

Orion-Eridanus Superbubble Imaging

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Abstract

In this lab we work with the 3.6 *m* dish from Leuschner Observatory, measuring the 21 *cm* line emissions from atomic hydrogen (HI), an abundant element in our galaxy. Analysing features of this line, we create an image of the Orion-Eridanus Superbubble, by using the total flux from HI lines to measure the thickness of a Hydrogen column, and evidencing the bubble shell from the center to the edges. The methods for tracking, recording and treating the data are presented and the choices justified. The final result is the image of Fig.?, made with ≈ 500 points, mapping the sky from galactic latitude -60° to -10° ($b = -10^\circ \rightarrow -70^\circ$ (JD)), and galactic longitude from 160° to 220° ($l = 160^\circ \rightarrow 220^\circ$ (JD)).

1 Introduction

In Radioastronomy, one of the greatest advantages is the hability of radio antennas on observing the hyperfine energy transition of neutral Hydrogen (HI), known as the 21 *cm* line, or 1420.4 *MHz*. This feature is largely explored due to the fact that this element is present in the whole universe, and many structures are comprised of molecular hydrogen. We explore this fact using the Leuschner dish (Fig.1) to measure the spectra of a large scale structure, and identify the HI lines to obtain a direct measurement of the quantity of this element.



Figure 1: A picture of the 3.6 *m* Leuschner dish used for this lab. Credits: Casper website.

Severall codes were developed, and the steps to obtain an image of the bubble, devided among the members of the group *Daveandpals* (Davud Galbraith, Kyle Moses, Eduardo Herrera and Leonardo Sattler), are presented in this article on the following steps:

On Section 2 we introduce the physical concepts and some of the equations underlying the physics of our measurements and data acquisition.

On Section 3, we present the aimed points in the sky and some of the math behind the construction of our grid of observation.

On Section 4, an overview of the developed codes is presented. We show the steps from data acquisition until the data calibration, before heading to the imaging task.

On Section 5 the data calibration and noise correction is discussed, before heading to the image construction. On the following Section the image is presented and its features discussed.

2 The Physics of The Bubble

The Orion-Eridanus Superbubble is a large cavity inside a huge hydrogen cloud, formed by stellar winds and the supernovae from Orion OB1 association, a group of several hot giant stars of spectral types O and B. Its position in the sky, in galactic coordinates, ranges from -10° to 10° in galactic latitude b , and from 160° to 220° in galactic longitude l . Because the column density of H atoms of this structure is directly proportional to the intensity of the 21 cm line, we use this transition to map the and build an image of its clouds. The equation used to measure the intensity of the lines was

$$N_{H1} = 1.8 \times 10^{18} \int T_B(v) dv \text{ cm}^{-2}, \quad (1)$$

where N_{H1} is the column density of H atoms, T_B is the brightness temperature of this transition, being a function of the velocity of the clouds v produced by the Doppler effect. We use the approximation $N_{HI} \approx \sum T_B(v) \cdot \Delta v$, where Δv is defined as follows for the 21 cm line:

$$\Delta = -c \frac{\Delta \nu}{\nu} = 0.31 \text{ km s}^{-1}. \quad (2)$$

With that, our task is to collect the spectra of a region in the sky that contains the Superbubble, integrating at a certain time the signal from points within a certain range, and also taking noise measurements to calibrate the data before calculating the column density. This work is described on the next section.

3 Points in The Sky

In order to build an image of the region of interest in the sky ($b = -10^\circ \rightarrow -70^\circ$ (JD), $l = 160^\circ \rightarrow 220^\circ$ (JD)), we define the measurement spots with a $\Delta b = 2^\circ$ degrees spacing within the galactic latitude values, giving a total of 30 points in latitude, and, for the longitudinal measurements, we define our spacing in terms of the b values as follows:

$$\Delta l = \frac{2^\circ}{\cos(b)}, \quad (3)$$

a foreshortening for observers of latitudes different than zero, since we can go over a full circle by fewer steps (if $b = 0^\circ$, no step is needed!). This will give us different number of longitudinal points per latitude value, ranging from around 11 points for $b = -70^\circ$ and 30 $b = -10^\circ$. The choice of 2° spacing is to achieve a good resolution by sampling 2 times per HPBW (Half-Power Beam Width), also known as the Full Width at Half Maximum (FWHM), which is $\sim 4^\circ$ for this dish. About the observation time spent at each point, it followed the sequency: 2 observations of 1 min and 20 sec to collect information about the HI spectra, and 2 other observations of 10 sec to collect noise measurements in order to calibrate the data. More information about calibration is presented on the following sections.

The Orion-Eridanus Superbubble stays visible in our sky (Longitude: $-122^\circ 09.4'$ East, Latitude: $37^\circ 55.1'$ North, Leuschner location) from around 11 pm until 9 pm, when all our target points set, so our observation schedules respected this window of time, calculated by a developed *Python* code. Besides that, our timing had to respect some altitude limits above the horizon due to some obstacles as trees and mountains, illustrated on Fig.2.

Our object in the sky should be represented by around 694 points, but due to timing issues this aimed numbers were revised, and although this range is displayed on the images presented on this article, the actual number of samples had to be redefined, and also the range of observation. To begin with, since we knew where to find the main features of the Orion-Eridanus Superbubble, we neglected observations in latitudes in the range $b = -70^\circ \rightarrow -60^\circ$, and $b = -12^\circ \rightarrow -10^\circ$. Also, since we aimed a full cover of the structure, we unfortunately had to downsample our observations to 4° spacing on longitude values, by skipping each calculated point of observation, and this resulted in a poor resolution image. However, the integration time for the spectra aquisition was the same throug all observation and remained as previously stated. A scheme of the final checked and unchecked points (and also the skipped ones) in our grid is presented by Fig.3. The green dots are representing the points we completely ignored, so we didn't try to collect any information about that region.

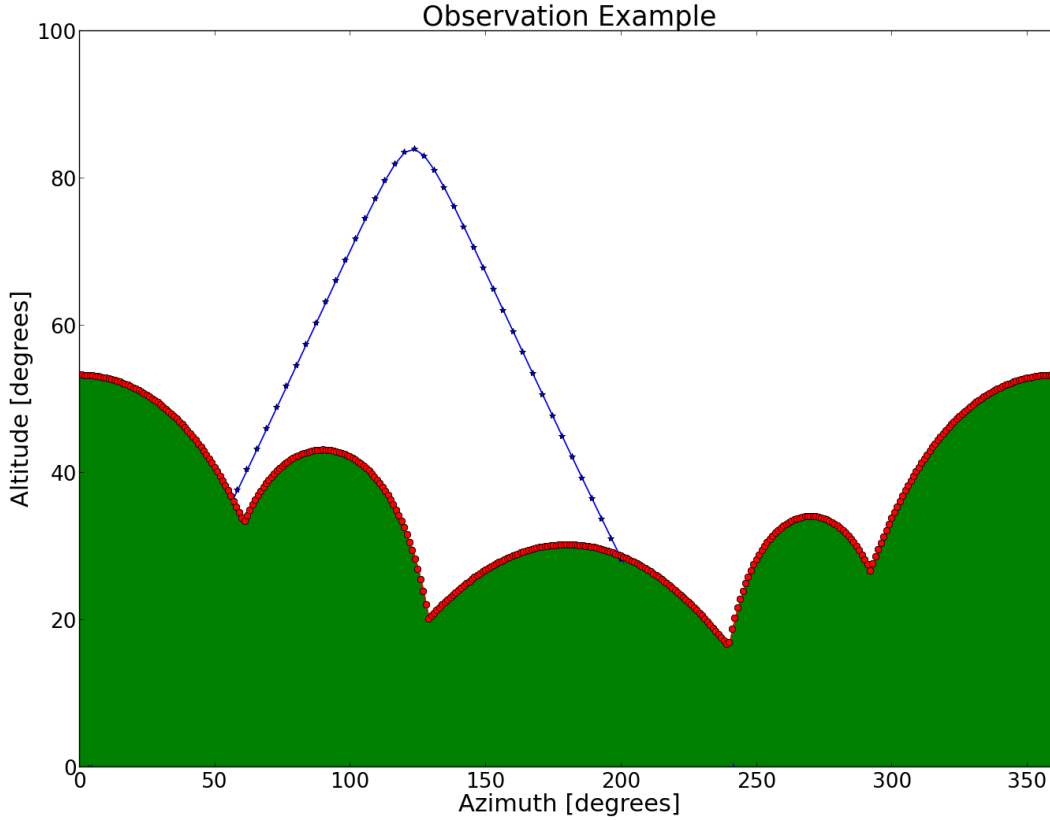


Figure 2: An Example of a day of observation, where the red dots mark the limit due to some local obstacles (at Leuschner Observatory) The star indicates the evolution of an aimed point in our grid in the course of a day.

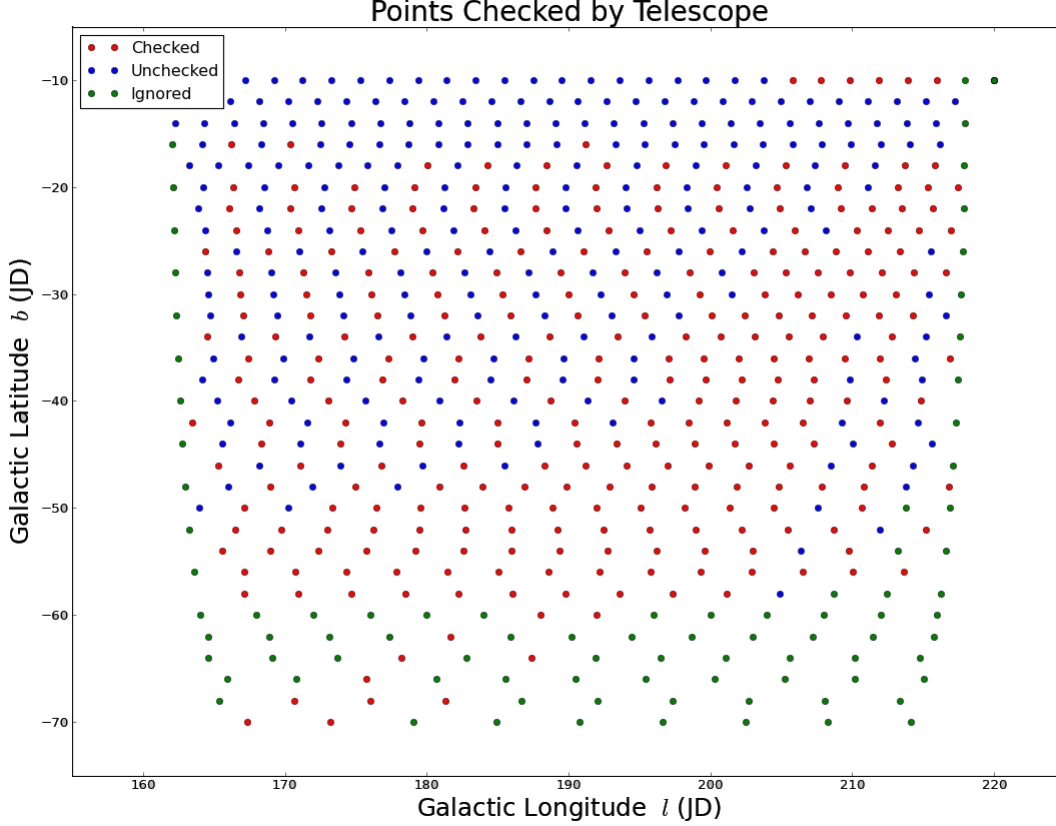


Figure 3: A grid of the points checked in the sky as a result of our observations. The blue ones correspond to the points we were about to check, but we didn't manage to collect the spectra of these positions. The red ones we were able to collect, and the green ones we ignored in order to optimize the information about the bubble collected in our observation time. As a result, our grid had around 400 points about the Orion-Eridanus Superbubble.

4 Controlling Leuschner

The whole data acquisition was made by *Python* scripts that tracked, set the telescope functions and saved the data files. A telescope control code worked together with a rotation matrix function, that changed the *Galactic Coordinates* of our points into *Horizontal Coordinates*, so that the dish could track, since the telescope function inputs must be *Altitude* and *Azimuth*. The codes and the math behind it was previously developed for the *Interferometry Lab*, and the details for the matrices construction and how they were applied is well described by the article on the following link: [git hub account](#), `lab_interf` folder. With the need of a conversion from Galactic Coordinates, an additional step was added, making use of the following matrix provided by the casper website:

$$\mathbf{R}_{(\alpha, \delta)2000 \rightarrow (l, b)} = \begin{bmatrix} -0.054876 & -0.873437 & -0.483835 \\ 0.494109 & -0.444830 & -0.746982 \\ -0.867666 & -0.198076 & 0.455984 \end{bmatrix}, \quad (4)$$

which is a conversion for the *epoch 2000*. The *PyEphem* and *radiolab* module were used to perform some calculations.

In fact the inverse of the previous matrix was used, and the following matrix operations were applied to get the desired points in the sky:

$$\mathbf{R}_{(l, b) \rightarrow (az, alt)} = \mathbf{R}_{(ha, \delta) \rightarrow (az, alt)} \cdot \mathbf{R}_{(\alpha, \delta) \rightarrow (ha, \delta)} \cdot \mathbf{R}_{(l, b) \rightarrow (\alpha, \delta)}. \quad (5)$$

For the antenna control, besides these modules, the following ones were used: *dish*, *dish-synth* and *takespec*. The first one was used to perform the movements of the telescope, as the tracking and homing, just turning the the noise diode of the telescope on and off, for purposes of measuring the instrumentation noise for data calibration. Only one homing was necessary (in the beginning of each observation), and the tracking was made after finding the position in Altitude and Azimuth, in degrees, for each point of interest. The second one was used to set some values to the dish, as amplitude and frequency for the Local Oscillator. The LO (Local Oscillator) frequency was 1272.4 MHz , and the amplitude was 10 dBm . The last module takes the data and save in *.log* files, later written with the module *readspec.mod*. At the end of each pointing procedure, we ended up with 4 different files later used to perform the calibration, discussed in the next section. All the codes for tracking and controlling the Leuschner dish can be found here.

5 Data Calibration

In order to measure the column density by analysing the HI line profiles, we first treat the data using the 4 files created for each point. They were the *Noise_On*, *Noise_Off*, *Spectra_On* and *Spectra_Off*, meaning that we took 2 spectra profiles: one 'On' our target line, and another 'Off' by -4 MHz . Together with these 2 spectra measurements, we recorded a noise for both instances, hence *Noise_On* (recording the noise 'On' the spectra) and *Noise_Off* (for the case we are off by 4 MHz).

The math to calibrate the data is presented on the handout provided by the Radiolab instructors, *Calibrating the Intensity and Shape of Spectral Lines*, by Carl Heilies. Several steps were performed by using the so called *cool method*. Basically, with all these measurements, if we plot them on a same figure we end up with 2 distinct peaks, and they are off by the value set on the data aquisition for the LO (4 MHz), where the 'On' measurements are around the value of 1420.4 MHz , as expected. Besides them, we have 2 spectra of the same profiles but with much higher intensity values. These are the noise values, used to calibrate the HI profile by correcting the instrument temperature. An example is shown in Fig.4.

After the corrections from the band pass filter shape and all the added amplitude, related to the noise associated to our instruments, we have a single featured emission line, which is the 21 cm line from the Orion-Eridanus Superbubble region. One of its features is shown in Fig.5. As we know, many things can determine the shape of a spectral line. Basically, its position tells, at a first glance, about the elements from the observed source. In our case we expect to see some line around 1420.4058 MHz . Its width reveals how hot the cloud is, just as the velocity range of the particles from the cloud, due to Doppler effect. The Doppler effect can also give a lot of information about the speed of the structure as, for example, if it rotates or expands. The shape of the peaks, and how far they are from the expected emission line (the one measured at the laboratory, for example), will tell about this.

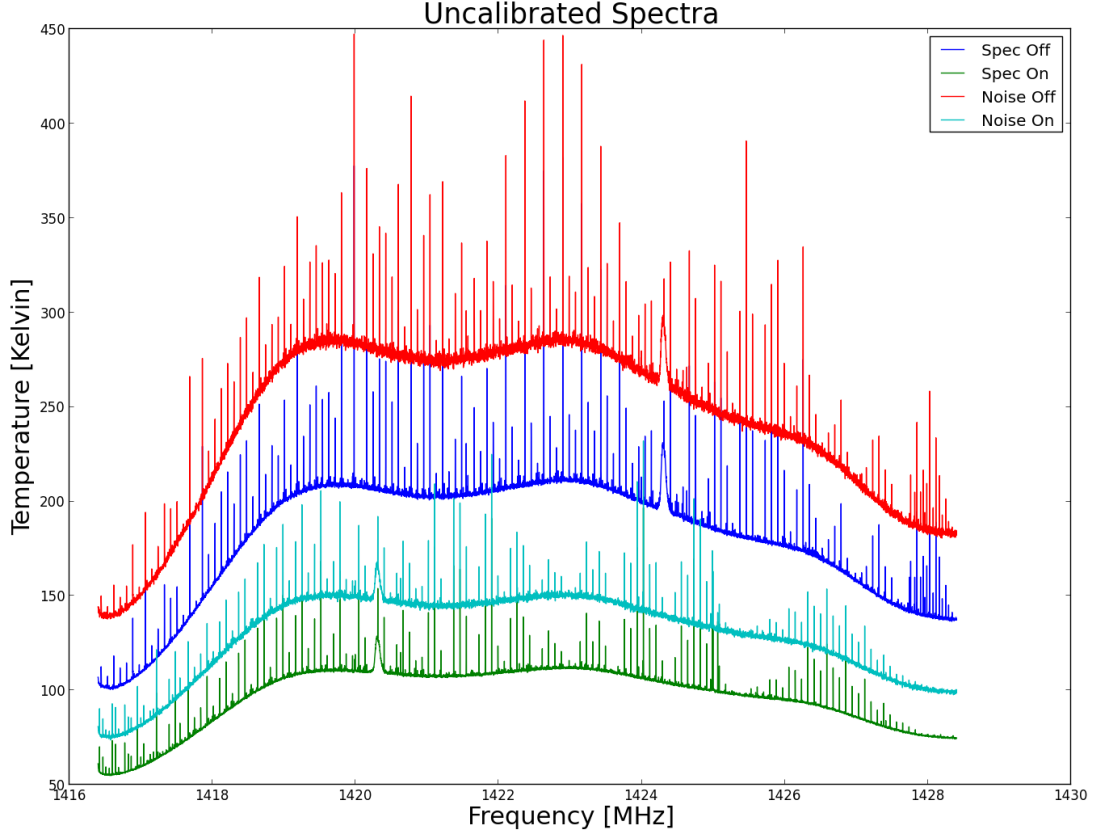


Figure 4: Figure showing the spectra for a point in the sky. These are the expected features for the observed points, presenting how our measurement looks like right before proceeding through the calibration. The noise measurements, as outlined before, surpass the *Noise Off* spectra. The several peaks are detections from the atmosphere and many other sources, due to the contamination of the city and other nearby emissions, for example. They are smoothed as a first calibration step. Besides those, we see the four distinctive peaks corresponding to our expected HI line emissions, that at this stage are dominated by all the noise present in our data.

As observed in Fig.5, the central peak is not quite at 1420.4 MHz , which means that the bubble itself has a mean velocity related to us. Also, some features of peaks rising to the right and to the left of the central value are observed, revealing an expanding shell around the cavity of the bubble, where the blueshifted spectra is an observation of material coming towards us, and the redshifted spectra is going away. In addition to that, we see a line with 2 peaks, which is probably the center of the expanding structure, showing both the approaching and distancing features (redshift and blueshift) along our line of sight. And, finally, a peak with no extra feature besides a single and narrow emission line, represents an observation around the very edge of the bubble, where no Doppler shift is expected at all.

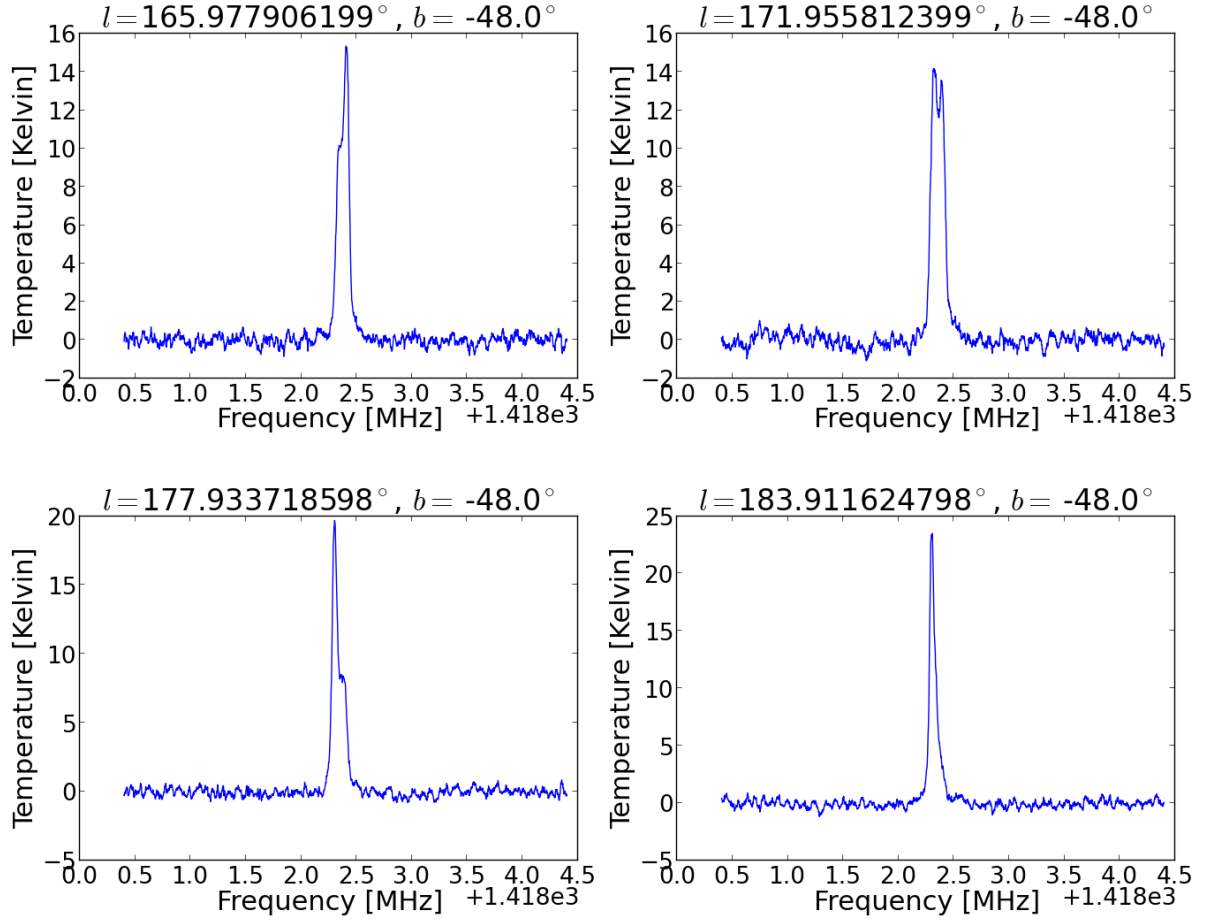


Figure 5: Figure of 4 calibrated spectra and its respective positions in the sky, in Galacti Coordinate (JD). These images show different features from the Orion-Eridanus Superbubble with respect to the Doppler effect. These lines represent observations near the center (upper right), with 2 shifted peaks, and on the very edge (bottom right), with no Doppler shift. The ones on the left represent portions of the cloud that are either expanding toward us (upper left) or going away from us (bottom left).

6 Final Image

As a result, after all the points were calibrated, by using the equations from Section 2, the final image of the Orion-Eridanus Superbubble is shown in the following pictures. The first one is how actually we see the bubble structure in the sky, respecting the grid constructed by the mapped points via Eq.3. We can compare with Fig.3 to in order to get a perception of the sampled points and which features they represent in our final image.

The second figure is a flat representation, with a rescaled grid to make a grid that can easilly show the position of each feature in the square grid. This is not actually how we see the bubble in the sky, but can help to indentify the l and b in order to work with this precise point, for purposes of reference or regions of interest, for example.

The construction of the images was made using a smoothing function, runing over a grid containing the integrated spectra of each point (resulting in a column density easurement via Eq.1). This smoothing was in fact a convoluitoin with a $2D$ gaussian function, containing a spreading factor with the size of half the resolution of the main grid. The result of this convolution was devided by the result of a second

convolution, from the same gaussian function with a grid containing only *ones*, placed at the same index values corresponding to those containing values different from zero in the main grid. This was done in order to normalize our first convolution, and the final result was more accurate in terms of how actually a point in the grid contributes for an intensity measurement.

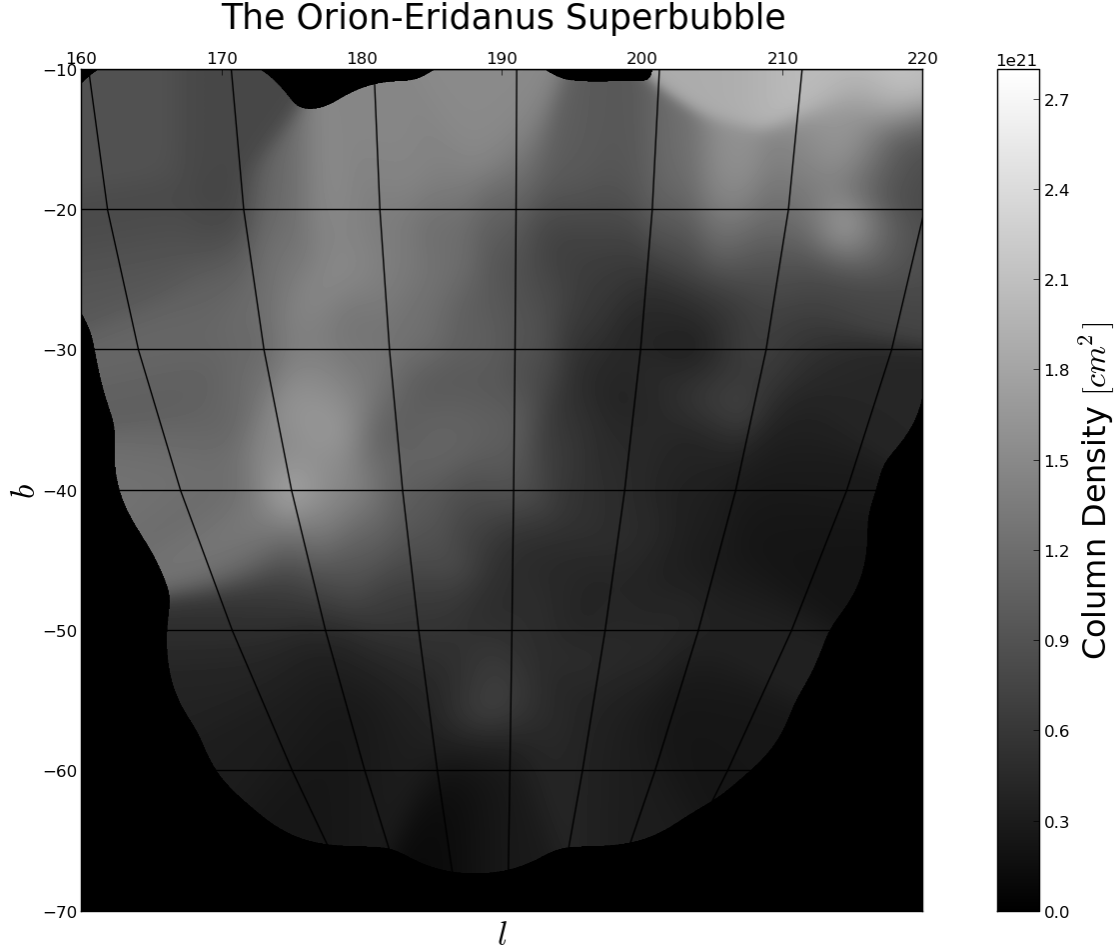


Figure 6: The Orion-Eridanus Superbubble, real representation. This image was constructed with a 2000×2000 grid by rescaling and replacing the points of the original grid illustrated by Fig.3. This main grid was then convolved and its convolution divided by a normalizing array. Many of the features of an expanding shell can be seen, just as a characteristic cavity surrounded by the cloud of Hydrogen. This thick cloud is the main source of emission of HI lines, leading to the measurement of the column density. We can observe that, in fact, in the center of the bubble there's a lack of material, what makes harder the detection of an expansion due to Doppler shift. The dark areas around the image show the lack of point information in our constructed grid, due to those that were neglected or those we could not achieve due to a limited time of observation. However, the main structure of the bubble can still be well observed.

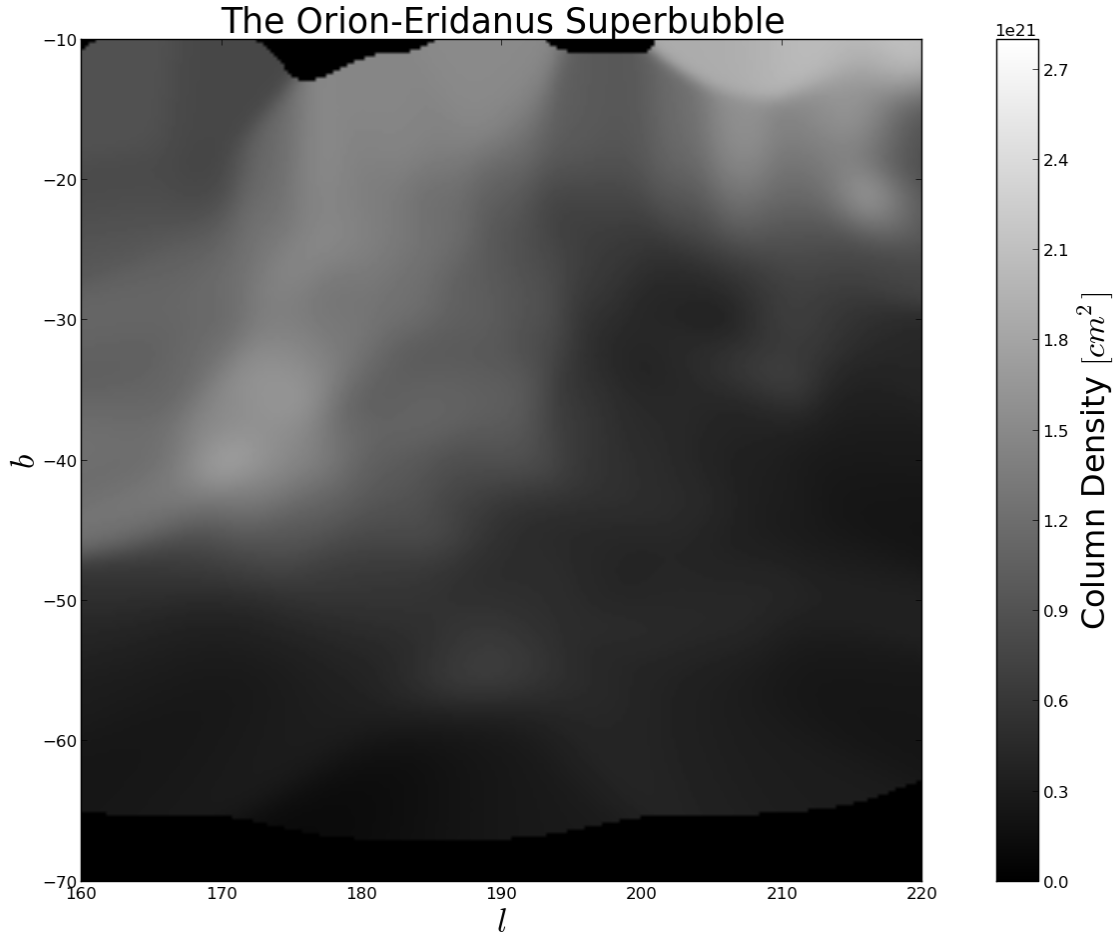


Figure 7: The Orion-Eridanus Superbubble, squared representation. This image was constructed with a 2000×2000 grid by rescaling and replacing the points of the original grid illustrated by Fig.3. This main grid was then convolved and its convolution divided by a normalizing array. At last, this grid was again rescaled to a square representation, in order to have a different representation of the same structure. Also, this image helps the comparison with the next figure also containing the Orion-Eridanus Superbubble, from A.G.A. Brown et. al. from the article *The Orion OB1 association*, build with data from the Galactic survey made with the 25 m Dwingeloo telescope, mapping the 21 cm emission line with a $36'$ beam width. Many of the features of an expanding shell can be seen and compared, just as a characteristic cavity surrounded by the cloud of Hydrogen. Again, we see a large amount of gas in the upper part, also meaning that we did not lose much information from the bubble by neglecting those points below $l = -70^{circ}$.

7 Conclusion

In this lab, we were able to accurately take and calibrate the measurement of intensity from a structure of Hydrogen, as shown by Fig. 5, where we can easily observe the 21 cm emission line and the features related to the structure it came from. Also, it means that the rotation matrix developed to take the data, just as all the telescope control scripts, were well built and in deed work.

The measurement of Hydrogen column density, in order to create an image, and all the procedures to finally create a grid with the information from all the points checked by the telescope, can be compared with the following picture, from A.G.A. Brown et. al. 1995, ApJ.:

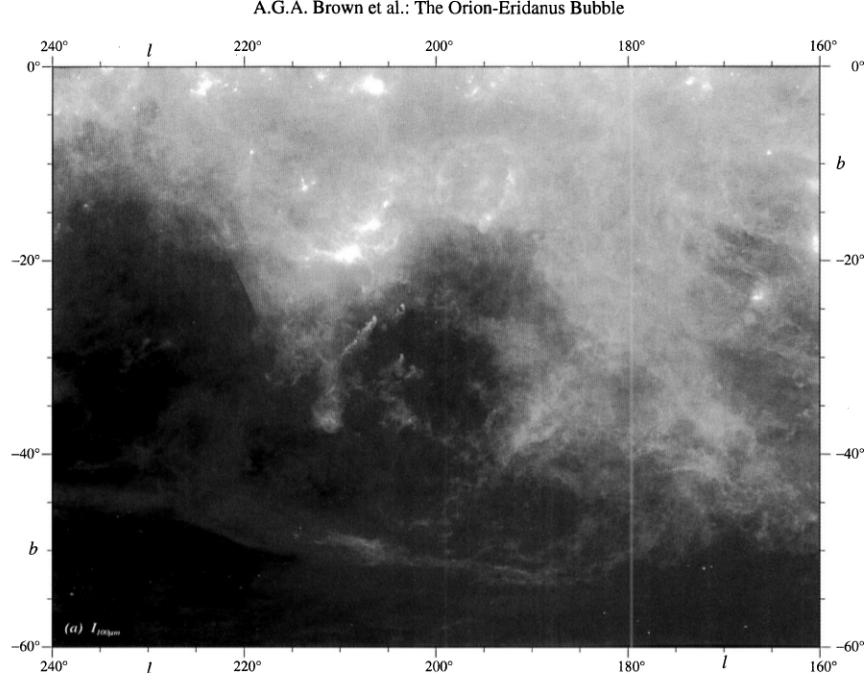


Figure 8: Image of the Orion-Eridanus Superbubble, build with data from the Galactic survey made with the 25 *m* Dwingeloo telescope, mapping the 21 *cm* emission line with a 36' beam width. The points in the sky are basically the same, the only difference is that here the longitude axis range from $l = 240^{\text{circ}} \rightarrow 160^{\text{circ}}$, being flipped if compared to the same axis of Fig.7. The overall shape of the bubble can be detected on both Fig.'s 6 and 7, by comparing them with this high resolution image. This indicates that the whole process, from data aquisition, untill the construction of a final grid containig the calculated column density, was accurately done, and despite our poor resolution conditions, our image is correctly illustrating the Orion-Eridanus Superbubble.

By comparing the last two images, knowing that their longitudinal axis grow in opposite directions, we are actually able to see the overall shape of a bubble and even the main features around its center. This basically shows that the procedure to get, treat and work with the data was well performed, and although we have a low resolution image, Fig.s 6 and 7 are acceptable representations of the Orion-Eridanus Superbubble.

Also, is a goal of the *Daveandpals* group members to achieve a higher resolution by taking more data as soon as possible, and also exploring the Doppler information present in our data, in order to evidenciate the parts of the bubble that are moving away from us and approaching us and plot this feature. Also, this could be another option for measuring the density of material on the observed region of the sky.