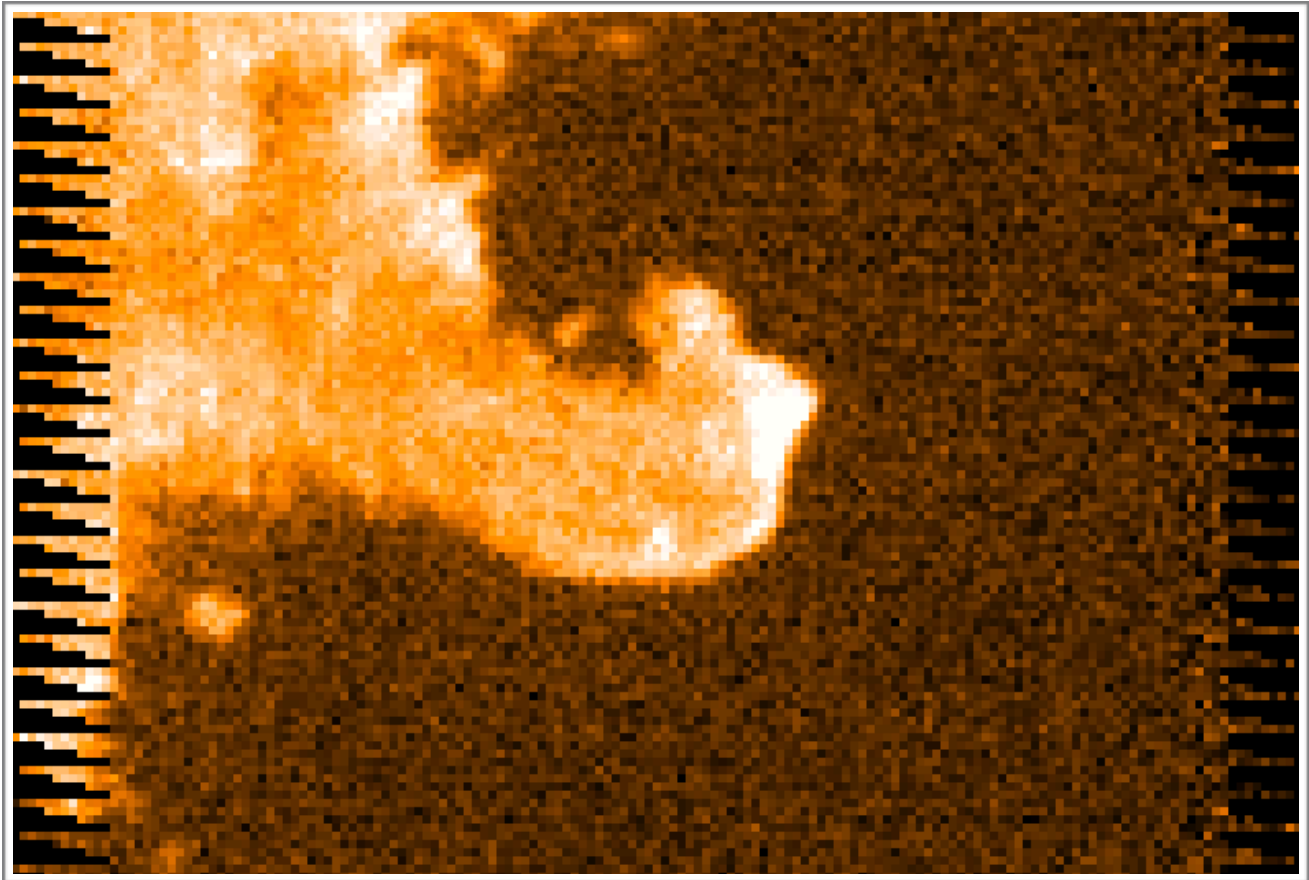# Assignment 6

Spectral Cubes and Space Horses

ASTR 351L

Spring 2019

Velocity Distributions
Using 3D Data Cubes

Link to Introductory Slides:
https://www.eaobservatory.org/~s.mairs/ASTR351/slides/ASTR351L_HARP.pdf

Procedure:

Part I: Exploring the Data

1. Download the file:

    https://www.eaobservatory.org/~s.mairs/ASTR351/assignments/HARP.tar.gz

    This is a compressed file containing a directory called "Assign6_HARP" that is home to:

    a. horsehead.sdf: A data cube of the Horsehead nebula observed at a frequency of 345.7959899 GHz (Molecule: 12CO, J=3-2 transition).

    b. G34_SCUBA2.sdf: The SCUBA-2 Map of the G34 star-forming region (from Assignment 1).

    c. G34_HARP.sdf: 12CO(J=3-2) integrated intensity (HARP) data covering the same area of G34 as the SCUBA-2 data.

    d. SpectralFit.ipynb: A Jupyter notebook that shows you how to fit an emission line using Python.

2. Copy this file to a suitable directory to work in (e.g. your local Desktop directory, *~/Desktop* , in the following example):

    %cp HARP.tar.gz ~/Desktop

3. Switch to the working directory using "cd", unzip the file using "gunzip" and untar the file using "tar -xvf". Change to the newly-created directory containing the data:

   %cd ~/Desktop
   %gunzip HARP.tar.gz
   %tar -xvf HARP.tar
   %cd Assign6_HARP

   Check the contents of this directory by using the linux command: %ls

4. Load the Starlink Software:

   %export STARLINK_DIR=/opt/star-2018A
   %source $STARLINK_DIR/etc/profile

5. Open the file called "horsehead.sdf" with Gaia: %gaia horsehead
   You'll notice that three windows open: The main viewer, a window labelled "Select NDF in container file" (this one looks familiar with our work using SCUBA-2), and a window labelled "Display image sections of a cube".

   Let's get familiar with the data.

   Zoom in using the large "Z" on the main viewer until the image fills the available space.
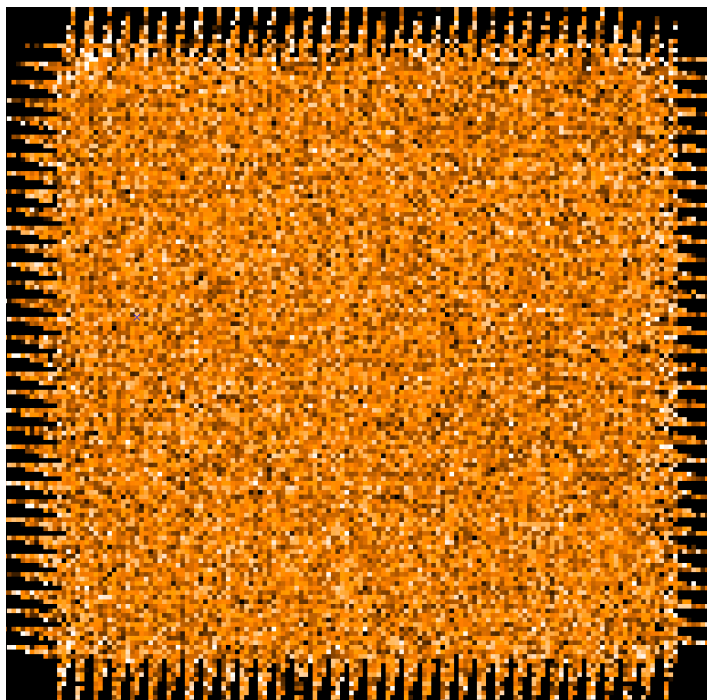
Right now, it looks kind of noisy and boring…but that is just because the third dimension (Velocity) isn't centred on the peak of the interesting gas emission. To see what I mean, click on one of the pixels in the very centre of the map. A new window pops up that is labelled: "GAIA: Spectral plot (1)" and it shows you a spectrum that is centered on the rest frequency of 12CO (J=3-2):
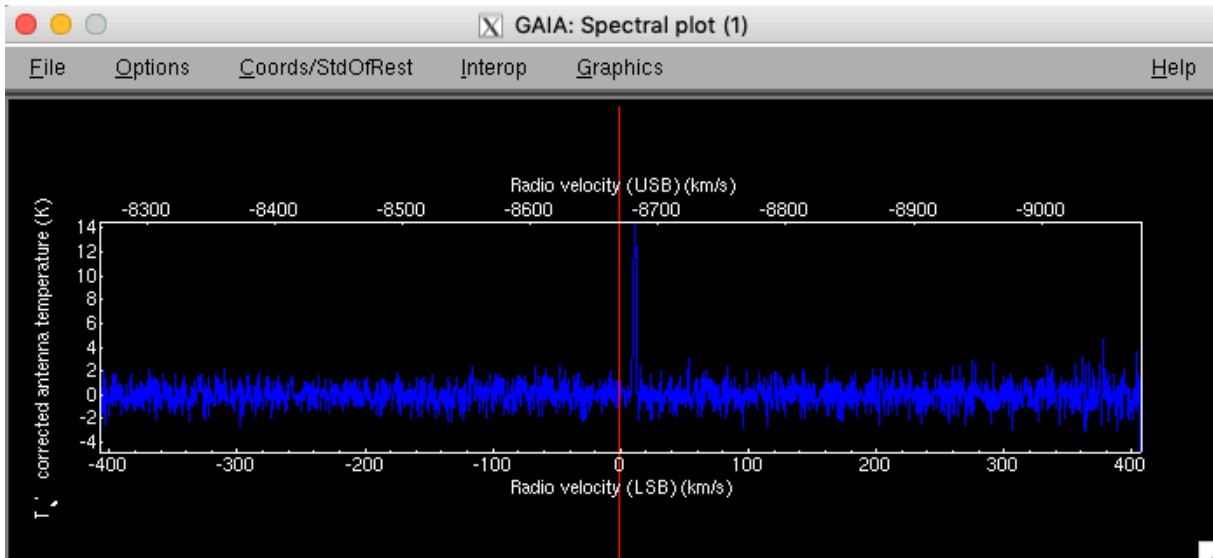
This shows you information about the emission this pixel has recorded at each individual frequency across the bandwidth. Remember, you can convert a small change in frequency (Δf) into a change in velocity (Δv) by using the average wavelength between the two frequencies (λ_{avg}):

$$\Delta f \sim \frac{\Delta v}{\lambda_{avg}}$$

Where λ_{avg} can be calculated using the familiar equation: $c = f\lambda$

$$\lambda_1 = \frac{c}{f_1}, \ \lambda_2 = \frac{c}{f_2}$$

$$\lambda_{avg} = \frac{\lambda_1 + \lambda_2}{2}$$

where c is the speed of light. Make sure you keep track of your units!

At what velocity is the peak of the spectrum (approximately)? The central frequency of this observation is 345.7959899 GHz - use this value as λ_{avg} since it will be a good approximation. Calculate the frequency associated with this velocity.

You can click and drag the red line in the spectrum window so that it overlaps with the peak of the spectrum. Look to see what happens to the image when you do!

As you drag the red line, you are flicking through each frequency (or, velocity!) channel - so every single pixel in the image is associated with a spectrum that spans a large range of velocities! HARP data is in the form of an **image cube.**

Adjust the "auto cut" or use the "Low" and "High" input boxes to adjust the stretch of the image until you can see the central Horse Head feature.
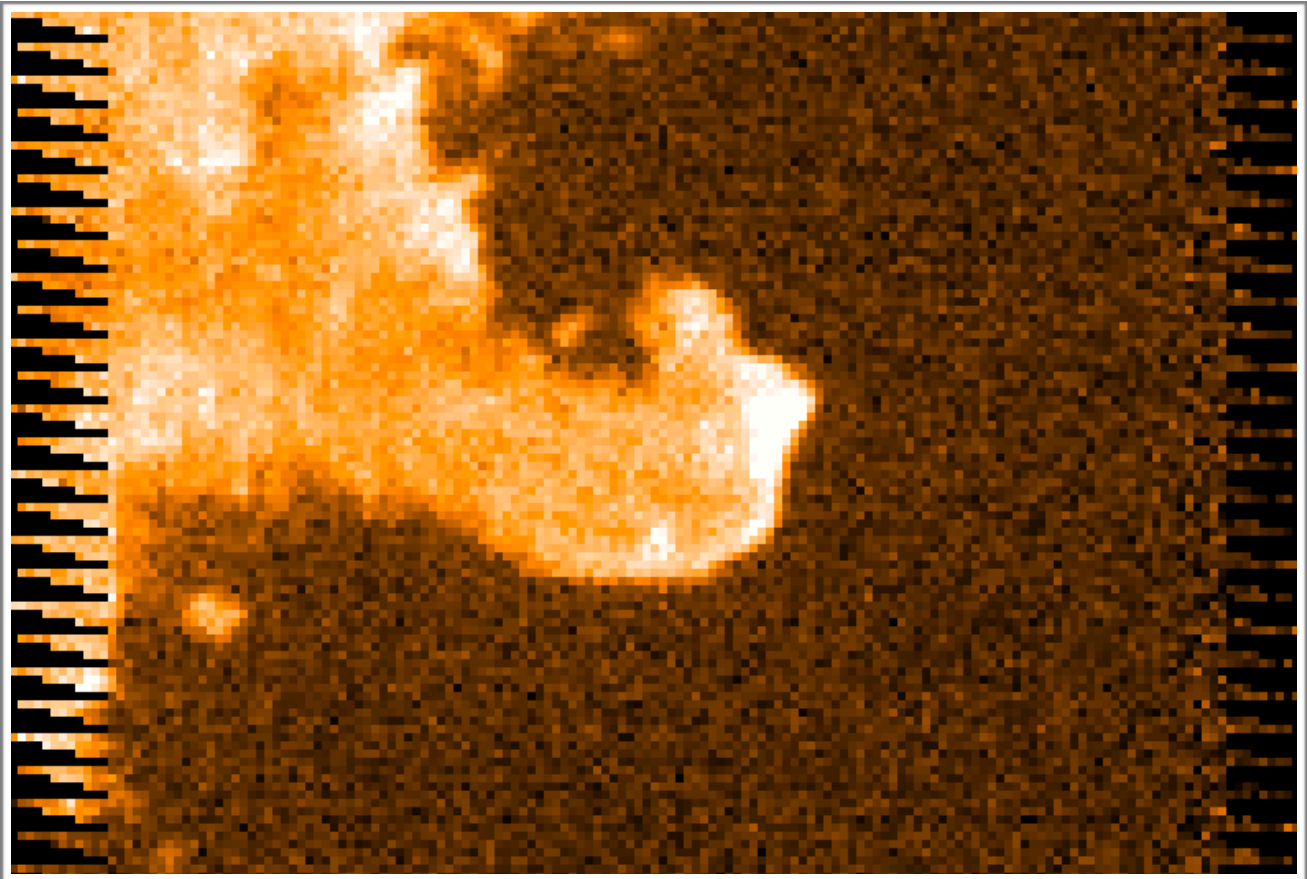
For fine tuning, you can adjust the "index of plane" slider in the "Display image sections of a cube" window.

6. Let's make an **animated gif** of our emission cube.

First, we are going to get rid of the noisy channels near the very edge of our velocity range. In the "Display image sections of a cube" window, click on the *animation tab*.
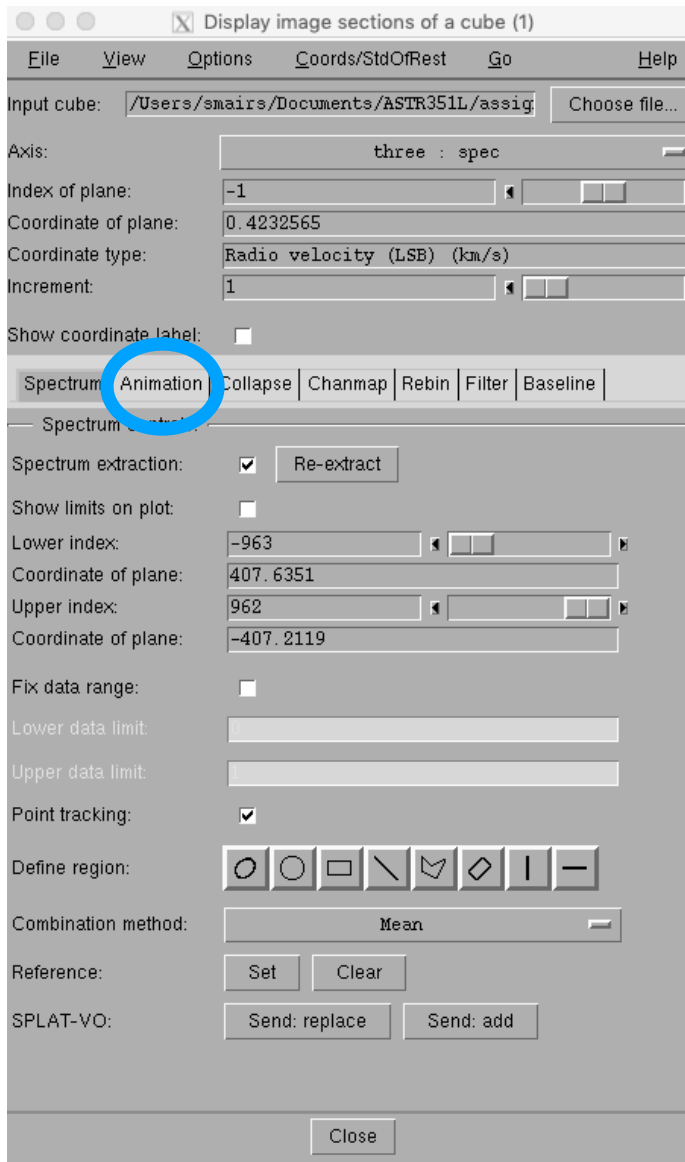
Click on a pixel in the image to get a spectral viewer, then click "start" under the animation tab. Do you see how far the main emission is from the red line? It will take a very long time to get to your emission. To help with this, click "stop", then adjust the lower index and upper index slider so that you are centred on the main emission present in the cube, avoiding all channels that are just noise. Use the "index of plane" slider near the top of the window to help you. *Make a note of these limits.*

Adjust the stretch of the image (the auto cut) and when you are satisfied with your movie, click Capture "on" and press start. This will save an animated gif to your current directory. **Submit your animated gif with your assignment.**

7. **Rebinning**. One common thing to do with data like this is to "rebin" the velocity axis so we can get a higher signal to noise. Effectively, we "squish" several channels together by adding them and taking the mean in bins across the spectrum. To see how this works, click on the "rebin" tab in the "Display image sections of a cube" window.

And set the Bin factor, axis 3 (velocity) to 8. Then click run. Click on a pixel in the centre of the image to see the difference!

What has happened to the velocity resolution?

What has happened to the signal to noise?
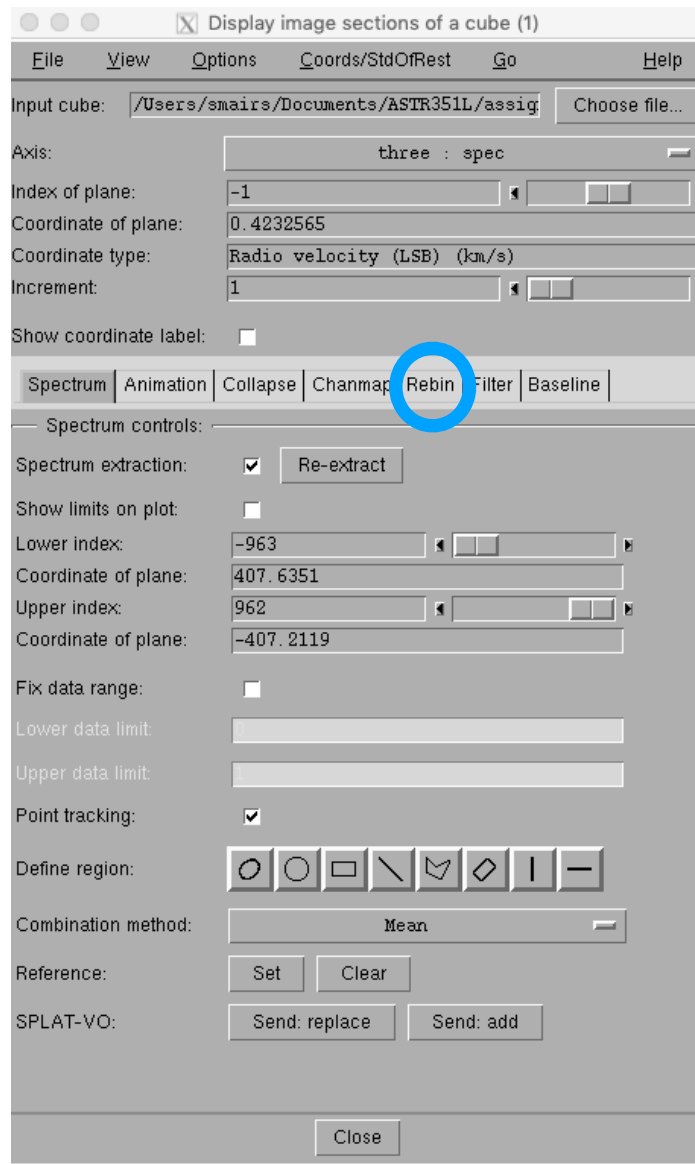
8. Close the main viewer of Gaia and reopen the original file (%gaia horsehead)
   Let's make an **integrated intensity map**. This is like rebinning, except we are going to average *all of the velocity channels together* to see what sort of emission exists across the whole frequency range. This is useful when you want a single snapshot of all the information present at different velocities (and in many cases, different distances, as velocity can be closely related to distance!).

   Click on the "collapse" tab in the "Display image sections of a cube" window. Then, adjust the lower index and upper index slider so that you are centred on the main emission. Click "run". Then, in the main image viewer, click "File -> Save as…". A window will come up that will allow you to choose a filename. Save the image.

9. Close the main viewer of Gaia and open the integrated intensity image you made. Note that it is not a cube, but an image! **Submit a screenshot of your integrated intensity map with your assignment.**

10. Another way to look at the data is in **channel maps.** There are easy ways to create images of evenly spaced channels so you can still retain the velocity information while looking at the structures that exist across the field. Ensure you have loaded the package "kappa": %kappa, then run "chanmap" and select an output name when prompted:

    %chanmap in=horsehead axis=3 low=2 high=17 nchan=16 shape=4 estimator=mean

    In this command, we are telling Starlink to select 16 channels evenly spaced between index 2 and index 17 and arrange them in a 4 x 4 grid for us. If we only asked for 3 channels, for example, it would split up our range evenly and rebin the range to produce 3 images, each containing information from several channel maps. Use Gaia to open your produced file to look at the channel maps.
   **Submit a screenshot of your channel maps with your assignment.**

Combining Channel Maps with an artistic eye is what produces some of the beautiful radio images of regions like the Orion Nebula:
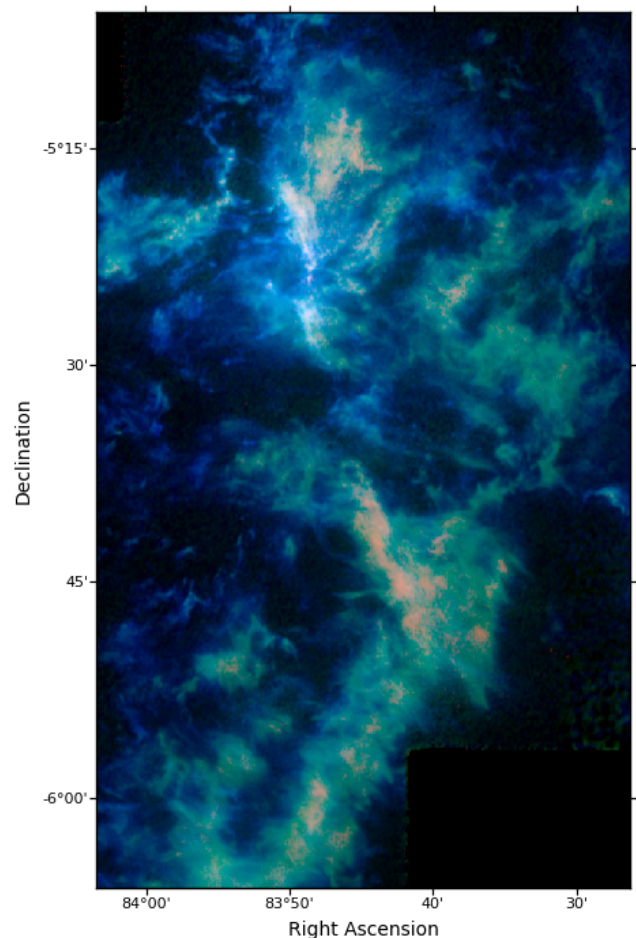
Part II: Linewidths

Now that we know what HARP data entails. Let's do a couple of useful things with it.

1. Open the Horse Head Nebula image in Gaia once more: %gaia horsehead
   Scroll to the channel containing the main emission and click on a central pixel that
   contains a good spectrum. **On the spectrum window, click "File -> Save as text"
   to save a copy of the spectrum in text format.**
   Then, in the "Display image sections of a cube" window, click "send-add" next to
   the words "SPLAT_VO":
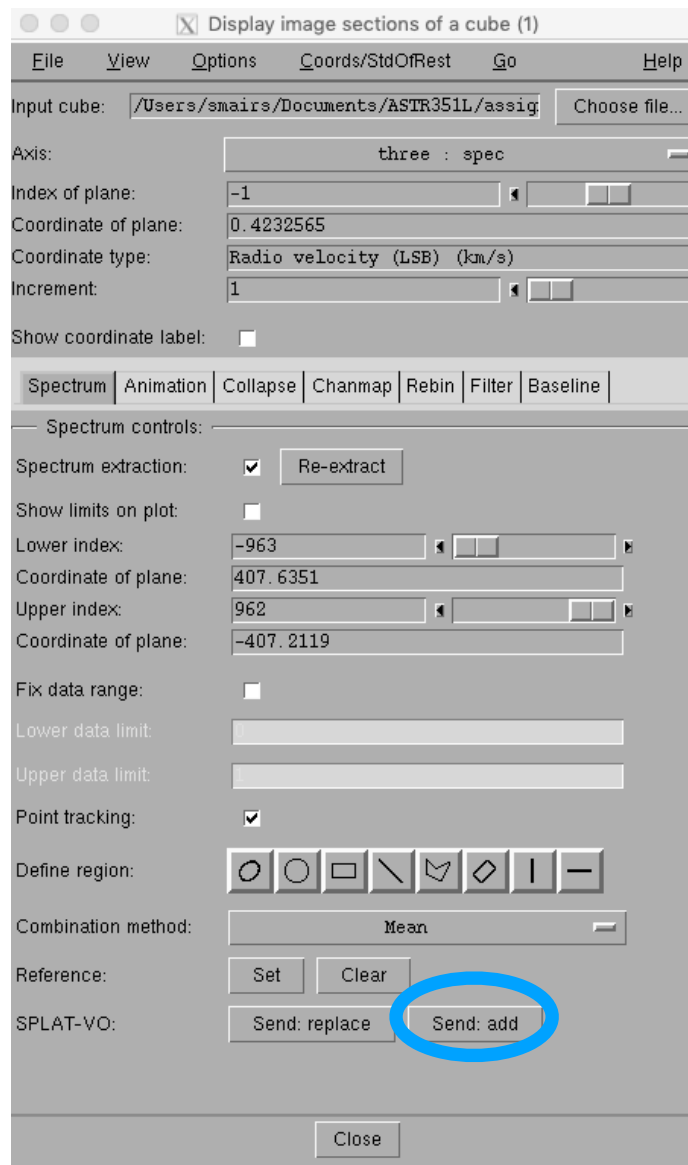
SPLAT stands for "Spectral Line Analysis Tool". As the name suggests, it helps us analyse spectral lines!
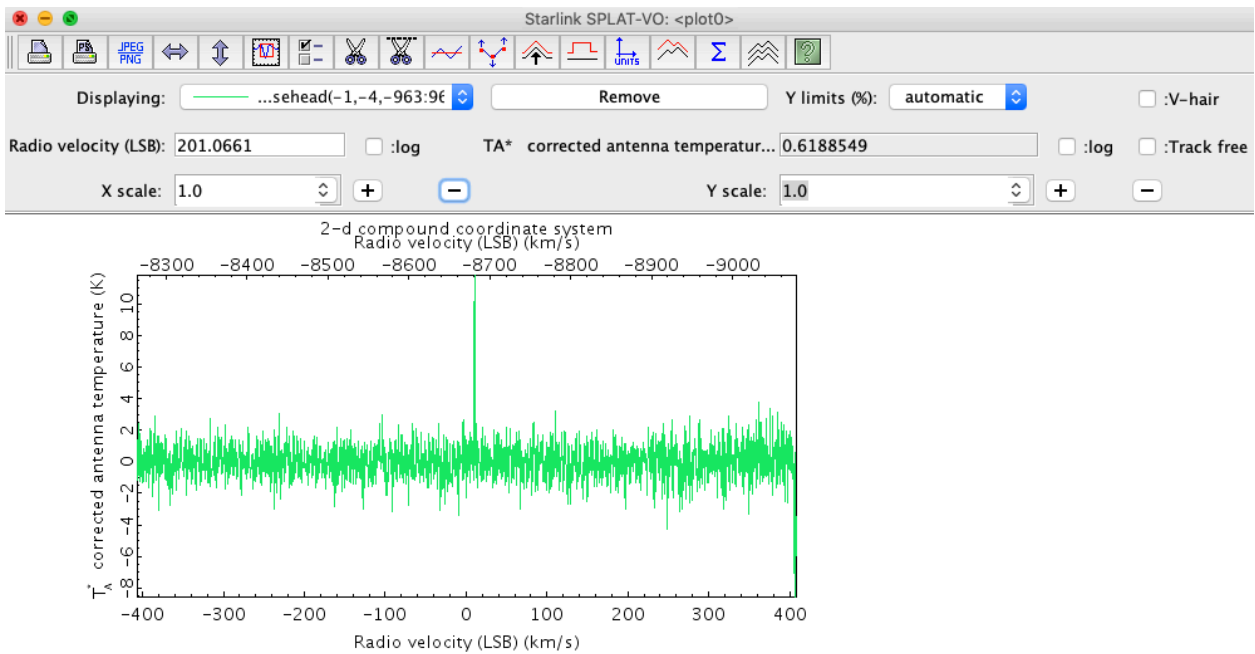
2. First, let's do something simple like measuring the noise. Select the Σ button from the top menu (Σ usually stands for "statistics"). Then, in the window that pops up, click "Add" and draw a region over the baseline of the spectrum that does not include any significant emission - only noise:
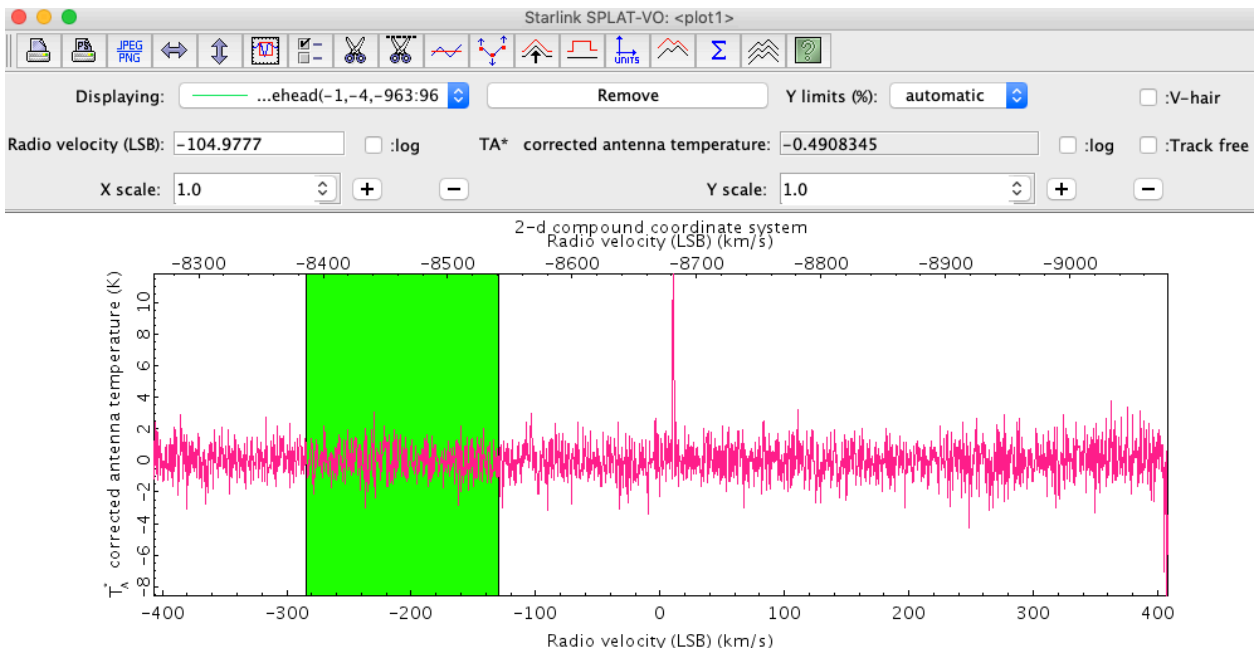
Then, in the statistics window, click "Selected stats". This gives you a lot of statistical information over that region. Which do you think represents the noise? **What is the noise in the spectrum?**

3. Next, you can use the "+" button next to the X scale to get a better view of the main emission. You can also play around with the units button (two over from the Σ button) to convert between velocity, frequency, and wavelength.

    Zoom in to the main emission and **approximate the Full Width at Half Maximum of the line with Velocity in km/s as the x-axis.** You can do this either by eye, or by trying to fit a polynomial using SPLAT's built in tools.

4. Now, we are going to measure the line width a little more robustly by fitting the spectrum. Remember that text file of the spectrum you saved back in Step 1? Let's use Python to read in the spectrum and perform a fit.

    Follow along in the Jupyter Notebook:

    SpectralFit.ipynb (Contained within HARP.tar.gz)

    If the line width was due entirely to thermal motions, you might expect that it will be the same as the speed of sound within the molecular cloud. Remembering that the sound speed, v_s, can be calculated by:

    $$v_s = \left(\frac{k_B T}{\mu m_H} \right)^{\frac{1}{2}}$$

    where k_B is Boltmann's constant, T is the temperature, μ is the mean molecular weight, and m_H is the mass of hydrogen, **assume a temperature of 15 K and a mean molecular weight of 2.3 and calculate the speed of sound. Compare it to your measured line width.**

    What might explain the difference between your calculation of the sound speed and the measurement of the line width in this molecular cloud?

Part III: Dust Fraction Map

Emission in SCUBA-2' 850 and 450 micron bands can be affected by the emission from molecular lines. At 450 μm, the centre of the bandpass filter at 664GHz is close to the 12CO(J=6-5) line (at 691.473 GHz). At 850 μm the centre of the bandpass filter at 347 GHz is close to the 12CO(J=3-2) line (at 345.796 GHz).

It is often important to disentangle the dust emission from the gas emission so you can calculate the physical characteristics of the dust with more accuracy (for instance, to calculate the masses of star-forming cores, which relies on a knowledge of the flux coming from dust alone!).

We can use CO observations from HARP taken in the same region as Dust observations from SCUBA-2 to subtract the gas from the dust. This subtraction relies on a conversion factor, C, to convert the CO flux from K km/s to mJy/beam. C depends on the amount of water vapour in the atmosphere at the time of the observations:

$$C = \alpha + \beta(PWV) - \gamma(PWV^2) + \delta(PWV^3) - \epsilon(PWV^4) \text{ mJy/beam (K km/s)}^{-1}$$

Where the coefficients differ for 450 and 850 μm:

coefficient	850 μm	450 μm
α	0.574	0.761
β	0.1151	0.0193
γ	0.0485	0.0506
δ	0.0109	0.0141
ϵ	0.000856	0.00125

1. G34_HARP.sdf contains an integrated intensity map in raw units of $T_A{}^*$. First, let's convert this to units of main beam temperature, $T_{MB} = \dfrac{T_A{}^*}{\eta_{MB}}$. η_{MB} is the efficiency of the main beam of the instrument+telescope combination, as found by measuring sources with known properties that are of similar size to the beam (Jupiter, Uranus or Mars).

    For the JCMT+HARP, we have determined that $\eta_{MB} = 0.64$.

So, to convert G34_HARP.sdf from units of T_A* to units of $T_{MB} = \dfrac{T_A*}{\eta_{MB}}$, we just need to divide the whole map by the value 0.64. We can do this using Starlink's *cdiv* (divide by a constant) command:

%cdiv G34_HARP.sdf 0.64 out=G34_HARP_Tmb.sdf

This gives you a new map called G34_HARP_Tmb.sdf.

2. Next, we need to convert T_{MB} (K km/s) into mJy/beam to match our SCUBA-2 data. To do this, we need to calculate C on the previous page. We are dealing with 850 μm data and the PWV on the night of the HARP observations was: 0.108 mm. Once you have calculated C, we can multiply our T_{MB} map by that value using, you guessed it, *cmult*:

%cmult G34_HARP_Tmb.sdf <YOUR C VALUE> out=G34_HARP_mJybeam.sdf

3. Next, we can align our HARP map to the SCUBA-2 map (so that it has the same pixel scale and covers the same region) by using the command: *wcsalign*:

%wcsalign G34_HARP_mJybeam.sdf out=G34_HARP_mJybeam_align.sdf
  ref=G34_SCUBA2.sdf

Compare G34_SCUBA2 with G34_HARP_mJybeam_align: comment on similarities and differences.

This is as far as we will go today, but after we have the HARP map in mJy/beam and align it to the SCUBA-2 data, we can convert it to SCUBA-2's raw units: picowatts and multiply the whole map by -1. Then, we re-reduce the SCUBA-2 map from scratch, adding the negative HARP map to the *raw data* to perform the subtraction.
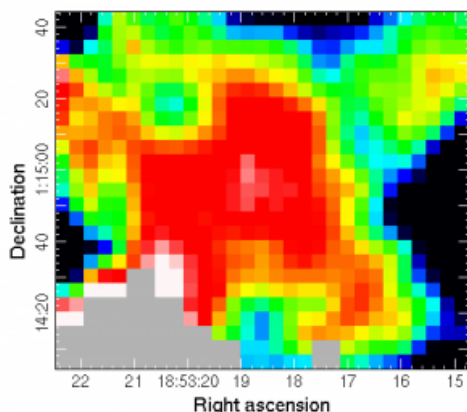
This is an image of the CO-subtracted SCUBA-2 data divided by the original SCUBA-2 data for a part of G34.

It is coloured on a linear scale from 0.95->1.0.

Questions/Plots:

Part I

1. At what velocity is the peak of the spectrum (approximately)? The central frequency of this observation is 345.7959899 GHz - use this value as λ_{avg} since it will be a good approximation. Calculate the frequency associated with this velocity.

2. Submit an animated gif centred on the main emission.

3. What has happened to the velocity resolution after you rebinned? What has happened to the signal to noise?

4. Submit a screenshot of your integrated intensity map.

5. Submit a screenshot of your channel maps

Part II

6. What is the noise in the spectrum?

7. Approximate the Full Width at Half Maximum of the emission line in SPLAT

8. Measure the Full Width at Half Maximum of the emission line by fitting a Gaussian to it in Python. What is the measured Full Width at Half Maximum?

9. Assuming a temperature of 15 K and a mean molecular weight of 2.3 and calculate the speed of sound in the Horse Head nebula and compare it to your measured line width. What might explain the difference between your calculation of the sound speed and the measurement of the line width in this molecular cloud?

Part III

10. Compare G34_SCUBA2 with G34_HARP_mJybeam_align: comment on similarities and differences. (Attach screenshots of the two maps).

References to use:

★ Slides from the lab:
https://www.eaobservatory.org/~s.mairs/ASTR351/slides/ASTR351L_HARP.pdf

★ HARP Calibration:
https://www.eaobservatory.org/jcmt/wp-content/uploads/sites/2/2015/01/HeterodyneCalibrationPresentation.pdf

★ Conversion from K km/s into mJy/beam:
https://www.eaobservatory.org/jcmt/instrumentation/continuum/scuba-2/contamination/

★ Subtracting HARP Maps from SCUBA-2 Maps:
https://www.eaobservatory.org/jcmt/science/reductionanalysis-tutorials/scuba-2-dr-tutorial-5/