Astronomy & Astrophysics manuscript no. main
August 31, 2016

Lab 4

Mapping the HI Line: A Big High Velocity Cloud

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August 31, 2016

ABSTRACT

Three moving clouds near the North Celestial Pole were imaged in both density and velocity using 21 centimeter line data from the Leuschner radio telescope. All three clouds are infalling towards the galactic plane, moving between 0 and 100 km/s. A fourth, fainter cloud of higher velocity was imaged in density only. Results match with observations of a similar object by the Temple Bars Research Group and all images show enough structure to qualify as successful cloud detections.

1. Introduction

The universe is full of hydrogen. Hydrogen is the simplest element and needs no other synthesis besides the pairing of a proton and an electron. This naturally leads to hydrogen being the most abundant element in the universe, whether it's fueling stars, locked in a planetary atmosphere, or floating through a galaxy in a cloud.

Hydrogen has a number of useful spectral lines that astronomers love; radio astronomers in particular are infatuated with the HI line. The HI line, also known as the 21 cm line, is an interesting hydrogen emission caused by a "forbidden" transition[1] in the ground state of hydrogen. The line, at about 1420.4 MHz, is often clearly visible in radio data and ever-present in the universe[2], so many radio astronomers use it to characterize the column density and range of velocities along some line of sight. By taking data along many lines of sight, impressively informative quasi-3D[3] density and velocity maps of hydrogen distributions in the universe can be produced.

The Hail Sagan Research Group selected an object known only to the group as the "Big High Velocity Cloud" and mapped its hydrogen content across 3700 square degrees. The project encompassed planning and executing the observation of 942 points in the sky in a time- and resource-efficient manner, cleaning and analyzing the data to pick out several different moving clouds of hydrogen, and mapping the data onto clear and helpful images.

1.1. Projections

This project involved deciding on a projection of the data onto a map. Everything the group is able to observe is inherently spherically curved, due to the nature of sight[4], but the objects on which the data is projected, such as sheets of paper and computer screens, are inherently flat. This raises some issues in how one should go about this projection, especially when the data cover a large solid angle and so have a lot of inherent curvature.

An extreme case is that of a world map. The surface of the Earth is spherical and lends itself to all kinds of failures of flat geometry, such as the fact that one can start walking a quarter of the way across the Earth in a straight line, make a 90 degree turn, walk another quarter, make the same 90 degree turn, walk a third quarter, and end up where he or she started. Non-commutative geometry evidently doesn't play well with flat planes; that example would be difficult to demonstrate on a sheet of paper.[5] A number of different projections exist; some project a sphere directly onto a plane, like the gnomic or stereographic azimuthal projections, and some "unwrap" a cylindrical projection, like the Aitoff or sinusoidal pseudocylindrical projections. Each projection has some benefits, some more than others, but all have one crucial detail in common: they sacrifice something as well. No projection is perfect and all must give up some aspect of accuracy in favor of another. It is up to the cartographer to choose the most appropriate projection for the job.

This project will use the sinusoidal projection, for reasons that will be discussed in more detail later. Most importantly, the area observed here was wide in longitude but relatively narrow in latitude; this lends itself to a pseudocylindrical projection, since the longitude should be preserved and the curvature of the change in latitude doesn't make too much of a difference. Had the project involved a large range of both latitude and longitude, a different style of projection may have been more appropriate.

[1] A transition that is not allowed under some general approximation but may occur after another level of correction to the initial approximation

[2] Because of all the, you know, hydrogen

[3] While radial velocity is evident from Doppler shift, radial distance isn't

[4] This is interesting on its own, but that's an entirely different discussion

[5] Well, not really, but we'll assume some suspension of disbelief

2. Observations

An area of galactic longitude l : 60 to 180 and latitude b : 20 to 60 was selected for observation. The group decided on a point spacing of 2° in latitude and $\frac{2^{\circ}}{\cos b}$; this lends itself to the sinusoidal map projection mentioned in the last section, since a sinusoidal projection is defined such that the horizontal distance goes as the cosine of vertical displacement from the equator. Additionally, lines of constant latitude are straight across the image, which does its part in preserving object shape.

2.1. The Points

The desired spacing led to 942 points. These points were transformed using the `GLACTC` procedure into equatorial coordinates and then through a previously utilized matrix algebra method to horizontal coordinates. The object happened to surround the North Celestial Pole, which simplified some of the observation; much of the object was always in the sky. Yet since some points still set, and the order of point creation was entirely arbitrary, some order had to be established. The desired order was a simple priority assignment based on how often the point was in a comfortable observing range. The comfortable observing range was decided by the specifics of the telescope antenna.

2.2. The Leuschner Dish

The Leuschner radio dish lies at `37.91934 N, 122.15385 W`, just a few miles north of Lafayette, CA and about 7 miles east of Berkeley, CA[6]. The telescope has certain limitations on motion; it cannot move above 85° or below 14° altitude, nor can it cross the 0°/360° boundary; it must make a full revolution. This places some hard limits on the parts of the sky it can observe.

The surrounding area places some other hard limits on the observing area. There is a wide hill to the north of the dish, extending from about −60° to 60° azimuth and from the horizon to about 23° altitude. The part of the hill on the positive half of 0° azimuth extends much higher, to nearly 40° altitude, making observations in that entire region much more difficult.

After considering all limitations, the group decided on an acceptable observing area of 280° to 359° azimuth and 25° to 84° altitude. This range avoids the high and low boundaries of telescope movement as well as the hill, and entirely avoids anything to the right (east) of 0° azimuth due to both the large hill and the 0°/360° boundary, thus limiting the amount of time the telescope can waste by moving across the sky[7]. Since the object of interest revolves around the North Celestial Pole, most of the object spends a lot of time within this range, and all of the object passes through this range at one time or another.

3 minute integration times were chosen for each point. The source in the sky is only about 1-2K in brightness, so some considerable integration time was necessary. The priority assignments and integration time were written into Leuschner-friendly IDL code and run throughout the course of two weeks for about 60 total hours.

Points were taken with two local oscillator settings: 1418.4MHz and 1422.4MHz. Pairs of opposite L.O. setting were matched up for calibration efficiency; one spectrum would serve as the offline spectrum for its partner, and vice versa. This did not end up being the best option; calibration was all done post-collection for reasons to be discussed later. No noise calibration was taken. The noise diode was malfunctioning and needed to be disconnected.

2.3. Initial Data Reduction

Data were collected as 942 YY-polarized spectra of 8192 channels each.

The XX polarization was discarded; it seemed to be corrupt, as it was often over 3 orders of magnitude weaker than the YY spectra and regularly drowned out in noise. Channel frequencies and `UGDOPPLER` outputs were derived from the Leuschner's save files and used to create LSR-corrected[8] channel velocities. Each spectrum was calibrated by fitting a polynomial to the local shape of the bandpass filter around the HI line using the `POLYFIT_MEDIAN` procedure[9].

The shape of the bandpass, and so the fit, were assumed to be 100K in intensity[10]. The spectrum was locally divided by the fit, so as to retain geometric ratios in the data, and then modified as $(spectrum - 1)\times 100K$ in order to get a final rough calibration. A calibrated spectrum is shown in Figure 3; the temperatures match the expected values of ≈1K for the smaller peaks and something around 5K for the ≈0 km/s peak. The entire process, letting yy be the raw spectrum and YY be the calibrated spectrum, looks like:

$$YY = \left[\frac{yy}{POLYFIT\_MEDIAN(yy)} - 1\right] \times 100K$$

Spectral features were fitted with the `GFIT` procedure, written by Berkeley's own Carl Heiles, which fits an arbitrary number of Gaussians to a data set, as in Figure 4. This procedure lends itself well to this usage, since it can be used to tell the location of peaks as well as whether they are significant or not. The location of the peaks was used to find the velocity of each feature.

The data were used for both column densities as well as velocities, which led to several different graphics. Column densities were calculated by summing the calibrated spectrum points over a given velocity increment dv of 40 km/s. The units are somewhat meaningless ($K \times km/s$) and not meant for numerical analysis; the diagram, as Professor Heiles once said, is meant to be processed by the computers in our heads. An animated 2D image of column density moving through velocity space from 50 km/s to -250 km/s was made; this involved creating a data cube, where 3 dimensions of data are stored: 2 spatial dimensions and 1 velocity dimension. The animation displayed both spatial dimensions and moved along the velocity axis.

2.4. Brief Note on Figures

Here it would be possible to discuss the art of creating effective figures. Brightness and color play a very important role in demonstrations, and an entire handout could be devoted to the topic. The group made effective use of color mapping, but a full discussion of the particulars would be too much of a departure from the astronomical content of the rest of the project, so that will be left for another time. The color images shown in this paper were generated using the `DISPLAY_2D` procedure, which

[6] 7 miles as the crow flies. Longer by car

[7] It is said to take about 2 minutes to make a full rotation, but we never had the luxury of time to test it

[8] Local Standard of Rest in our galaxy

[9] The median part helps discount noise during the fit, and the data were quite noisy

[10] A reasonable assumption

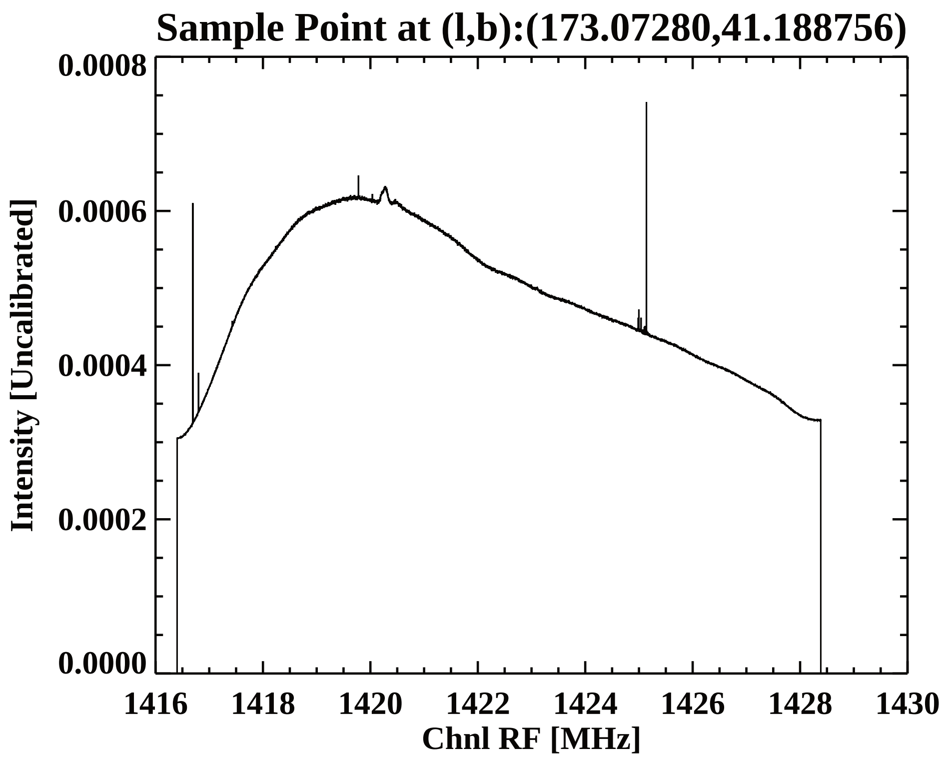

Fig. 1. Raw YY-polarized spectrum; this spectrum was evidently taken at an L.O. setting of 1422.4. The shape of the bandpass and some spectral noise is evident, but the HI line clearly visible at the top of the hill.

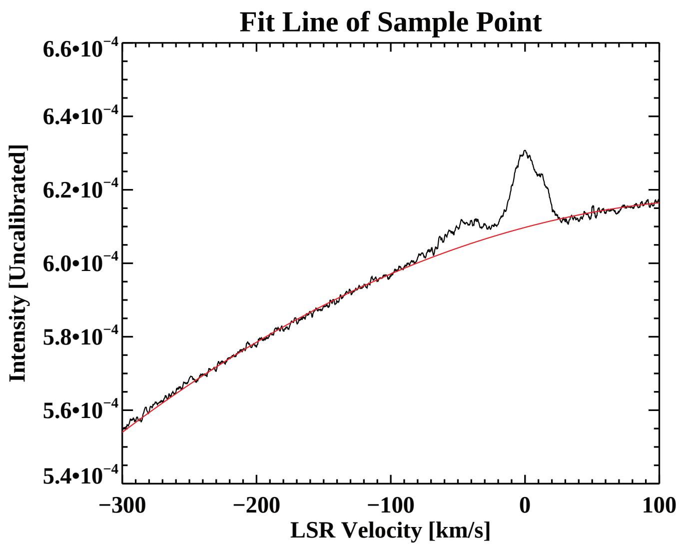

Fig. 2. The POLYFIT MEDIAN procedure produces an accurate fit to the local area of the HI line, which makes it possible to remove the shape of the bandpass. The fitted line is also assumed to be a constant 100K.

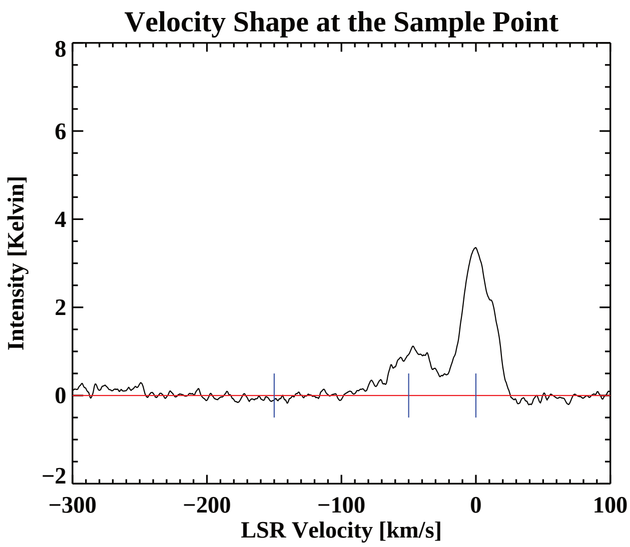

Fig. 3. The same spectrum from Figure 2 with its fit divided out. Both the fit and the spectrum were lowered arithmetically by 1 so that they are centered around 0K.

generously handles all the intensity and velocity plotting as well as the color bar.

3. Analysis

To very briefly summarize the data analysis, the signals were weak. The original subject of observation was a high velocity cloud moving towards the solar system at about 150 to 200 km/s[11]. The signal from that cloud was barely noticeable with the 3 minute integration times. While more time would have been preferable, a sacrifice was to be made either in integration time or in number of points, and the group chose to go for quantity over quality and sacrificed integration time. 180 second integration times were used and all 942 points were obtained. Using the LSR-corrected channel velocities, the group only noticed HI

[11] All velocities are LSR corrected. "Towards" is meant for directional reference

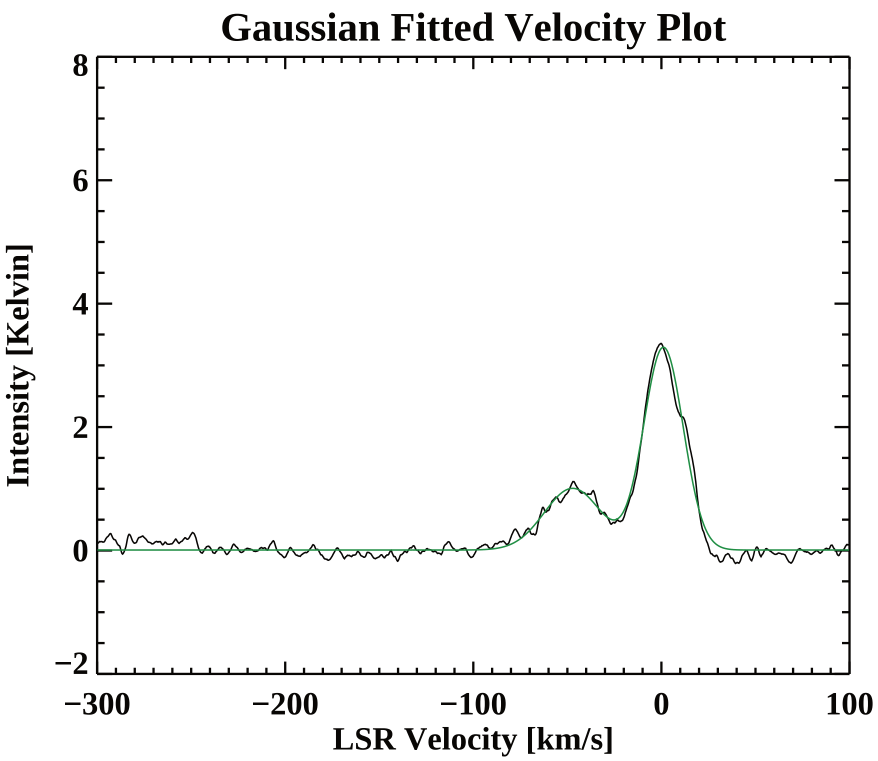

Fig. 4. Note the close fit of these two Gaussians to the two visible peaks in this spectrum. The centers and heights of the Gaussians are returned with the GFIT procedure and become useful in calculating velocity and peak intensity.

line signals corresponding to ≈-150 km/s in a small fraction of the points, and it was nearly impossible to computationally locate these peaks without devoting a disproportionate amount of time to that particular endeavor.

After some discussion, the group decided to switch focus to an intermediate velocity cloud moving towards the solar system at about 50 to 80 km/s. The signal from that velocity range was much more visible, and it was evident that there was some mass of hydrogen across the observation area there. Also clearly visible was an low-intermediate velocity cloud[12], moving towards the solar system at about 20 to 40 km/s, and a low velocity cloud with some near-stationary segments and other segments moving around 10 km/s. The group decided to fit three Gaussians to this data using the `GFIT` procedure, which worked remarkably well for most of the data. These three clouds were plotted in full 2D color. The plots will be included and discussed in the next section. A 3D plot of the clouds was attempted, but the `RGBIMG` procedure that the group intended to use was not fully understood at the time. The group would be highly interested in some further guidance in using this procedure, as a 3D image of these three clouds may be quite enlightening.

The column density animation shows the most hydrogen below galactic latitude $b : 40°$ or so, and in its limited scope, shows most of the gas density around 0 km/s. The velocity plots, which use both intensity and velocity to create a "2D" color image, tell a little more about the gas. These plots will be analyzed in more detail in the next section.

[12] Following a strictly practical naming scheme

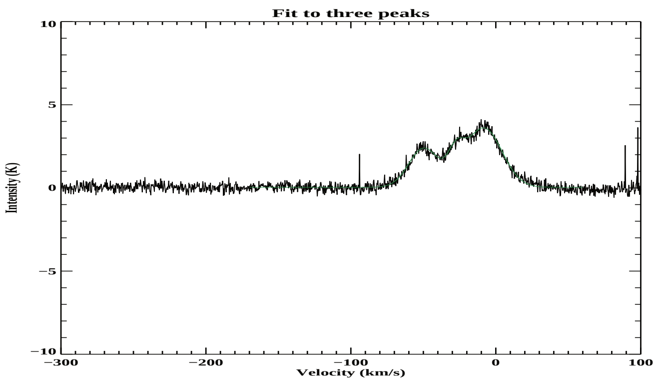

Fig. 5. Sample spectrum showing the necessity of the 3-peak fit. The third peak is obvious in this spectrum, somewhere around -20 km/s. In Figure 4, the dual-peak structure of the main peak is visible on the right half of the 0 km/s peak.

3.1. The High Velocity Cloud

It is unfortunate that the high velocity cloud was too dim in the data to be analyzed more properly. It did not go completely unobserved by the group, however; that will also be discussed in the next section. The primary issue with properly imaging this cloud was the fitting. The `GFIT` procedure was used to fit peaks, as mentioned in Section 2, and that method fails if a stronger feature is too close to the peak of interest. A noise spike or an odd feature on another peak could both catch the `GFIT` procedure before it notices the very low peak of the high velocity cloud. Furthermore, in cases where the high velocity peak was essentially nonexistent, the fit would catch any nearby noise immediately; one group member attempted to solve this issue by manually examining every spectrum and marking down the number

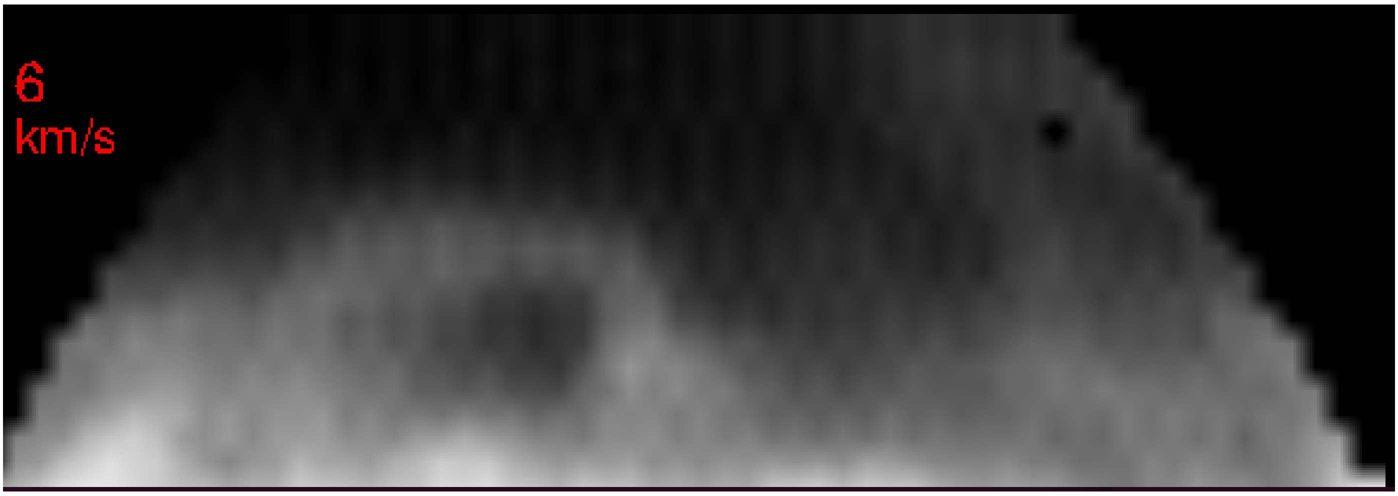

Fig. 6. This capture of the column density animation shows the gas traveling within 20 km/s in either direction (in velocity space) of 6 km/s. The brightest signals come from this region around 0 km/s, and some shape can clearly be seen. The dark spot slightly lower-left of the center of the image appears to fit the profile, in both shape and velocity, of the object imaged by the Temple Bars Research Group.

of peaks, which would be passed to GFIT. While this method could certainly work, the obvious issue is efficiency. That group member had to view 942 spectra and decide if each one had a high velocity peak. His dedication was admirable, but the data set could easily be hundreds of times that size in future projects, so it didn't seem to be a very effective method, nor could it be used consistently across all similar projects. The rest of the group deemed it computationally impossible within the time frame of the project. The group was very satisfied with the progress made with the other three clouds.

4. Results

Three moving clouds were mapped: the Intermediate Velocity Cloud, the Low-Intermediate Velocity Cloud, and the Low Velocity Cloud.[13]

The Low Velocity Cloud appears to be a stationary cloud; it has velocities on both the positive and negative side of 0 km/s, implying that the velocities are artifacts of random particle movement, although it does occasionally appear to lean more towards the negative (infalling) side. Most of the gas observed is contained in this cloud, as seen in Figures 6 and 7. The gas here is moving at 0-10 km/s.

The Low-Intermediate Velocity Cloud is moving at something around 20 km/s, infalling. The data show a different structure to this cloud; it appears to be missing structure around 100° to 140° longitude and 20° to 35° latitude. The slower-moving (redder, in Figure 8) portion at $(l, b) = (140°, 40°)$ is likely just part of the Low Velocity Cloud that was caught in this cloud's image data. It is evident that this gas is moving faster than the Low Velocity Cloud, but not as fast as the Intermediate Velocity Cloud[14].

Finally, the Intermediate Velocity Cloud was found around 50-80 km/s. Figure 9 shows the structure of the cloud; it is distinct from both the Low and Low-Intermediate Velocity Clouds; it fills out the lower latitude more than either of them and is evidently traveling a lot faster. Most of the gas here is moving at an average of 60 km/s, but the bluer regions of Figure 9 show some gas moving around 80 km/s. The red regions in this plot are areas where the fitting failed; the analysis worked very well, but was not absolutely perfect.

The High Velocity Cloud was too difficult to map using the GFIT procedure, so it was not possible to construct a velocity map of the object. However, the "computers in our brains" were able to detect it in the column density animation. Some structure of the High Velocity Cloud is shown in Figure 10 The brightness of Figure 10 had to be freed from the brightness scale of the animation, making the image very all-around bright. With enough contrast, one can see some structure slightly above the center of the image; this would have been too weak for a computer to detect (within the scope of the project) but is enough for the human eye.

5. Conclusion

Three distinct clouds were mapped. The Low, Low-Intermediate, and Intermediate Velocity Clouds showed up clearly in the data, but the High Velocity Cloud proved to be much more elusive. Nevertheless, the High Velocity Cloud was still imaged via column density.

Clouds like these are common in the galaxy. The galactic rotation likely throws these gases slightly out of the galactic plane so that they end up falling back towards the plane. It is important to note that the velocities measured in this project are *projections* along an observer's line of sight of the actual velocities. The clouds are likely rotating around the galactic center about as fast as the solar system or anything else in the galaxy[15], so the velocities measured here are likely line-of-sight projections of an LSR-corrected velocity approximately perpendicular to the galactic plane.

This project not only yielded some impressive 2D color images of three different hydrogen clouds, but also evidenced the importance of the HI line in radio astronomy. With a single dish and 60 hours, the group was able to measure the column density and velocity of these clouds and image them. Even the High Velocity Cloud couldn't fully escape detection. In the future, the group hopes to utilize the HI line to its full potential, given more time, resources, and knowledge of IDL, and perhaps complete the 3D image of the three clouds.

[13] All names were assigned by our group; none of them are official
[14] Hence the name
[15] In terms of angular velocity

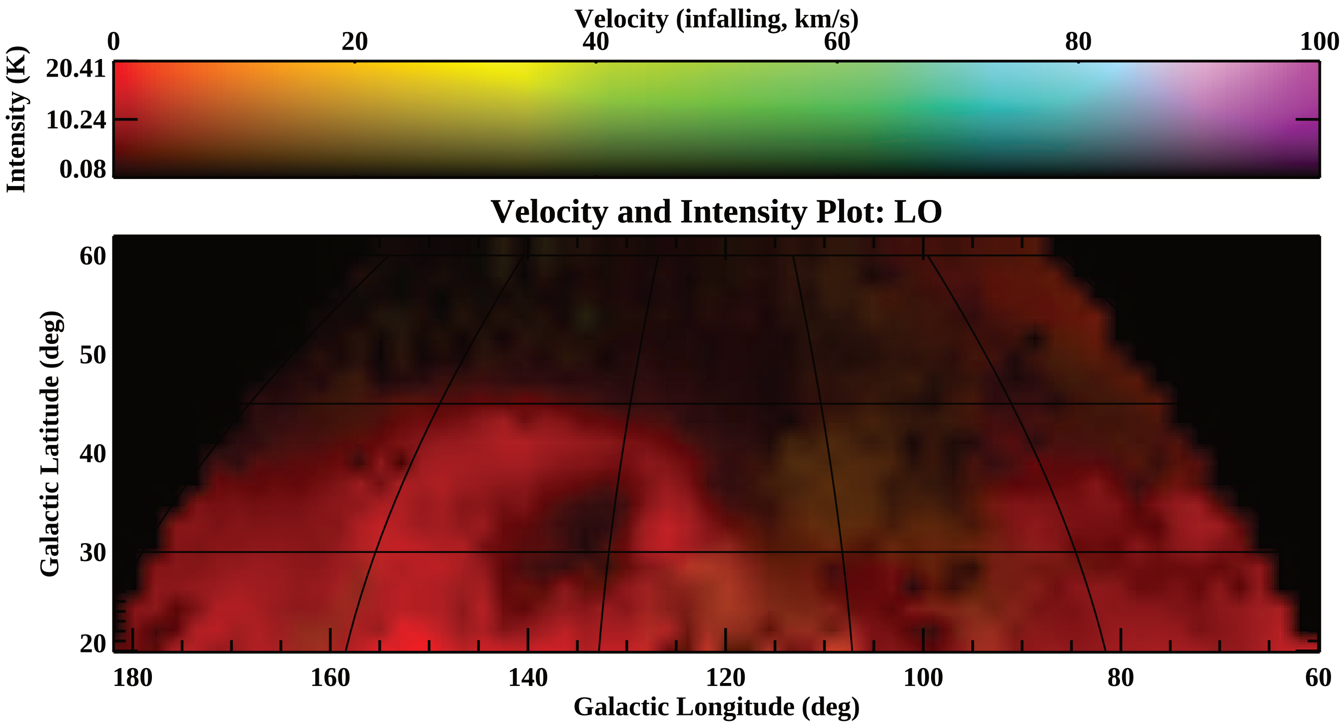

Fig. 7. The Low Velocity Cloud, in 2D (brightness and intensity). The intensity scale is not truly in Kelvins, but is meant to be taken more symbolically for comparison with the other clouds. Note the brightness at around 20 units in some areas.

6. References

Thanks is due to:

- Lab Partners Robert Bentley and Sam Wishnek, without whom I would have never caught any of my typos. I appreciate your patience and hard work and hope to see you in the field.
- Professor Carl Heiles, who shared with us his extensive knowledge of IDL, radio astronomy, circuitry, astrophysical intuition, and computer advice. I'll be sure to keep many backups of what we did in this lab.
- GSIs Cherie and Deepthi, who were always available for questions despite having their own courseloads to worry about.
- The lab group HFA, who shared their Leuschner hill map with our group.
- All lab groups for making it through the class and continuing on our journeys into the field of astronomy. I hope all of you succeed, whether it be in this field or another.

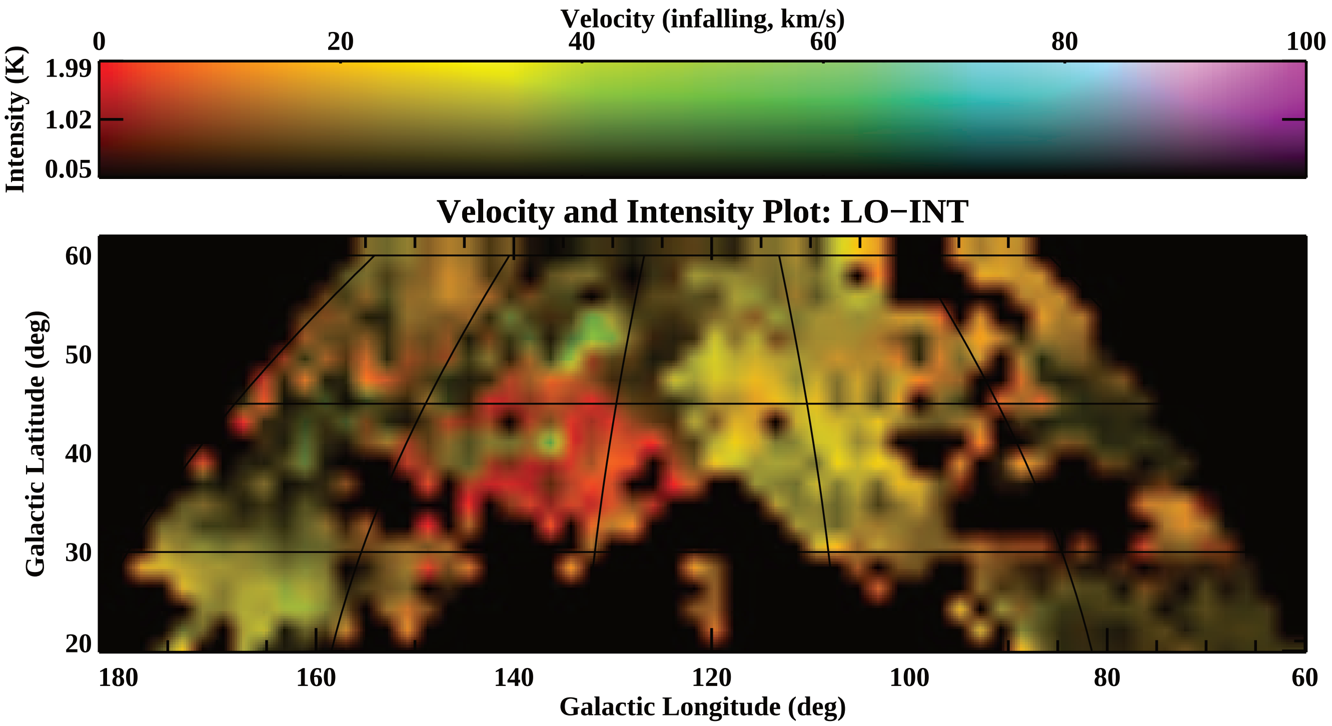

Fig. 8. The Low-Intermediate Velocity Cloud, in 2D. Intensity scale is comparable with Figure 7. Note the much lower intensity of around 1 or 2 units.

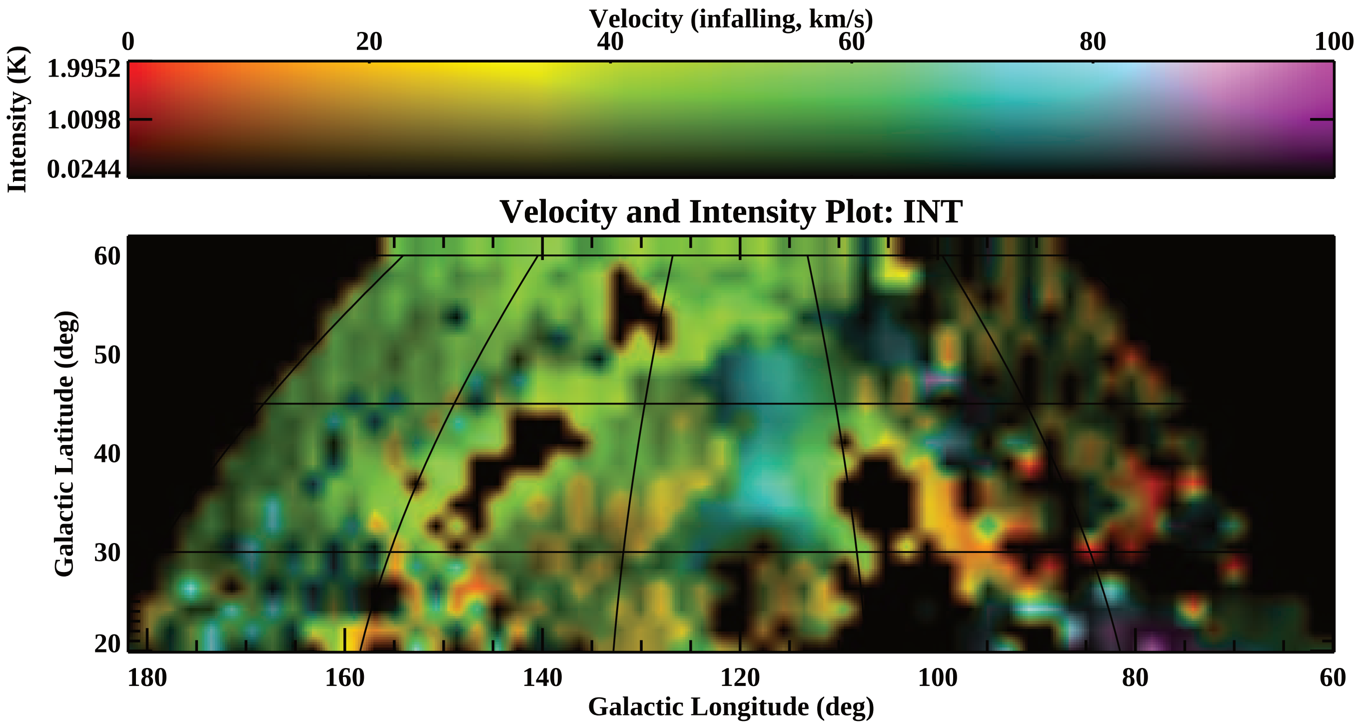

Fig. 9. The Intermediate Velocity Cloud, in 2D. Note the low intensity compared to the Low Velocity Cloud.

Fig. 10. This capture of the column density animation shows gas traveling within 20 km/s of -155 km/s. Structure can be seen slightly up and to the left of the center of the image.