The "Astropeiler Stockert Story"

Part 3: Spectral Observations:

Neutral Hydrogen Observations with the 25m Dish in the Milky Way

Wolfgang Herrmann

1. Introduction

This is the third part of a series of articles to introduce and describe the "Astropeiler Stockert", a radio observatory located on the Stockert Mountain in Germany. This observatory comprises a 25m dish, a 10m dish and some other smaller instruments. It is maintained and operated by a group of amateurs and is as of today the world's most capable radio observatory in the hands of amateurs.

In this series of articles I wish to describe the setup, the instrumentation and the observational results achieved.

This fourth part of the series will deal with the observation of neutral hydrogen in our own galaxy, the Milky Way.

2. Origin of the Neutral Hydrogen Line

The emission line of neutral hydrogen is one of the most prominent phenomenon of radio astronomy delivering a wealth of information about the structure of the Milky Way and other galaxies. It is also a relatively strong emission which can be received with small telescopes and is therefore one of the favorite subjects among amateur radio astronomers.

This emission originates from a transition between the hyperfine structure levels in the 1s electronic ground state of the hydrogen atom, which differ by the spin orientation of the proton and the electron (figure 1):

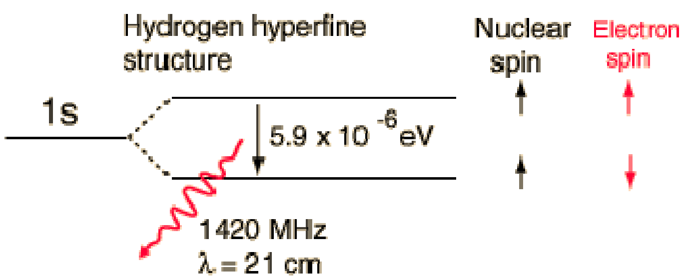


Figure 1: Hyperfine structure transition
Graphic from [1]

This transition was predicted by van de Hulst [2] and detected first by Ewen and Purcell [3].

The dominant process for the excitation of upper level is collisions of one hydrogen with another in the interstellar medium [4]. It is worth noting that the probability of a hydrogen atom to collide with another atom in the typical interstellar medium is about once in every sixty years.

Furthermore, the transition has a very high lifetime of about 11 million years (which means very low transition probability). The reason why this transition is still easily observable (by today's standards, not by the standards of the early 50s when the line was first observed) is because there are just lots of hydrogen atoms out there and today's observational methods are quite sensitive.

3. Observational method

3.1. Fast Fourier Transformation

The method of choice for doing spectral observation today is to do Fast Fourier Transformation. This has replaced correlator systems or even older methods such as scanning receivers and analog filter banks.
At the Astropeiler Stockert we use a Fast Fourier Transform spectrometer developed by the digital group of the Effelsberg telescope [5].
This spectrometer digitizes the intermediate frequency (IF) (100-200 MHz) of our instrument directly and performs a Fourier Transform using a FPGA.
The wide bandwidth allows us to do spectral observation over a wide range simultaneously. In the case of observation of the 21cm line of hydrogen, however, this capability is not necessarily needed. A smaller bandwidth suffices and therefore we were able to demonstrate (and many amateurs have done the same) that even low end software defined radios such as the RTL-SDR can be used for hydrogen line observations. Nevertheless, all observations reported here were done with our "full blown" spectrometer.

Data is recorded as "Flexible Image Transport System (FITS)" files, which is a standard adopted by the International Astronomical Union (IAU). It allows easy post-processing with standard tools. For routine analysis we use the program package "Continuum and Line Analysis Single-dish Software (CLASS)" from the "Grenoble Image and Line Data Analysis Software (GILDAS)" suite developed at IRAM-Grenoble, France [6]. For some more specialized tasks self-developed software is used.

3.2. Local Standard of Rest

When observing the spectrum of hydrogen (or any other atom or molecule) one has to keep in mind that the measurement result is affected by the motion of the observer with respect to the observed target. The motion of the earth around the sun, the rotation of the earth itself and other smaller perturbations like the moon change the observer's velocity and hence, the Doppler Effect will change the measured spectrum. This leads to a dependency of the result on the time of the measurement. In order to avoid this, it is common practice to relate the observation to a common reference frame. For spectral observations in our galaxy this reference frame is called the "Local Standard of Rest" and it is defined as a point which is rotating around the galactic center at the distance of the sun.

For each observation the required correction is calculated. The practical implementation of the transition from the observer's reference frame to the Local Standard of Rest is to apply a correction to the observed frequency. This again is typically done by slightly adjusting the local oscillator of the receive chain. This method is also used at our telescope, and all velocities presented in this paper are velocities with respect to the Local Standard of Rest (V_{LSR}).

3.3. Baseline Correction and Calibration

Unfortunately the baseline of receiver systems is never completely flat. In order to compensate for this, various methods can be used. For hydrogen line observations where the line is relatively strong and narrow, one can use a polynomial fit to the baseline as demonstrated below using CLASS:

The raw data is loaded (figure 2):

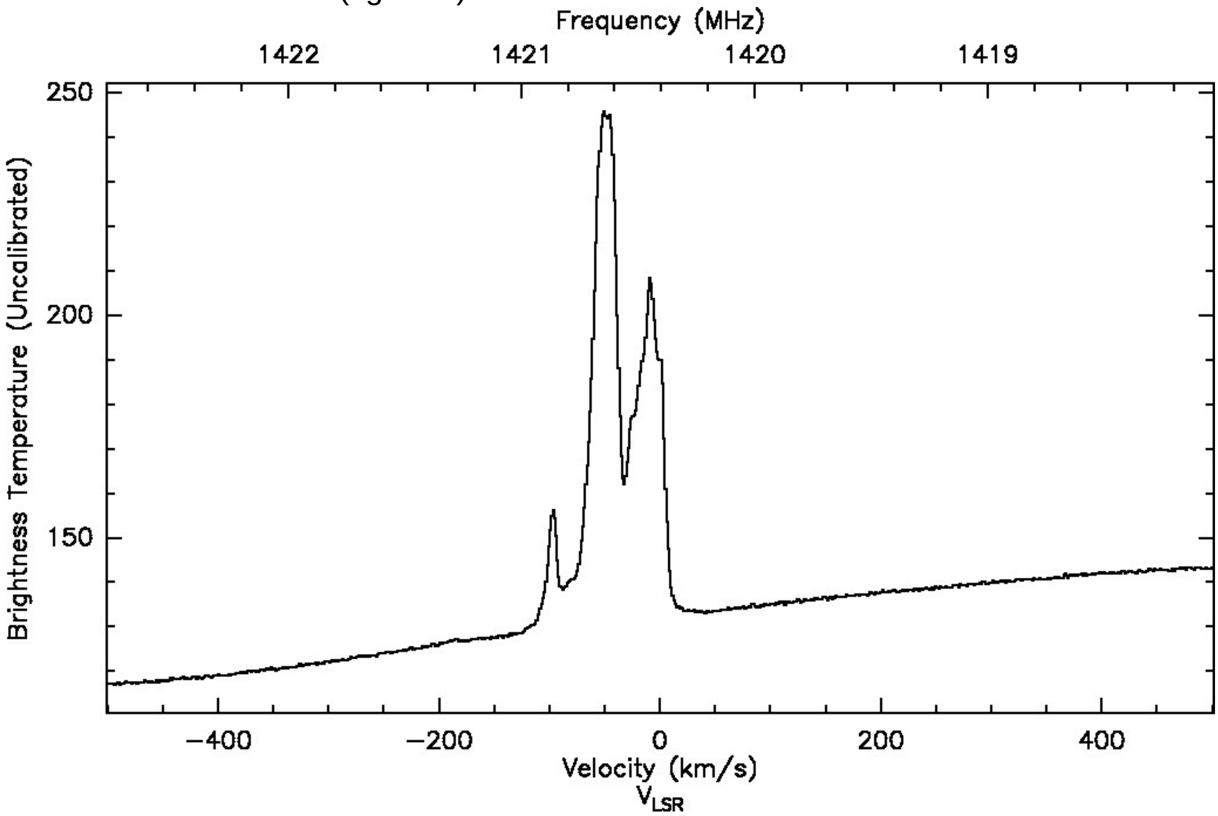


Figure 2: Raw data

Then a window is defined and data outside this window is fitted with a polynomial (in this case 5th degree) (figure 3):

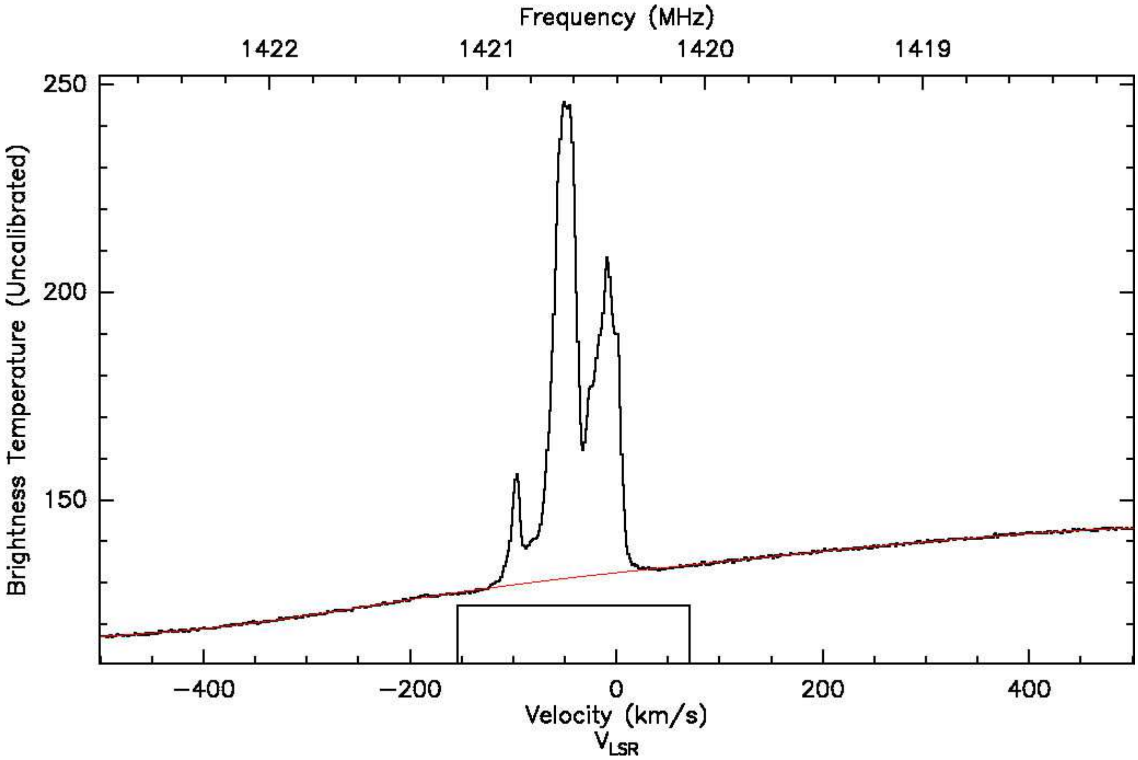


Figure 3: Fitted polynomial

This polynomial is subtracted from the data (figure 4):

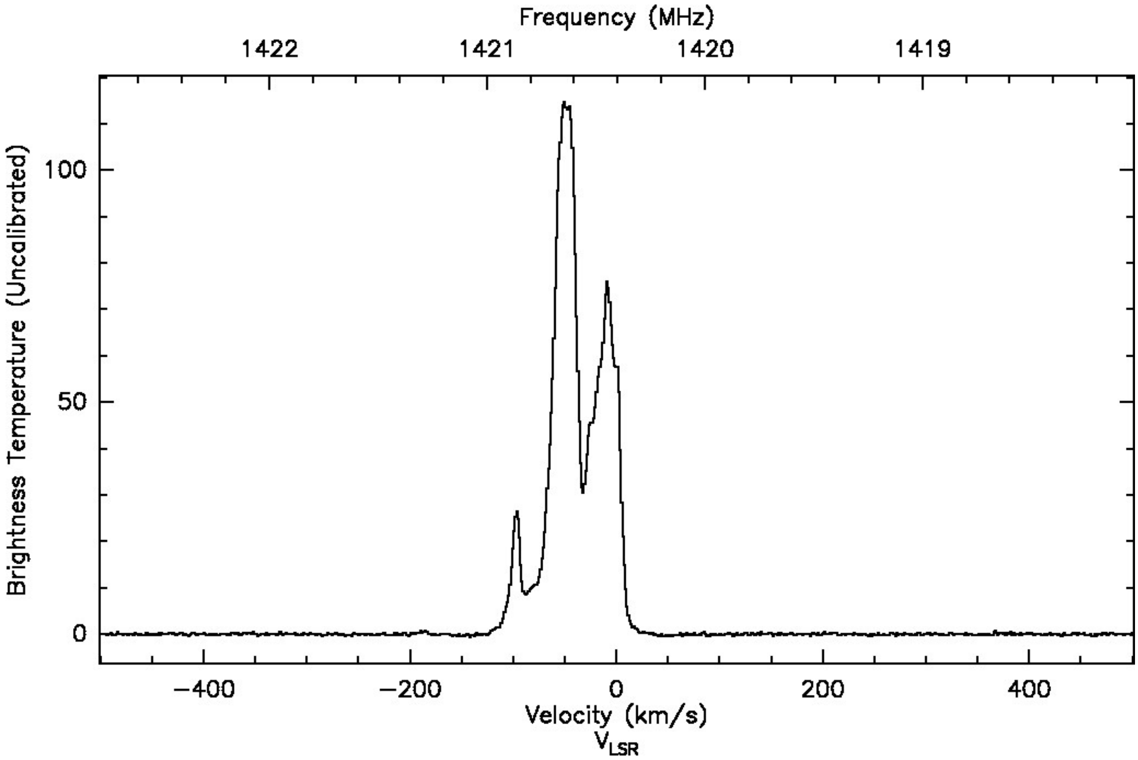


Figure 4: Baseline subtracted

In order to get properly calibrated data, one more step is needed. There is a location in the sky called "S7" which has been adopted by the International Astronomical Union as calibration standard for hydrogen line observations. This location is characterized by a uniform brightness over a larger area, and therefore the calibration is relatively independent on the telescope resolution.
The brightness of this location has been precisely measured [7].

The spectrum shown above has been taken at the S7 location. As the final step a correction factor is applied so that the peak of the spectrum shows the proper brightness temperature[i] of 96.3 kelvin (figure 5).

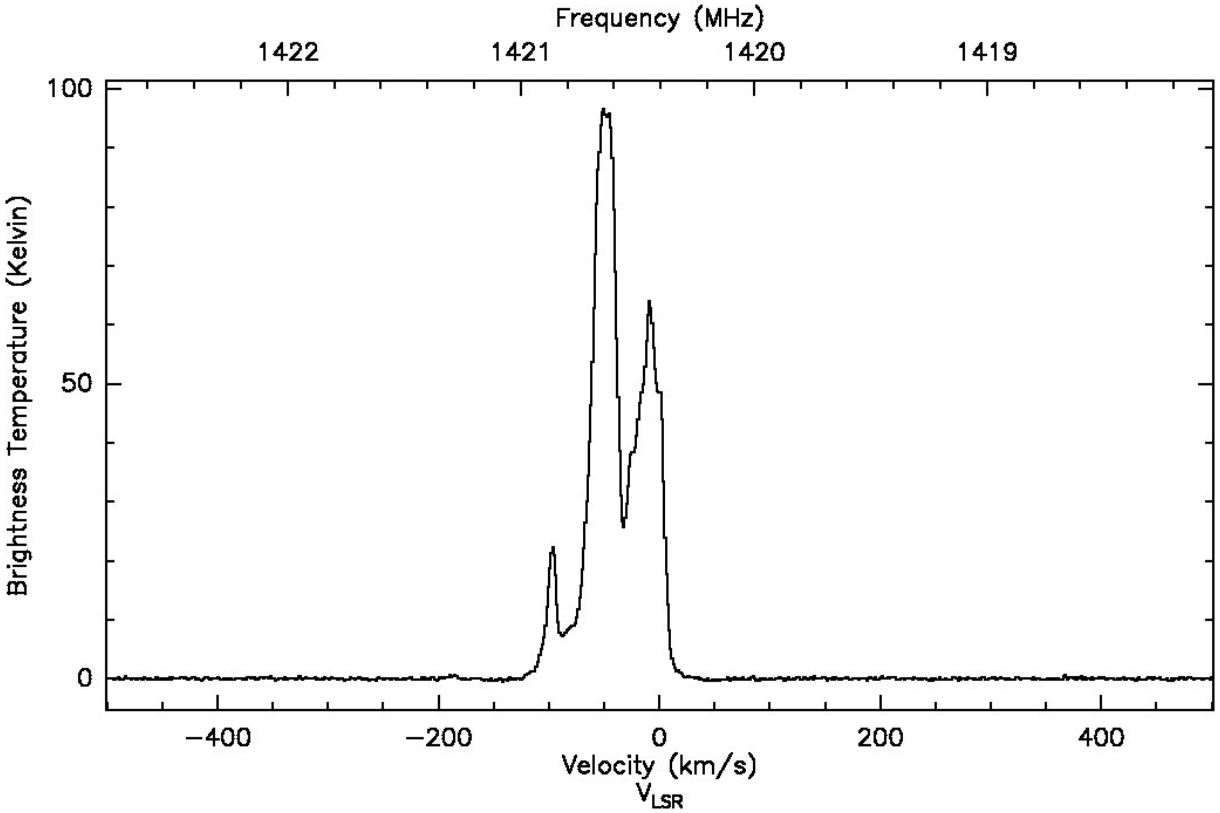


Figure 5: Spectrum calibrated

This correction factor will then be applied to all subsequent measurements. The calibration procedure is repeated regularly.

4. Observation Examples: The Galactic Plane

4.1. Example 1: Scan of the Galactic Plane

The Galactic Plane (galactic latitude 0°) has been scanned from -6° to 253° galactic longitude. A spectrum of the hydrogen was taken every 0.2° of galactic longitude, giving a total of almost 1300 spectra.
Each spectrum was calibrated and base line corrected by taking regular observations of the S7 calibration source and fitting a 5th degree polynomial to the observed spectra as demonstrated in section 3 above.
Then all spectra have been combined to generate a "velocity picture" or "heat-map" of the Galactic Plane (figure 6):

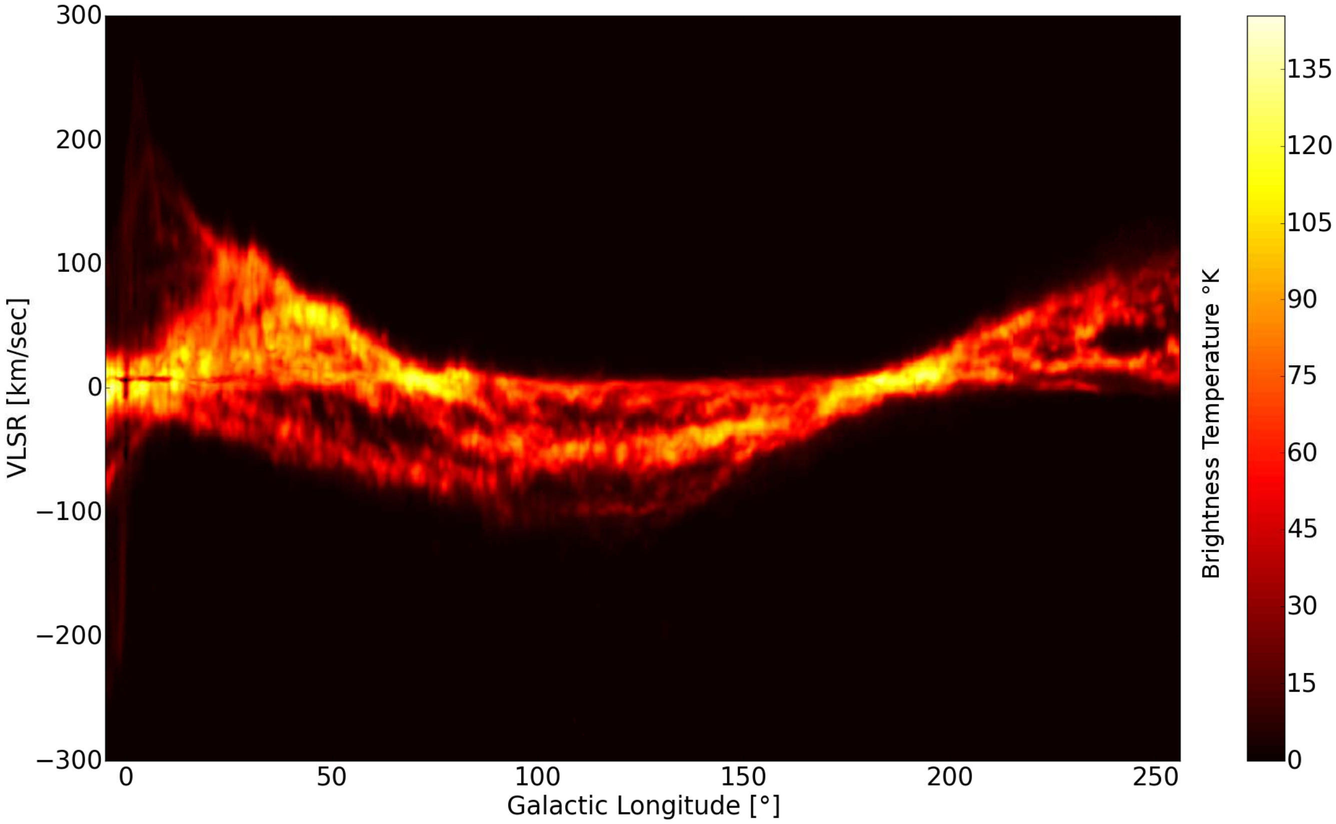


Figure 6: Galactic Plane
Colour scale is brightness temperature in kelvin

Absorption feature towards the galactic center

At the Galactic Center (0° longitude), there is a dark spot which may be surprising. It is pointed out, that this has nothing to do with the black hole! In fact, it is a pure coincidence that this effect occurs towards the Galactic Center. The reason is that in the direction of the Galactic Center there are strong continuum sources (Sagittarius A West and Sagittarius A East, unresolved with our telescope). Radiation from these sources is absorbed by the hydrogen between the source and the observer. Since we remove all continuum signals from the data in the processing, this absorption appears as completely black in the velocity picture. The corresponding spectrum is shown below (figure 7):

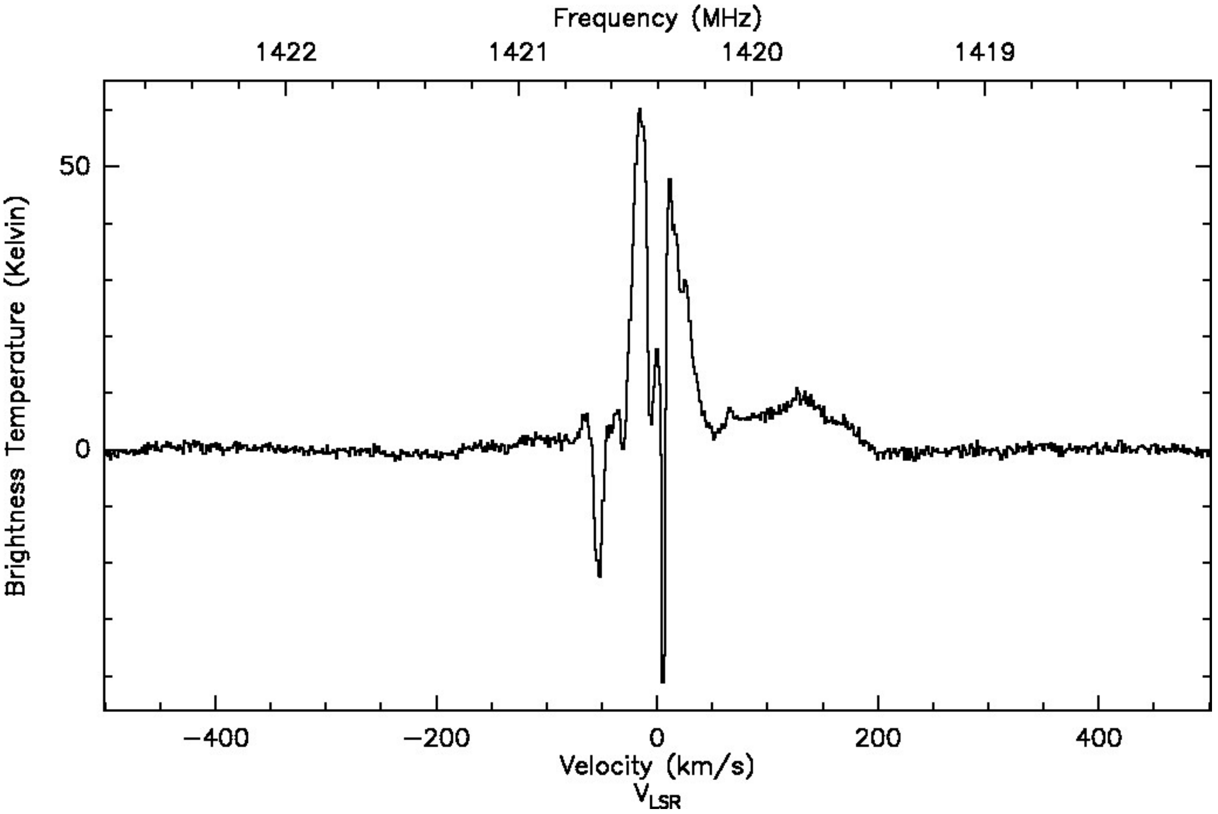


Figure 7: Absorption towards Galactic Centre

We will deal with the effect of absorption in more detail in the observation example 3 further below.

Rotation curve

Principle of evaluation

The classical "must do" with a galactic scan is to determine the rotation speed of our galaxy as it evolves over the distance from the Galactic Center.
How do you do that?
The starting point is to consider the geometry of the observation: Let's assume we have three hydrogen clouds in our line of sight as depicted below (figure 8). Each cloud has a speed and direction of rotation as demonstrated by the black vector. The speed observed is then the projection of that vector onto the line of sight. Only for the innermost cloud the direction of the cloud and the line of sight coincide. Therefore this will be the fastest cloud observed.

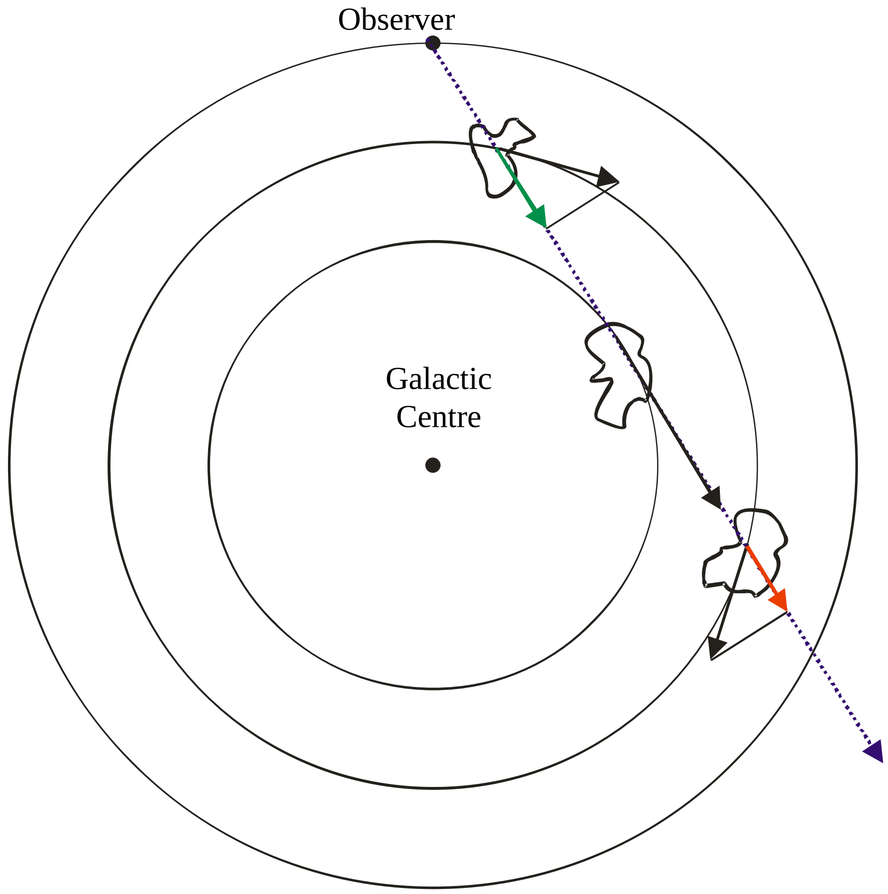


Figure 8: Geometry of observation

Therefore one would observe a spectrum looking something like shown below (figure 9) as the blue line, consisting of the three components from the three clouds (depicted in red, green and black).

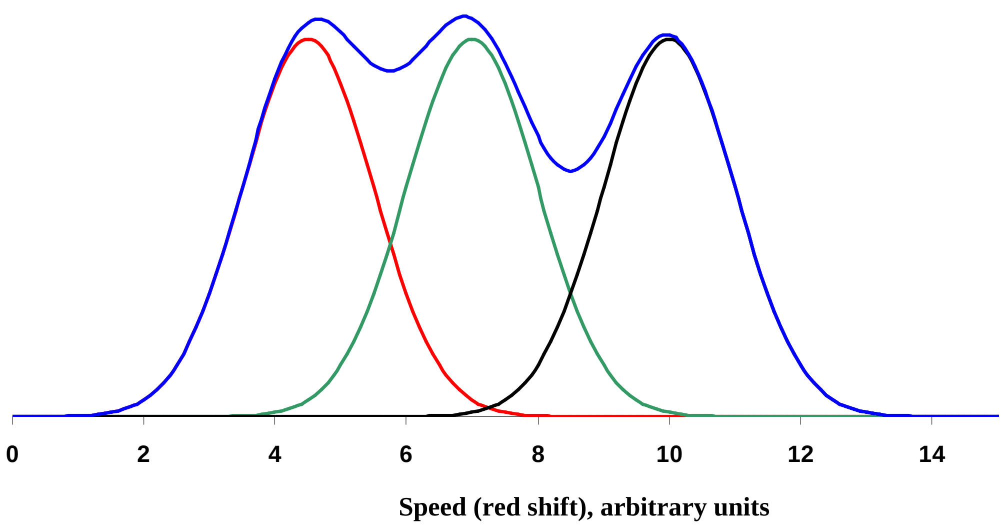


Figure 9: Example for a received spectrum

One would pick the highest red shifted speed observed as the speed (relative to the observer, v_{max}) of the innermost cloud observed.

The distance of this cloud from the Galactic Center can be inferred from the galactic longitude of the observation λ and the distance R_0 of the observer (solar system) from the Galactic Center.
In addition, the speed of the rotation of the solar system around the galactic center needs to be known and included in the calculation.

The distance R of the cloud from the Galactic Center can be calculated as:

$$R = R_0 * \sin(\lambda); \qquad (1)$$

and the speed of the cloud is determined as:

$$v = v_{max} + v_0 * \sin(\lambda); \qquad (2)$$

Standard values for v_0 are 220 km/sec and for R_0 8,5 kpc.

The geometry for this consideration is shown below (figure 10):

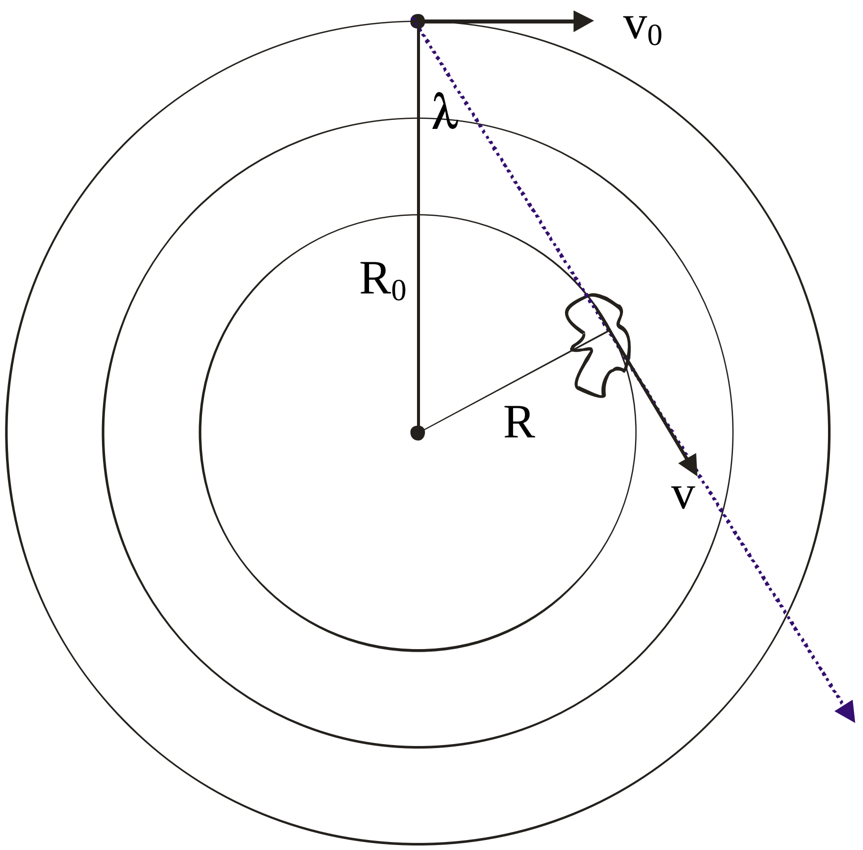


Figure 10: Geometry for inferring the distance from the galactic center

It should be noted that this scheme is only applicable for galactic longitudes up to 90° from the Galactic Center. Beyond that, the determination of the distance is no longer unambiguous, and therefore one can only determine the rotation speed at distances up to 8.5 kpc with this type of observation.

Rotation curve
Result from observation

The data from our galactic plane hydrogen spectrum observations have been processed where each spectrum was searched for the highest red shifted spectral component and equations (1) and (2) have then been applied.
The resulting rotation curve is shown below (figure. 11).

It is a well known result that the galactic rotation curve does not behave as one would expect. The rotation speed stays practically constant for larger distances from the Galactic Center. This is considered as a strong indication for the existence of dark matter which could provide the gravitational force to allow such high rotation speeds.

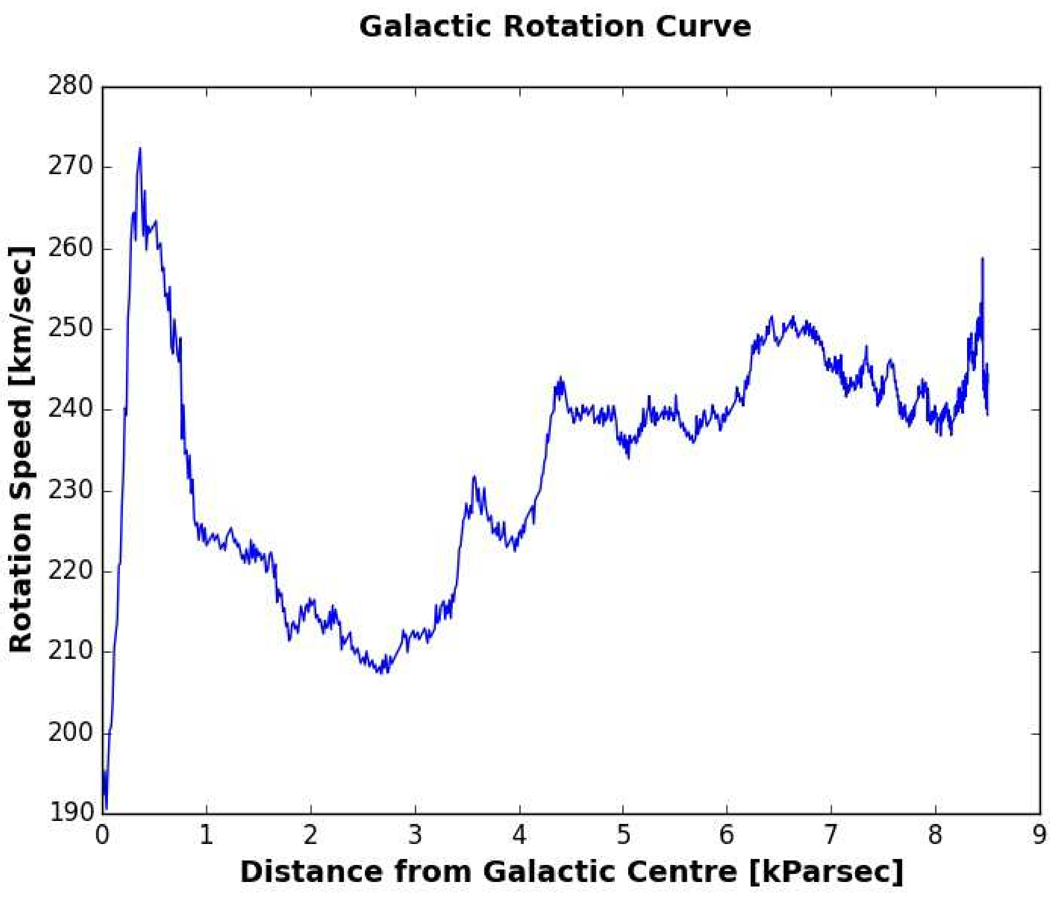


Figure 11: Rotation curve resulting from observations

Observation Example 2: Transit of the Galactic Plane

A straightforward observation is to record the neutral hydrogen spectrum over a sidereal day with the telescope in parking position. In our case, this provides a scan at a declination of 61° 36'.
A spectrum has been recorded every 20 seconds, so over day more than 4000 spectra have been recorded. Similar to the graph of the galactic plane, a heat-map has been generated from the data (figure 12). This heat-map shows the brightness and velocity as it evolves as the galactic plane passes through the telescope beam due to the rotation of the earth.

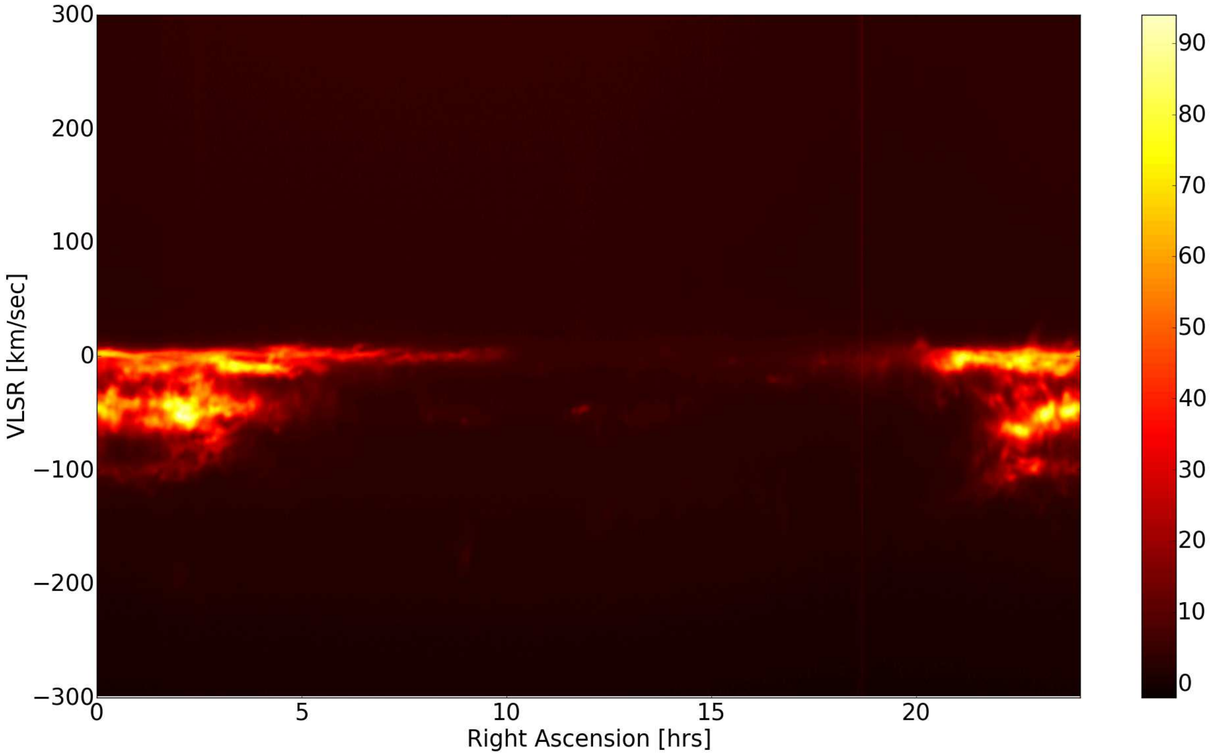


**Figure 12: Transit of the galactic plane observed with the telescope parked DEC: 61° 36'
Colour scale is brightness temperature in kelvin**

It can nicely be seen how the neutral hydrogen is concentrated in the galactic plane. The main transit of the galactic plane is from RA 20 hrs through to 5 hrs.

Integrating the data over all velocities then yields the column density (figure 13):

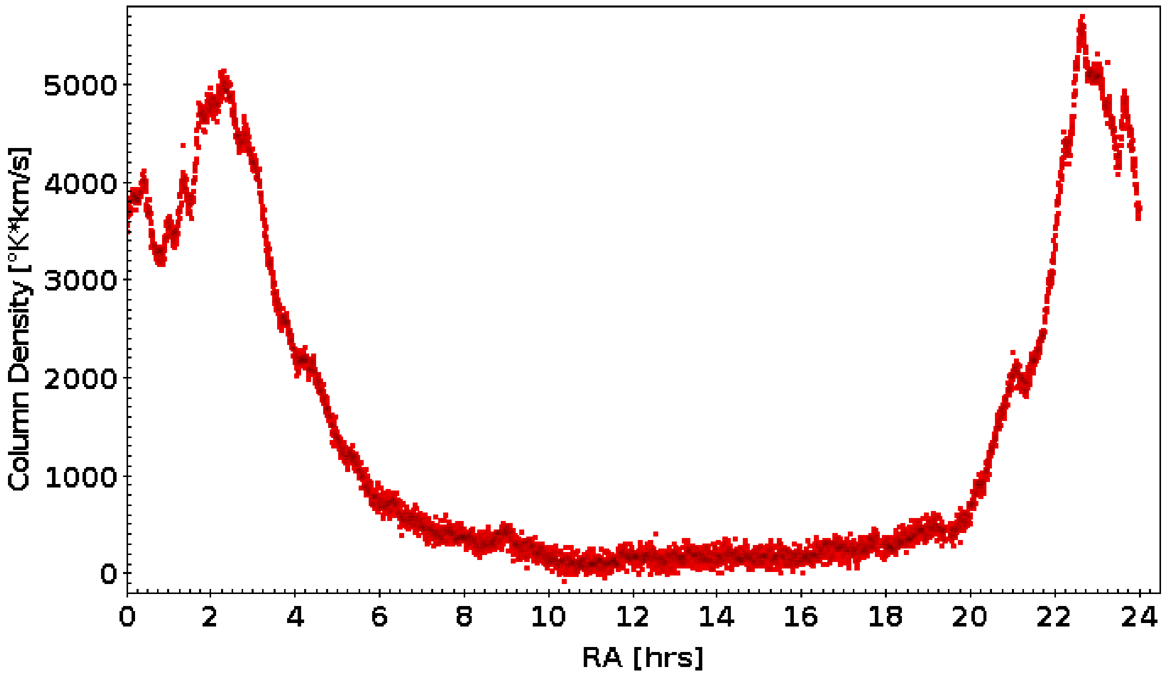


Figure 13: Hydrogen column density at DEC 61° 36'

The column density is a measure of the total hydrogen mass along the line of sight.

Observation Example 3:
Absorption spectra towards strong continuum sources

As already demonstrated in the observation towards the Galactic Center, one can observe absorption from hydrogen if there is background radiation from a continuum source.
The most prominent example is the absorption towards the strongest radio source, Cassiopeia A, which has first been reported by Hagen, Lilley and McClain in 1955 [8]. When observing absorption, the on-target / off-target method is used. In this method two spectra are taken. One spectrum is taken by pointing directly at the target (in this case CAS A). This will represent the sum of both emission and absorption from hydrogen along the line of sight. The other spectrum is taken by pointing slightly beside the target. This will represent the emission only. If one assumes that the emission component is almost the same in both pointings, subtracting the two observations will reveal the pure absorption spectrum. This is demonstrated in the spectra below (figure 14):

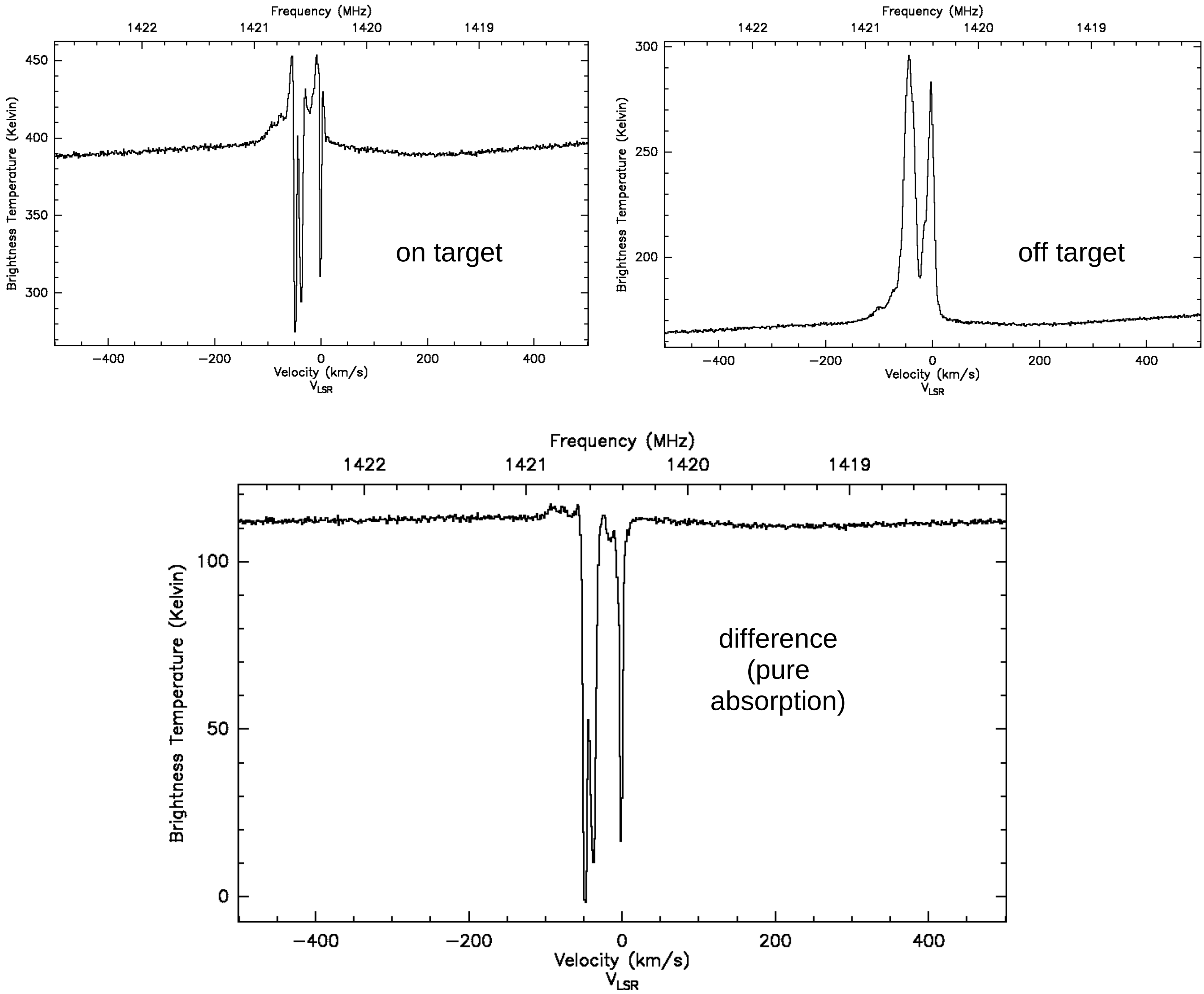


Figure 14: Absorption Spectrum of Cassiopeia A

The structure of the emission line towards this region can be explained by two spiral arms: The Orion arm at ~ 1km/sec and the Perseus arm at ~ 40km/s.

But why are the absorption lines so much narrower than the emission lines?
And why is the absorption from the Perseus arm split up into two components?

This effect is due to the fact that the continuum source is much smaller than the beam width (figure 15):

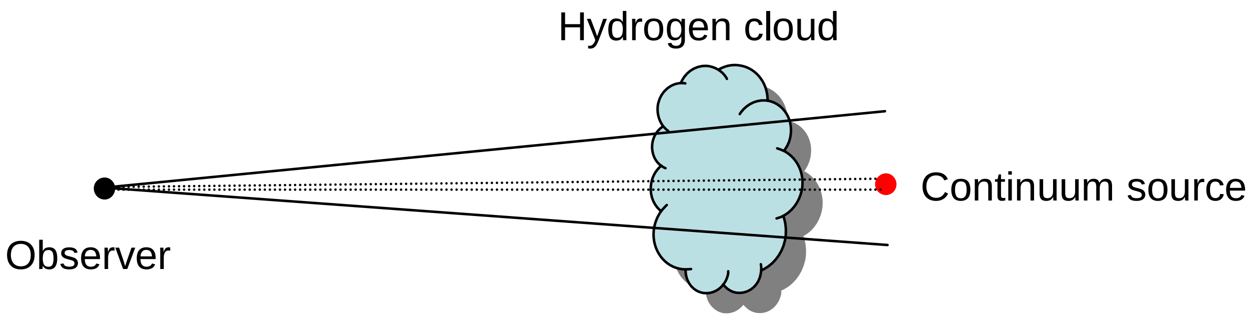


Figure 15: Geometry of observation

Therefore, the absorption is due to a much smaller region of the hydrogen cloud compared to the observed emission. In this way, the angular resolution for the absorption is determined by the angle subtended by the continuum source rather than by the beam width of the telescope.
As the hydrogen cloud is turbulent, the Doppler broadening leads to a broader line width due to the various velocity components for the emission observation signals received over the wider beam of the telescope.

Due to the narrower absorption line width it can be observed that the Perseus arm is split up into two arms with slightly different velocities, hence the double line at ~ 40 km/s.

Also, it can be concluded from this observation that CAS A must lie behind both the Orion and the Perseus arm (otherwise there would be no absorption). This allows us to put a lower limit to the distance of CAS A, provided the distance of the Orion and Perseus arm are known.

One may notice that the noise of the on-target observation is higher compared to the off-target observation, even though they were both recorded with the same integration time. This is due to the high background from the continuum source.

Observation Example 4:
Narrow line location

Usually the line width observed from galactic hydrogen is relatively broad. However, there are some locations where a narrow line width can be observed. As an example, here is the spectrum as recorded at 88° galactic longitude and 33° galactic latitude (figure 16):

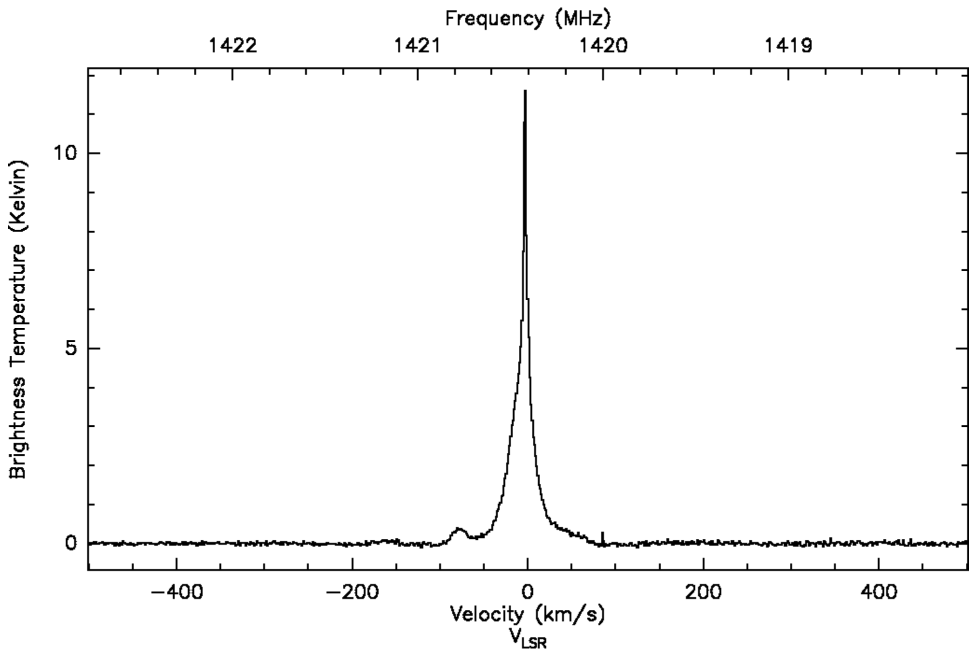


Figure 16: Spectrum at 88° galactic latitude and 33° galactic longitude

The line profile has a narrow feature, obviously superimposed on some broader features. The complete profile can be fitted assuming 4 Gaussian lines of different positions, width and brightness temperatures (figure 17).

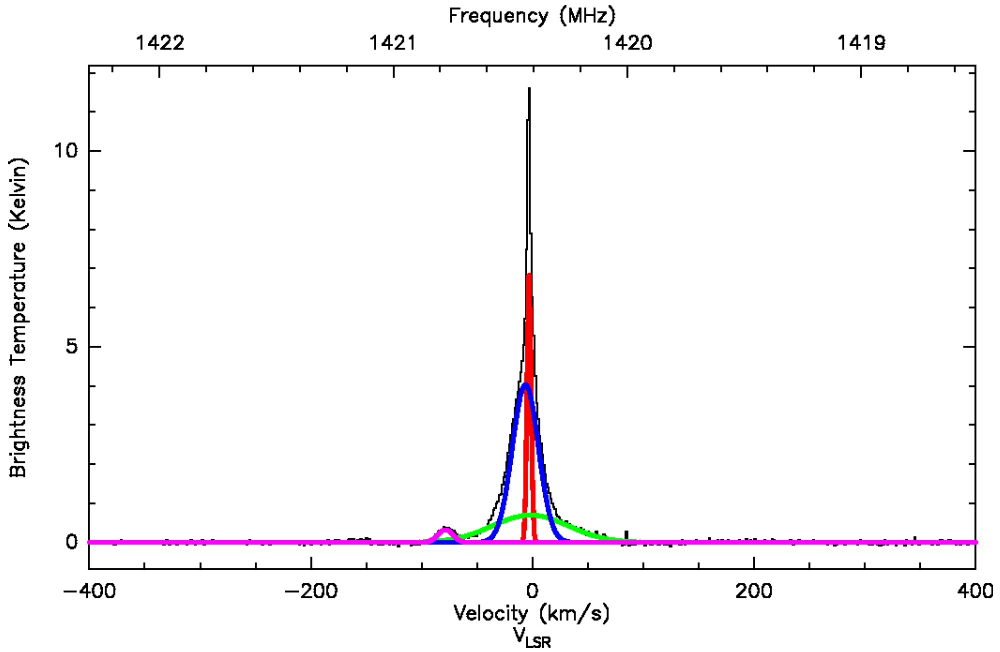


Figure 17: Fitted Gaussian lines

The fitted parameters are as follows:

Line	Position [km/s]	Brightness Temperature [K]	Width FWHM [km/s]
red	-3	6.8	4.1
blue	-6.3	4.0	27.6
green	-1.8	0.7	80.8
magenta	-78.6	0.3	15.8

One of the features is very narrow with a width of only 4.1 km/s.

The summation of the four fitted Gaussians are in good agreement with the observed profile (figure 18):

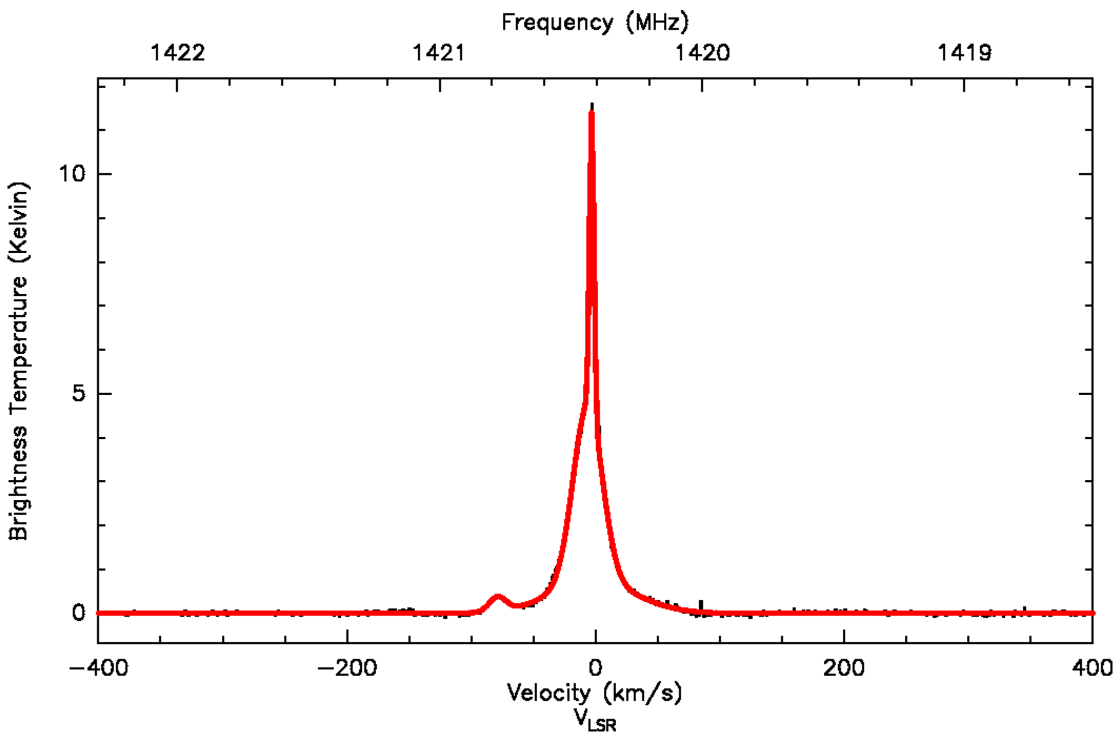


Figure 18: Sum of fitted Gaussian lines

The physical interpretation of this observation would be that there are different clouds of hydrogen within the line of sight which differ significantly in turbulence and/or temperature.
The narrow line would correspond it a temperature of about 360 K. This represents an upper limit to the "actual" temperature as the Doppler broadening is caused both by thermal motion and turbulence.

Obervation Example 5:
High Velocity Clouds (HVC)

When observing the sky at the hydrogen line spectral range one finds patches where there is a weak emission at high speeds, usually blue shifted. These patches seem not to fit in the normal rotation speed scheme and location.

As an example, below (figure 19) is a transit scan over a full sidereal day at Declination 62.85°. A different colour scheme has been chosen here to better show the weaker emissions.. Also, most of the hydrogen emission from the galactic plane has been cut off for better visibility of these features.

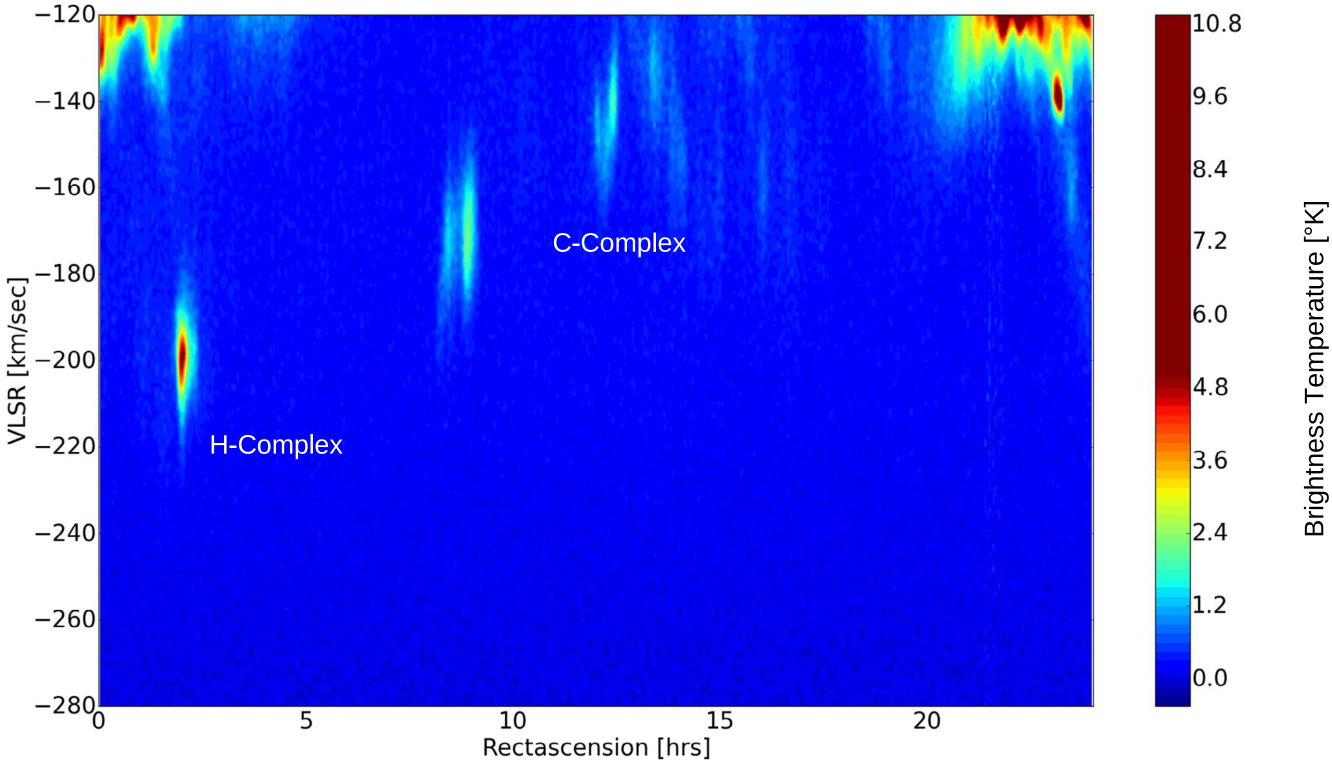


Figure 19: Transit scan at 62.85° Declination

The features marked as "H-Complex" and "C-Complex" are known as "High Velocity Clouds (HVC)". These clouds "fall" into the galaxy from various directions.
The origin of these HVCs is still under discussion, and several theories exist as depicted in figure 20.

One theory explains the HVC as material which has been ejected by a supernova ("galactic fountain") and is now falling back. Another theory assumes that gas clouds from intergalactic material are attracted by the galaxy's gravity, while a third theory explains the effect by condensing gas in the halo. None of these theories is fully consistent with the observations, and it is quite likely that all of these effects play a role.

However, there is one major HVC which is well explainable by gas which is "pulled away" from the neighboring galaxy. This is the Magellanic stream where gas is pulled from the Magellanic clouds.

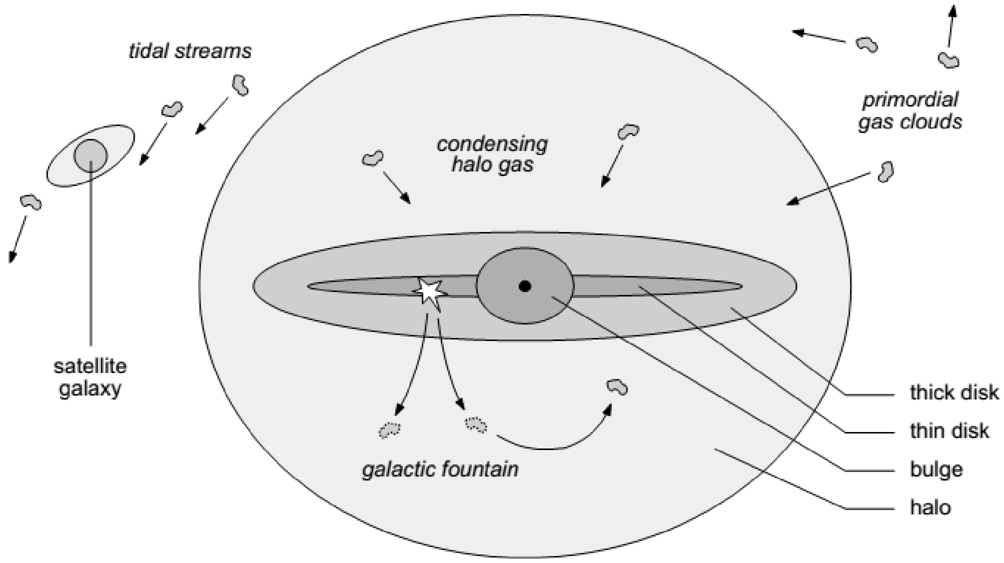
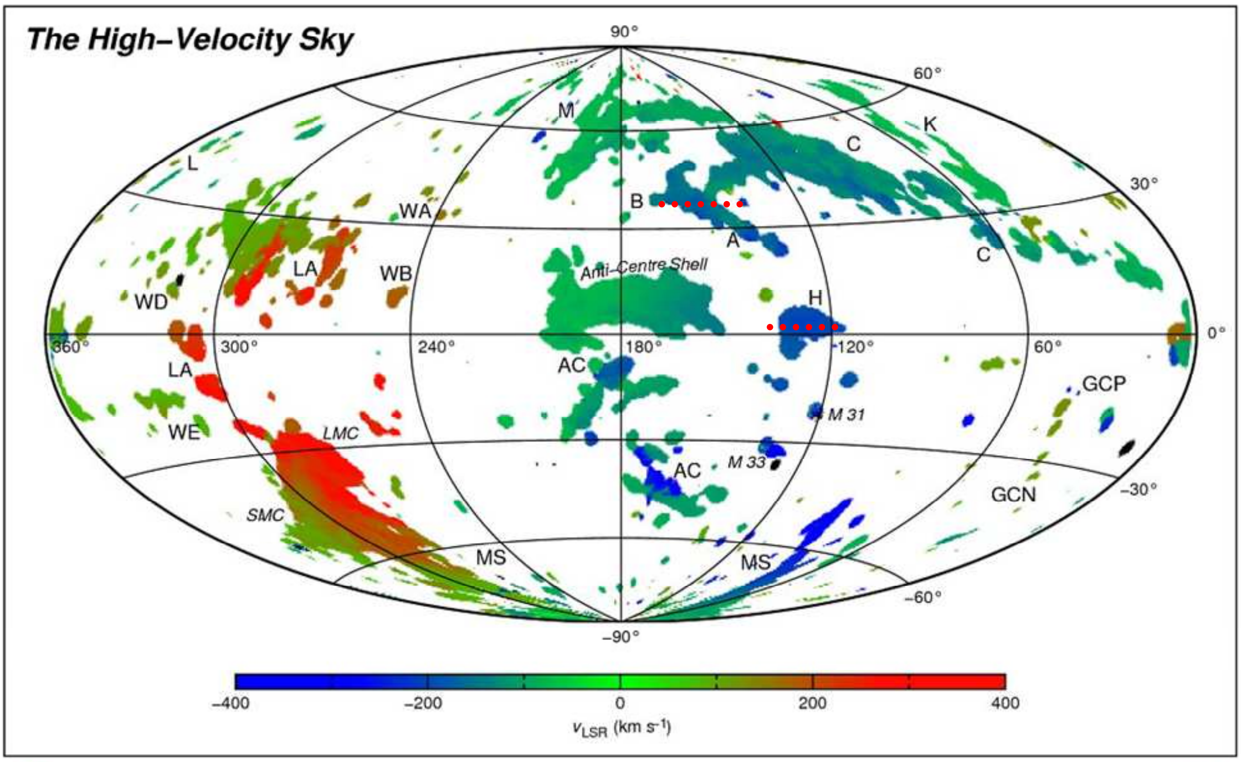


Figure 20: Potential origins of High Velocity Clouds
Drawing from [9]

These HVC cover quite a bit of the sky as can be seen in the graph below (figure 21):



Tobias Westmeier, CSIRO Australia Telescope National Facility
Based on the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005, A&A 440, 775) and the Milky Way model of P. Kalberla (Kalberla et al. 2007, A&A, in press).

Figure 21: Sky covered by HVC

In figure 21 there are two red dotted lines which represent scans (at 1 and 35° galactic latitude) which were performed to demonstrate the HVCs. The results are shown as heat maps below (figure 22 and 23). Spectra were taken every 0.25° of galactic longitude.

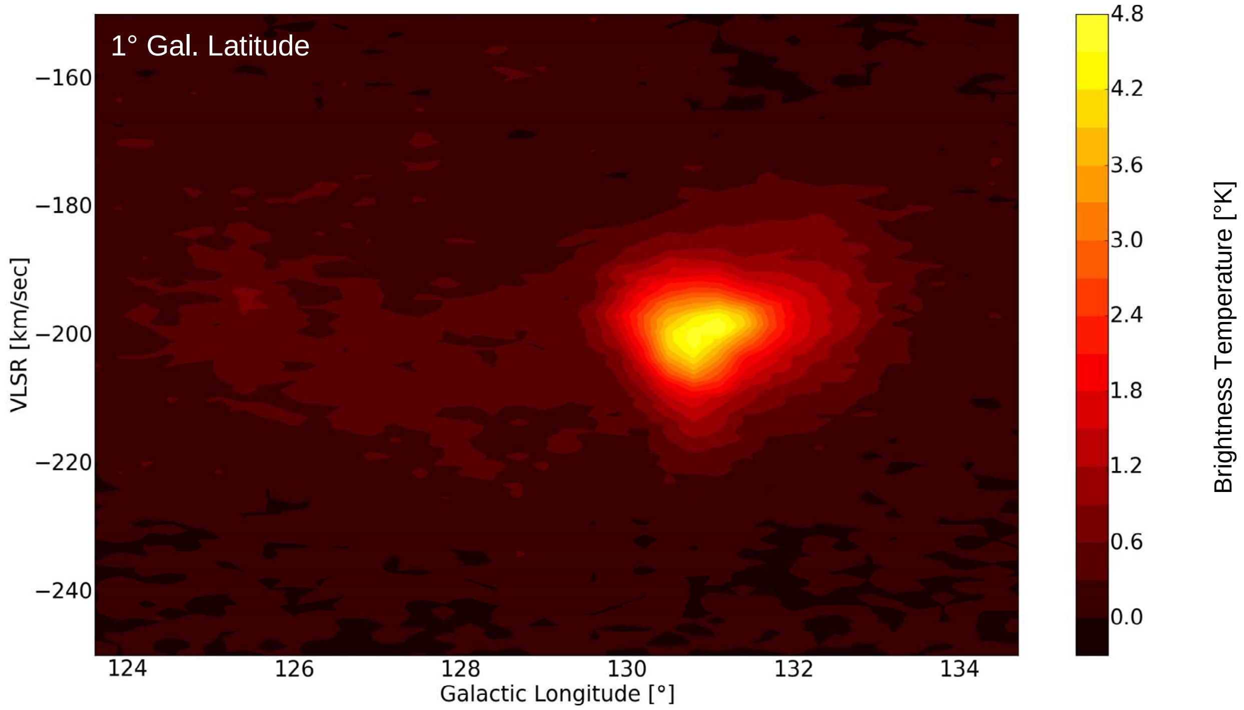


Figure 22: Scan along the "H Complex" at 1° galactic latitude

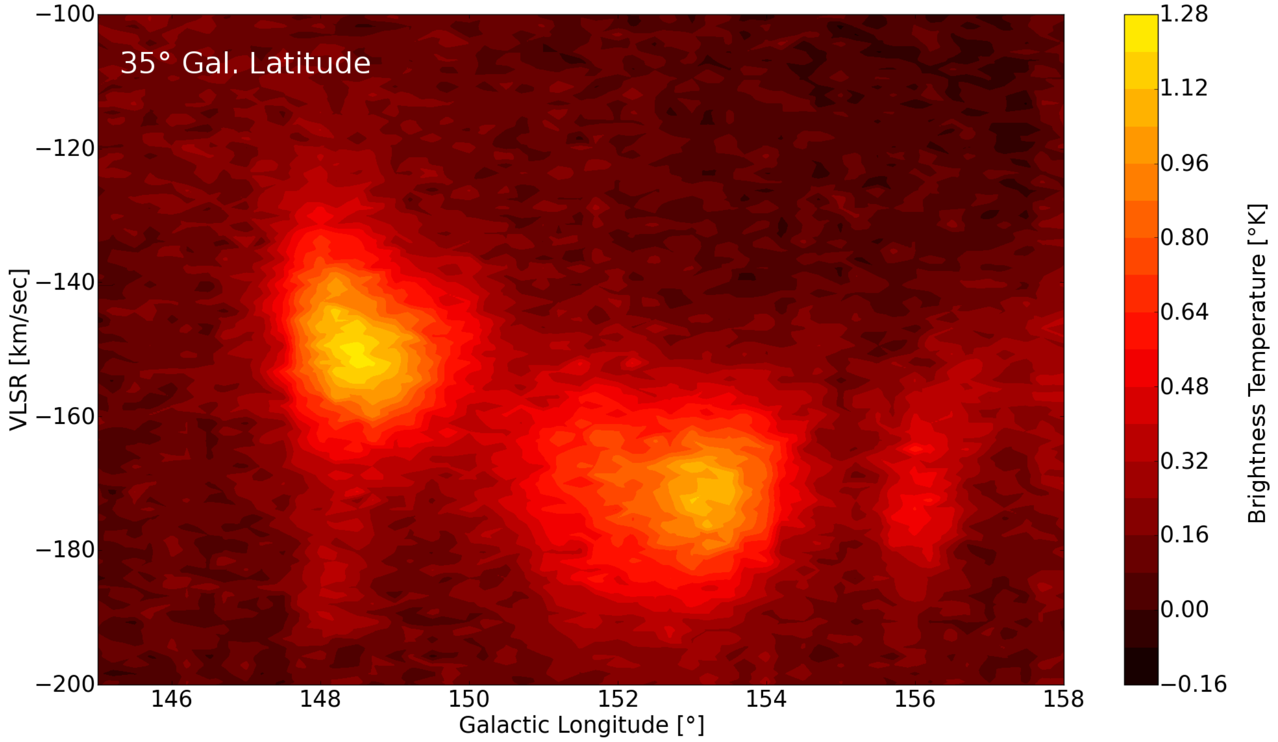


Figure 23: Scan along the "B Complex" at 35° galactic latitude

It can be seen that the HVC complexes are quite extended encompassing several degrees in galactic longitude. In case of the B complex, different clouds with different speeds can be identified.

Summary and conclusions

The observation of hydrogen emission and absorption in the Milky Way is a fascinating subject, revealing a lot of features of our home galaxy. For the amateur radio astronomer it is a rewarding area to deal with. Many of the observations presented here are within the realm of typical amateur instruments such as a 3 m dish or even smaller. This has been successfully demonstrated by various amateurs. The exception will be the absorption observation which requires a narrower beam to reveal this effect. A 10 m dish or above is likely to be needed for this.

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[8] J.P. Hagen, A.E. Lilley, E.F. McClain, Ap J, 122, p. 361 , 1955

[9] T. Westmeier, PhD Thesis, Bonn 2007

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[i] Brightness temperature: This is the temperature which a blackbody radiator would have to produce the same energy in the same bandwidth