

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

CONTENTS

- 1 Introduction**
- 2 Measurement Equipment**
- 3 Setting Transit Scan Parameters**
- 4 Data Capture Format**
- 5 Graphical results**
- 6 Representation of Changing H Line Spectra**
- 7 Doppler Shifted H Line Spectra as a Function of Right Ascension**
- 8 Frequency / Velocity as a Function of Position /Right Ascension**
- 9 Conclusions**

Appendix A Further interesting H Line Spectral Data

Appendix B Hydrogen Line map of part of the Galactic Plane

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

1 INTRODUCTION

In this article we present a means of measuring the spectrum between 1420.2MHz and 1420.8MHz of Neutral Hydrogen in the Milky Way. The automatic detection system first developed in 2007 accumulates spectra as a function of time (and Right Ascension) as the antenna beam transits through the galactic plane at a fixed Declination.

It is possible to recover the series of individual spectra taken at different Right Ascensions and plot them in a number of ways to reveal the Doppler shifted features of the various concentrations of Hydrogen over the range of Right Ascension positions.

Although it was not done in this particular exercise, it is possible to repeat the measurement at a number of Declinations and produce maps of Hydrogen velocities over a large area of the sky. See Appendix B.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

2 MEASUREMENT EQUIPMENT

A 3m diameter dish was used as the antenna for these transit measurements. A suitable circular waveguide feed and temperature stabilised low noise head amplifiers were used at the focus of the dish to collect the hydrogen spectral signal amplitude over the frequency range of 1420.2MHz to 1420.8 MHz .



Figure 1 3m diameter dish with integrated feed / LNA

The RF signal was conveyed to the receiver via 25m of URM67 coaxial cable. The ICOM IC-R7000 receiver was programmed to scan between the required frequency limits at a suitable rate per stepped receiver bandwidth. The automatic frequency scan produced 264 signal amplitude measurements at a rate of approximately one per second. The frequency step was ~2.3kHz and each scan lasted for approximately 4 minutes and 24 seconds.



Figure 2 The ICOM IC- R7000 scanning receiver

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

During the scan, the centre of the beam moves about 1.1° . This is much less than the 8° half power beamwidth of the antenna and the measurement can be considered to be a static one. The scan rate is a compromise between the requirement for a small beam travel angle and the integration time required to reduce noise in the signal measurement. The post detector scaling and signal integration electronics is shown below.



Figure 3 Post detector scaling and integration electronics

The output of the post detector electronic unit is digitised using a 12 bit ADC and the data accumulated in a PC over a period of several hours for each transit, as the antenna beam scans across the galactic plane.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

3 SETTING THE TRANSIT SCAN PARAMETERS

The position of the antenna is set by using the Radio Eyes software package¹. The 1420MHz sky map is selected along with a full range of relevant coordinate systems. The display – shown in Figure 4 – is used to set the position of the antenna for the transit scan.

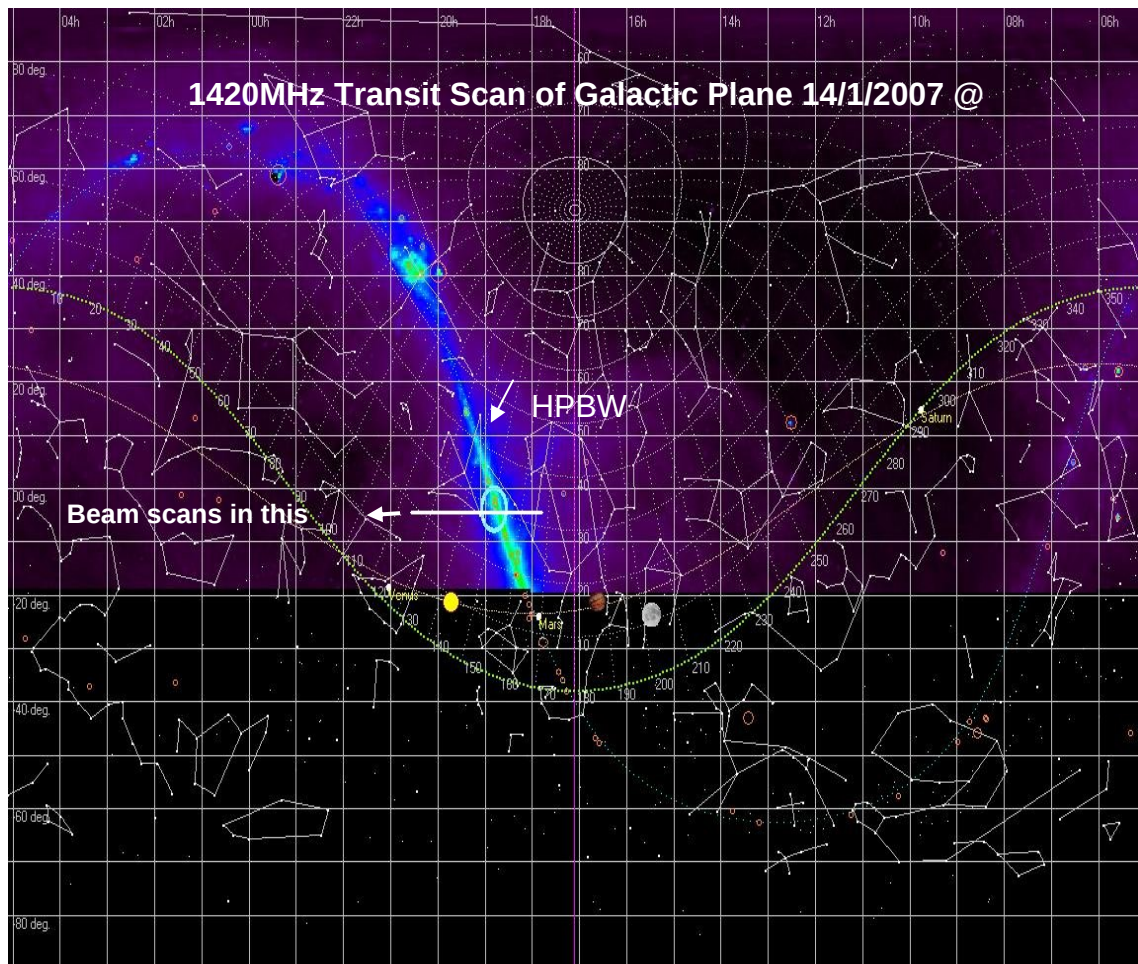


Figure 4 The Radio Eyes screen

In this particular case the scan was made across the galactic plane as close to the galactic centre as was practical at the observation site. This was determined by the minimum elevation of the antenna before thermal ground noise and terrestrial interference start to enter the antenna beam and corrupt the measurement.

The minimum elevation above the horizon was set to be 30° . This gave a 'cut' across the galactic plane at a declination of approximately -4° as shown in Figure 4. The antenna azimuth angle was set at 150° to avoid ground obstacles and the scan was made from 08:40hrs to 11:25 hrs GMT on the 14th of January 2007.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

The range of Right Ascension scanned was 17:48 hrs to 20:31 hrs which put the crossing of the galactic plane just before half way through the scan at 18:50hrs RA.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

4 DATA CAPTURE FORMAT

Each frequency scan generated 264 amplitude measurements at a rate of one per second. The data were recorded in sequence for the whole transit scan of the section of sky. Time / amplitude pairs were stored as a .csv file for later manipulation in Microsoft Excel.

The post processing of this data required the start and end times of each scan to be determined and the corresponding amplitude data 'cut' from the sequence and stored in the manner shown in Figure 5. Each set of scan amplitudes was arranged as shown in the 2D data table. The end of one scan is linked to the start of the next as shown by the orange dotted line in Figure 5.

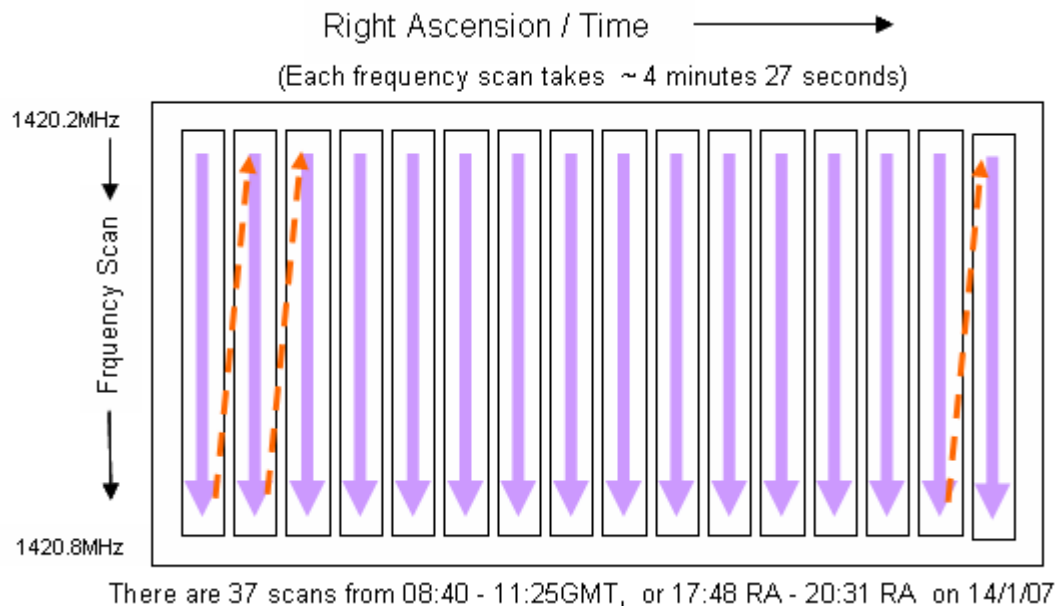
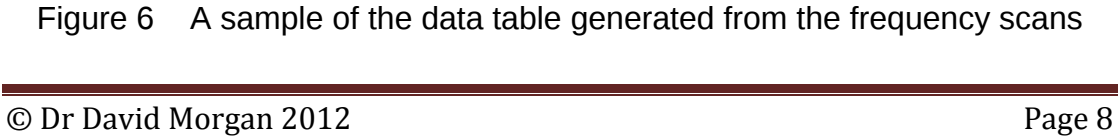


Figure 5 Scan Data format

The whole data table contains 37 scans, each of 264 frequency points. With this format, the spectra as a function of position (Right Ascension) can be plotted in a number of ways to show how the emissions at each frequency change with position across the Galactic Plane.

Because a single frequency scan takes only approximately four and a half minutes the beam only moves 1.1° across the sky during this time. With an antenna half power beamwidth of 8° we can consider the measurement to be static – avoiding any significant smearing out of spectral detail.

A sample of the data generated is shown in Figure 6.



Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

5 GRAPHICAL RESULTS

If all the contiguous frequency scans are plotted sequentially over the period of the transit scan, we produce the result shown in Figure 7. Here we see the succession of peaks in the dark blue signal level trace, as the receiver sweeps through the Doppler shifted frequency of the Hydrogen Line in each frequency scan.

On closer examination we can see the evolution of the spectra from a simple single feature to a more complex spectrum as the beam crosses the galactic plane centred on 18:50hrs Right Ascension.

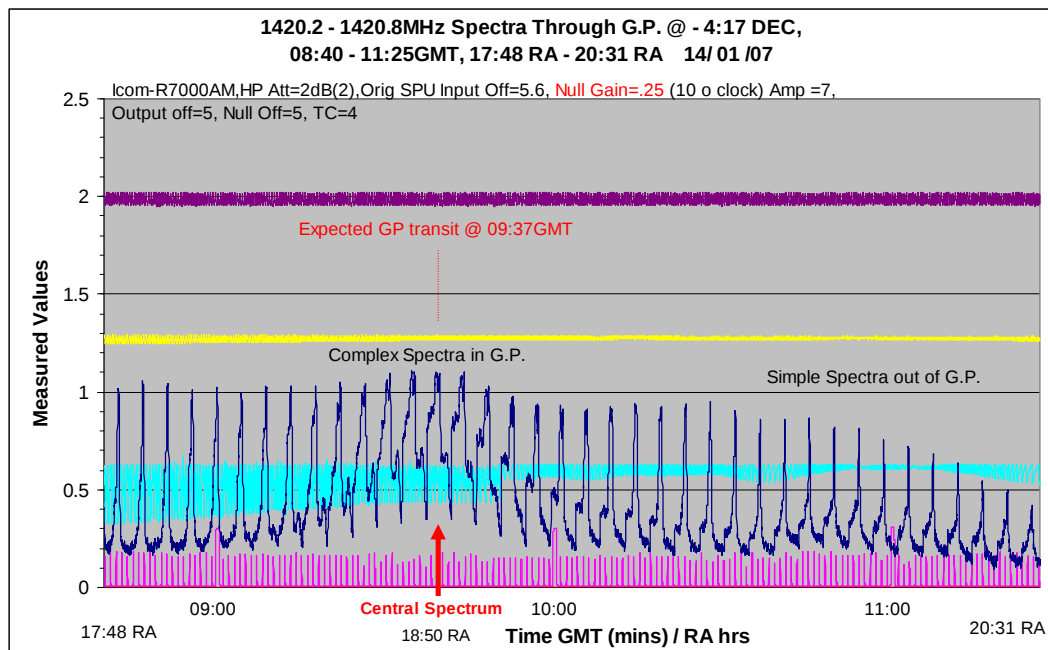


Figure 7 Recordings of H Line signal levels as a function of transit scan time

It should also be noticed that the 'base level' of spectra rises as the beam crosses the galactic plane. This may be due to the presence of multiple patches of Hydrogen, with Doppler shifted velocities spanning the whole frequency band – but is more likely to be due to the broadband Synchrotron emission produced within the galactic plane.

The other traces in Figure 7 are recordings of instrument parameters such as:

- Receiver temperature – purple trace
- RF line driver amplifier temperature - yellow trace
- Head LNA temperature - light blue trace
- Clock timing marks - cyan trace

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

If we take a sample spectrum from the last in the series of frequency scans during the transit scan, when the beam is well south of the galactic plane, we see a simple single line spectrum with the frequency close to 1420.44 MHz. This implies that there is a single region of Hydrogen with a small line-of-sight velocity with respect to the antenna. See Figure 8.

The hydrogen line rest frequency is 1420.4MHz.

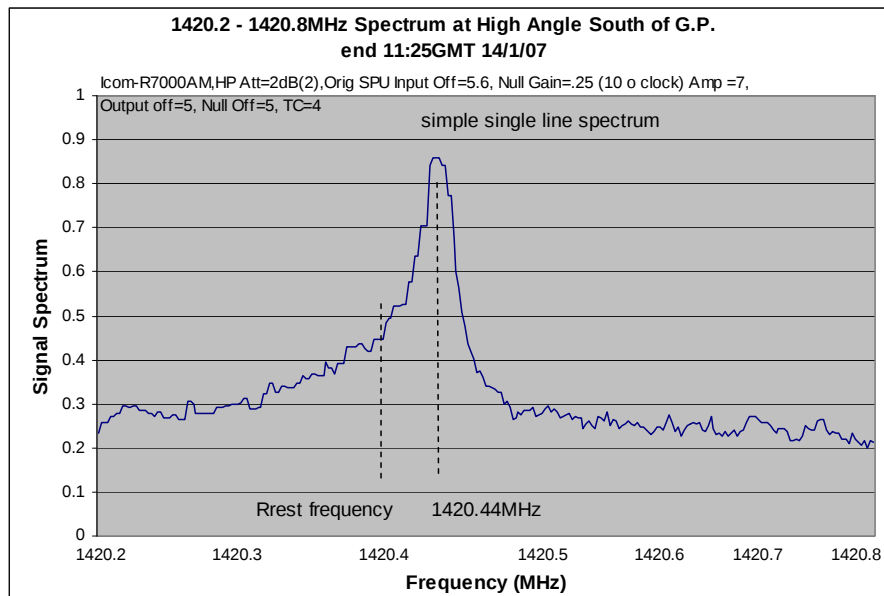


Figure 8 An example of a simple H Line spectrum
when observed away from the Galactic Plane

By contrast, Figure 9 shows a complex spectrum with component sources at multiple Doppler shifted frequencies (red lines) when the antenna beam is looking within the galactic plane.

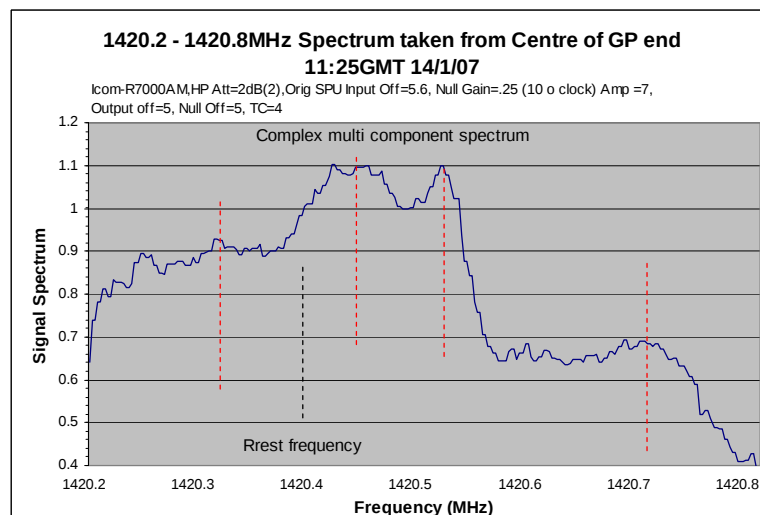


Figure 9 A Complex Spectrum when observing within the Galactic Plane

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

6 REPRESENTATION OF CHANGING H LINE SPECTRA

Each of the thirty seven, four and a half minute long frequency scans, can be plotted together in a 3D format to show clearly how the Hydrogen Line spectrum changes with position with respect to the galactic plane. This view gives some insight into the way different Doppler shifted frequency components build and decay as the beam passes into and through the galactic plane.

For clarity, two images have been produced: the first one in Figure10, shows the H Line evolution as the beam moves from galactic north to the centre of the galactic plane. The second, shown in Figure 11, shows the evolution from the mid-galactic plane towards galactic south.

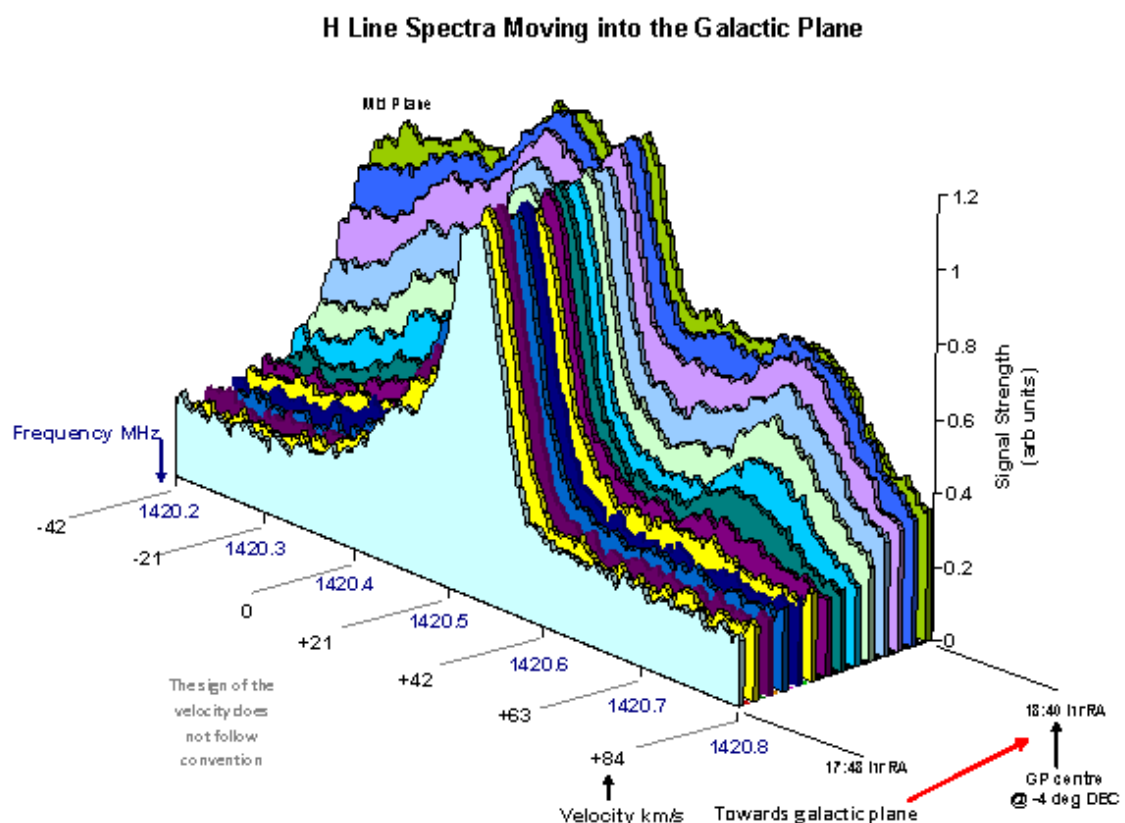


Figure 10 Evolution of H line Spectra towards the Galactic Plane

It is clear that the complexity of the spectrum increases towards the galactic plane and then reverts to a simple one when moving away again. The signal strength of the central 1420.45MHz line increases toward the galactic plane

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

and then falls away again in response to the integrated density of neutral Hydrogen along the line of sight.

The H Line signal strength is greater along the track into the galactic plane than it is moving out of the plane and may be due to extensions or wisps of material on the northern side of the plane, possibly connected with the northern galactic spur.

Presentation of the spectra in this form can be useful in showing the development of multiple spectral features deriving from the emission of Doppler shifted signals from individual elements of the spiral galaxy structure – notably the spiral arms.

H Line Spectra Moving out of Galactic Plane

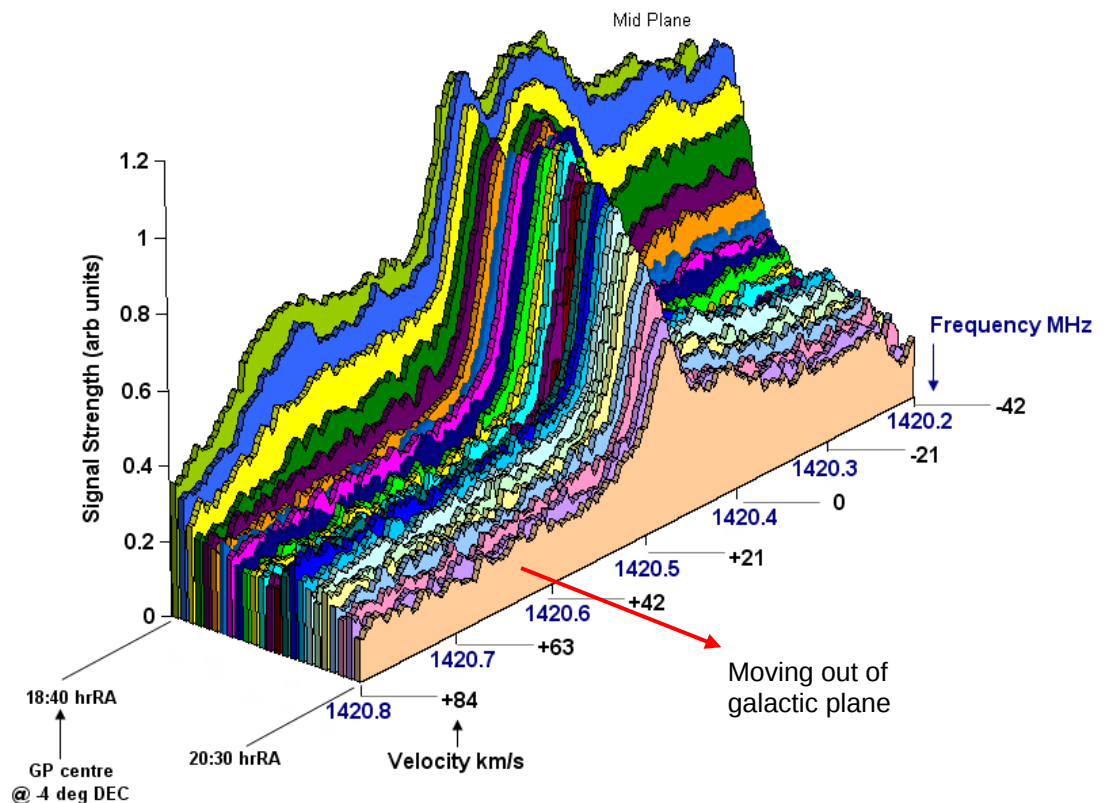


Figure 11 Evolution of H line Spectra when moving out of the Galactic Plane
By plotting the data in a 2D form we can estimate the Doppler shifted frequencies of some of the neutral Hydrogen structural components that are emitting. In Figure 12 we see that there are 4 main components present at: 1420.32MHz, 1420.42MHz, 1420.53MHz and 1420.69MHz.

The approximate corresponding line-of-sight velocities can also be seen in Figure 12. (Approaching velocities are shown as +ve - this is opposite to the accepted convention)

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

H Lines Spectra Moving into the Galactic Plane

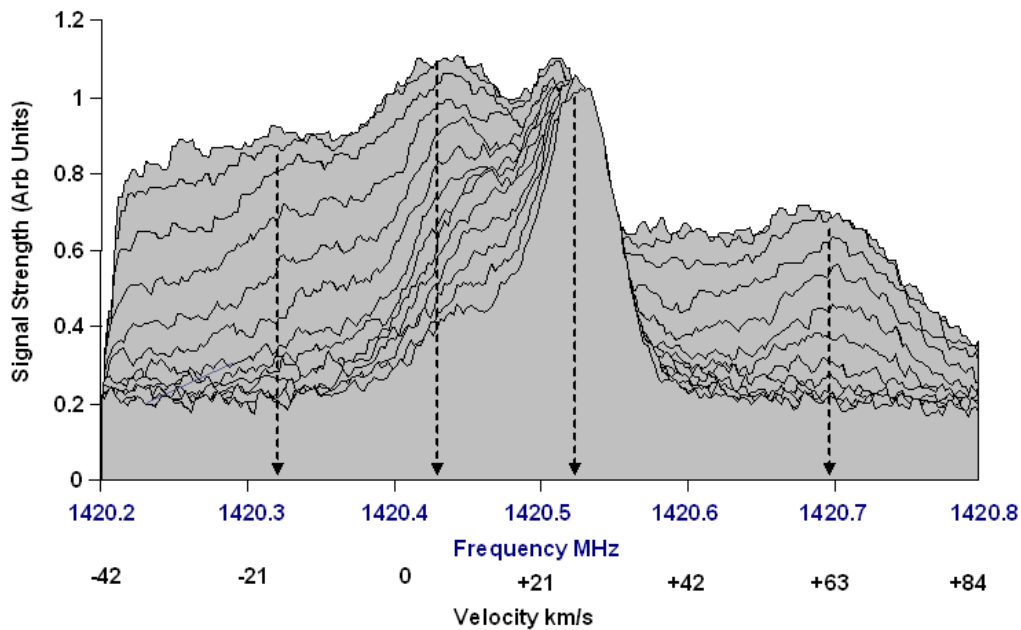


Figure 12 Doppler shifted Frequency Components within the Galactic Plane

With some detailed investigation, it should be possible to set out the galactic geometry appropriate to this measurement and try to determine the probable sources of these different Doppler shifted contributions. However, this is quite a complicated process as the line-of-sight velocity components of the Earth's rotation, the orbital velocity component and any velocity of the Sun with respect to the Galaxy as a whole, would need to be taken into account².

The situation is depicted in Figure 13.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

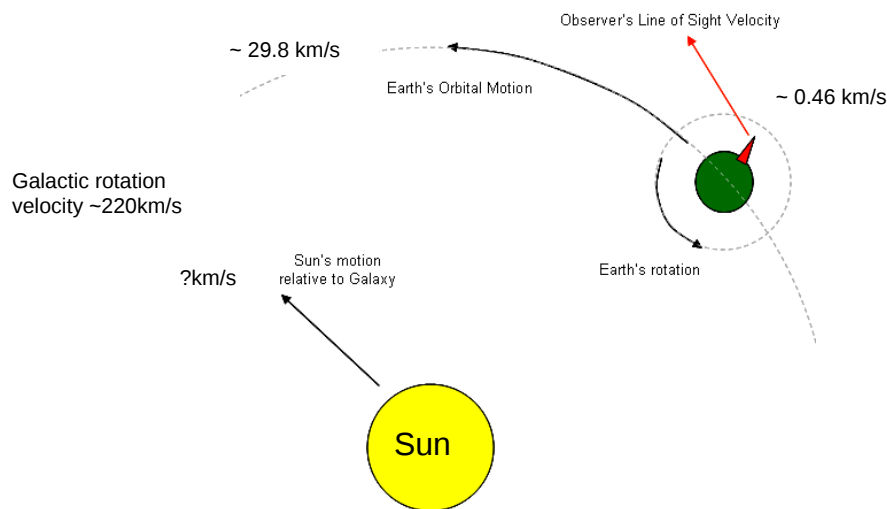


Figure 13 Components of Observer's Motion

This is a complicated picture and requires access to a professional Ephemeris to go back to the date the records were taken and find the appropriate velocities for the different components that contribute to the observer's motion. This has not been attempted in this exercise, however a good description of this process is given by Köppen ².

Professional radio astronomers (Kerr & Westerhout 1964) have been able to take all the relative motions into account and, by assuming a rotational model of the galaxy, processed the Doppler shifted H Line signals to produce an almost complete map of the Hydrogen distribution in the galaxy as shown in Figure 14. The yellow dot indicates the position of the Sun. The spiral arm structure of the galaxy is quite clear in this plot. The blank segments are regions where the line-of-sight Doppler shift is very small and processing is difficult, or signals are obscured by the absorption in the galactic centre.

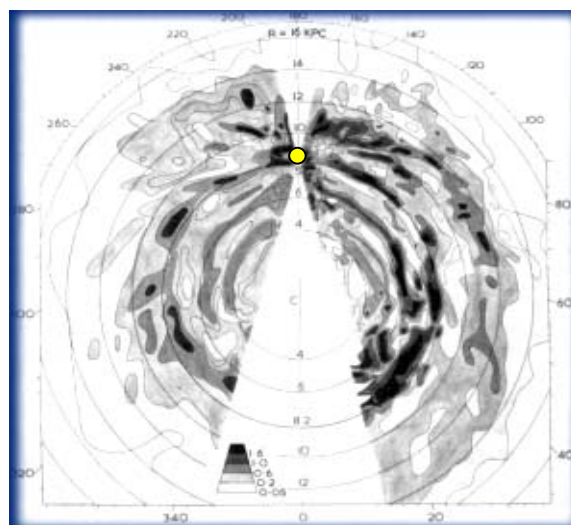


Figure 14 H Line map of the Milky Way (Kerr & Westerhout 1964)

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

It is useful to have a view of the Milky Way that shows the spiral arms and the position of the Sun relative to the various galactic features. In Figure 15 we see the assumed make up of the galaxy with named spiral arms, the position of the Sun and the system of galactic coordinates with the Sun as the origin.

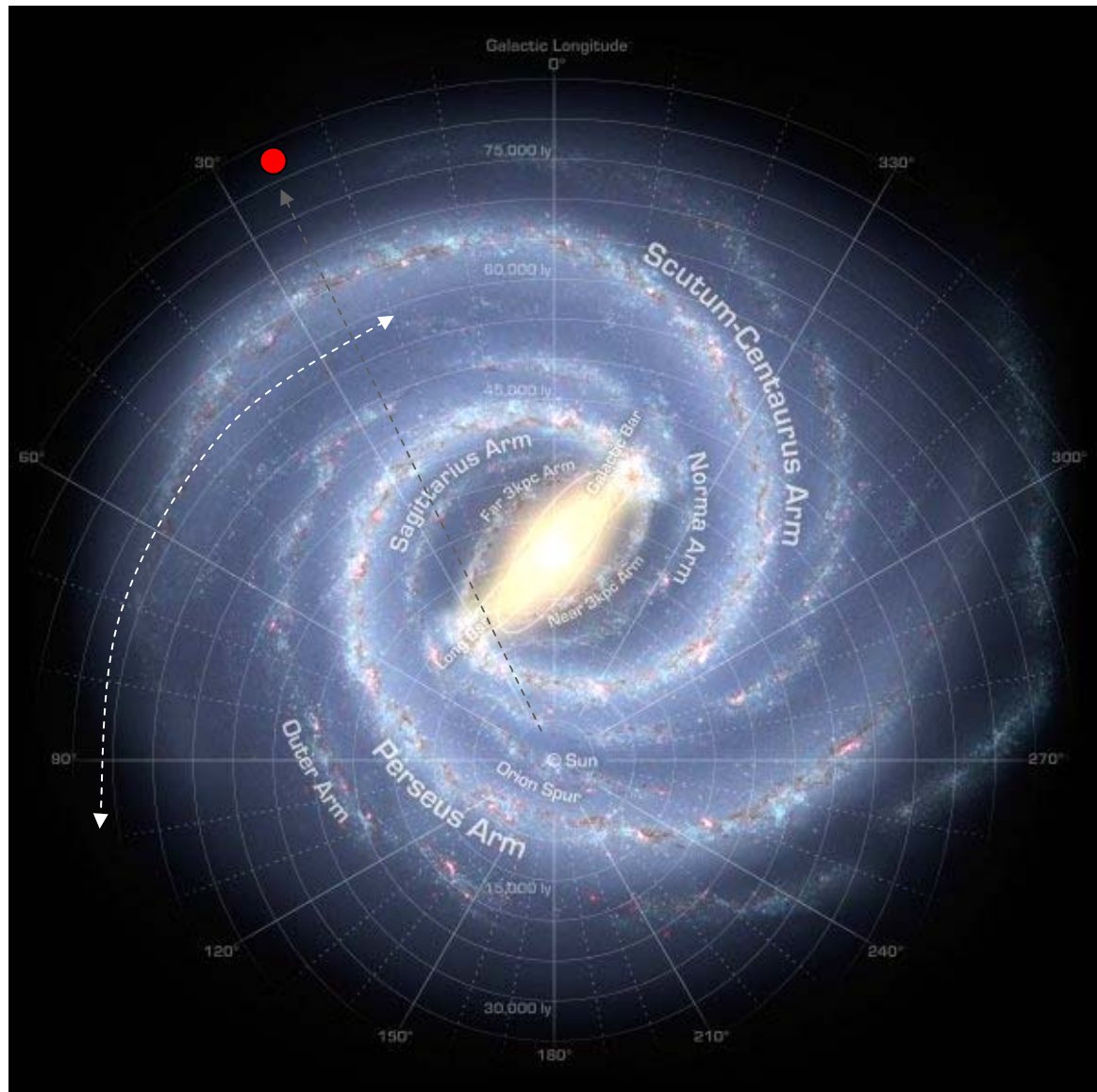


Figure 15 The Milky Way with Galactic Coordinates

The measurement of H line spectra across the galactic plane reported in this document was made at $\sim 25^\circ$ galactic longitude and is indicated by the red circle in Figure 15.

The white broken line indicates the range of galactic longitudes covered by the H Line map generated by the author in 2007 and shown in Figure 19.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

7 DOPPLER SHIFTED H LINE EMISSIONS AS A FUNCTION OF RIGHT ASCENSION

It is possible to 'cut' the spectrum data, shown in Figure 6, by nominating a frequency and plotting the signal strength as a function of position (Right Ascension). This shows the way the emission at this particular Doppler shift (velocity) changes, as we move across the galactic plane. From Figures 10 and 11 it is clear that the shape of the plot will be different near the central frequency around 1420.5MHz, from those above and below at 1420.8 and 1420.3 MHz. These plots can be seen in Figures 16 to 18.

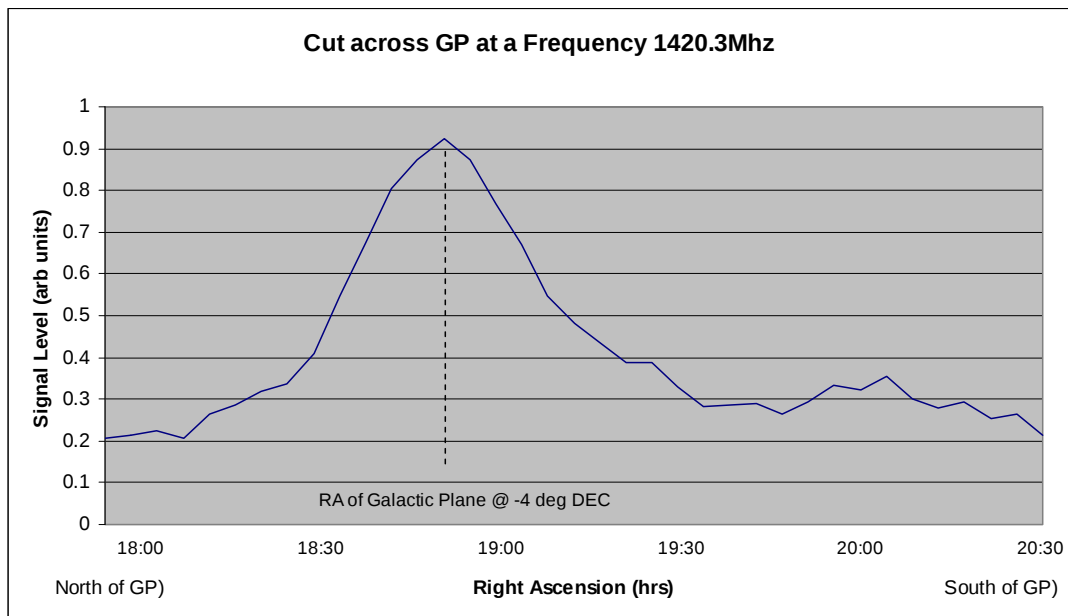
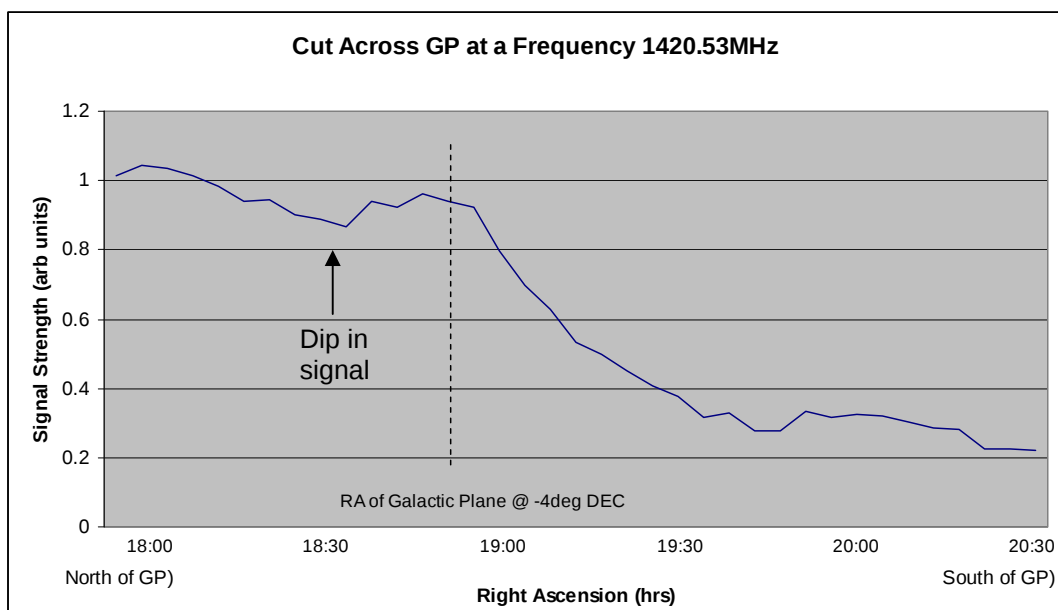


Figure 16 Variation of Signal Strength at 1420.3MHz with Position



Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Figure 17 Variation of Signal Strength at 1420.53MHz with Position

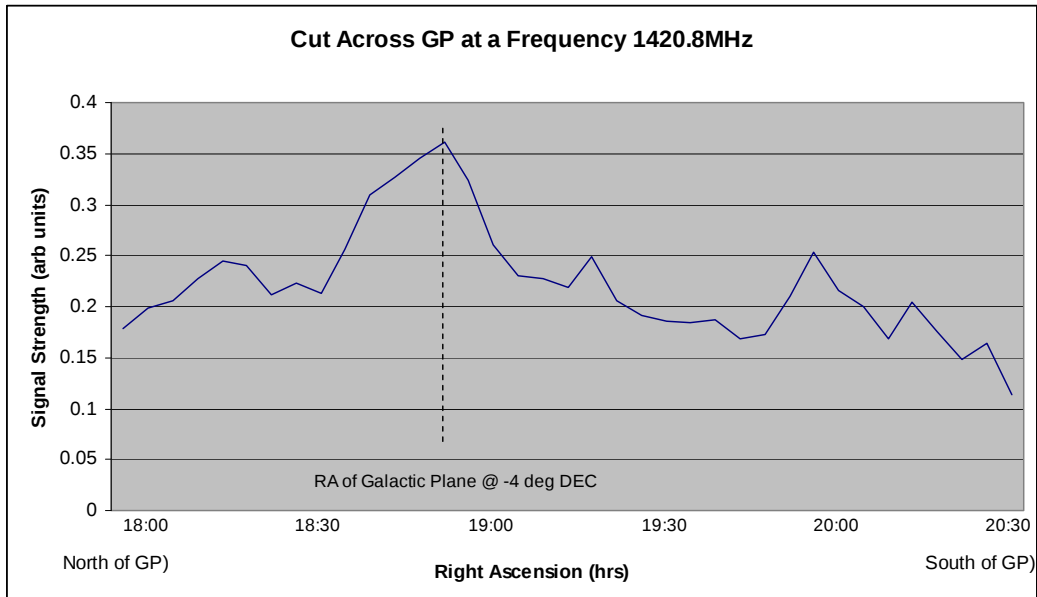


Figure 18 Variation of Signal Strength at 1420.8MHz with Position

In Figure 16 we see the profile of the signal strength at 1420.3MHz as a function of position (Right Ascension). It is a simple single peak at ~ 18:45hrs RA and this corresponds to the position of the galactic plane at a Declination of -4° . In Figure 17 we choose a frequency of 1420.53MHz which is much closer to the Hydrogen line rest frequency and would be emitted by gas with low relative velocities. The profile in this case is very different from Figure 16 and shows strong emission to the north of the galactic plane, with another peak at the centre of the galactic plane and then falling away sharply to the south of the plane. These features can also be recognised in the Hydrogen Line map shown in Figure 19.

This Hydrogen line intensity map was produced by the author, by a process described in Appendix B. If we look in detail at the signal levels along the RA track of the beam from 17:48hrs to 20:30hrs - denoted by the horizontal dashed black and white line - we can see some similarities with Figure 17.

Starting from the right side of the track on the map, we have a high signal level denoted by the yellow contours. The signal strength then diminishes somewhat as we enter a region of green contours. The intensity then increases again as we cross more yellow contours, before falling away through greens to blues (blue = low signal).

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

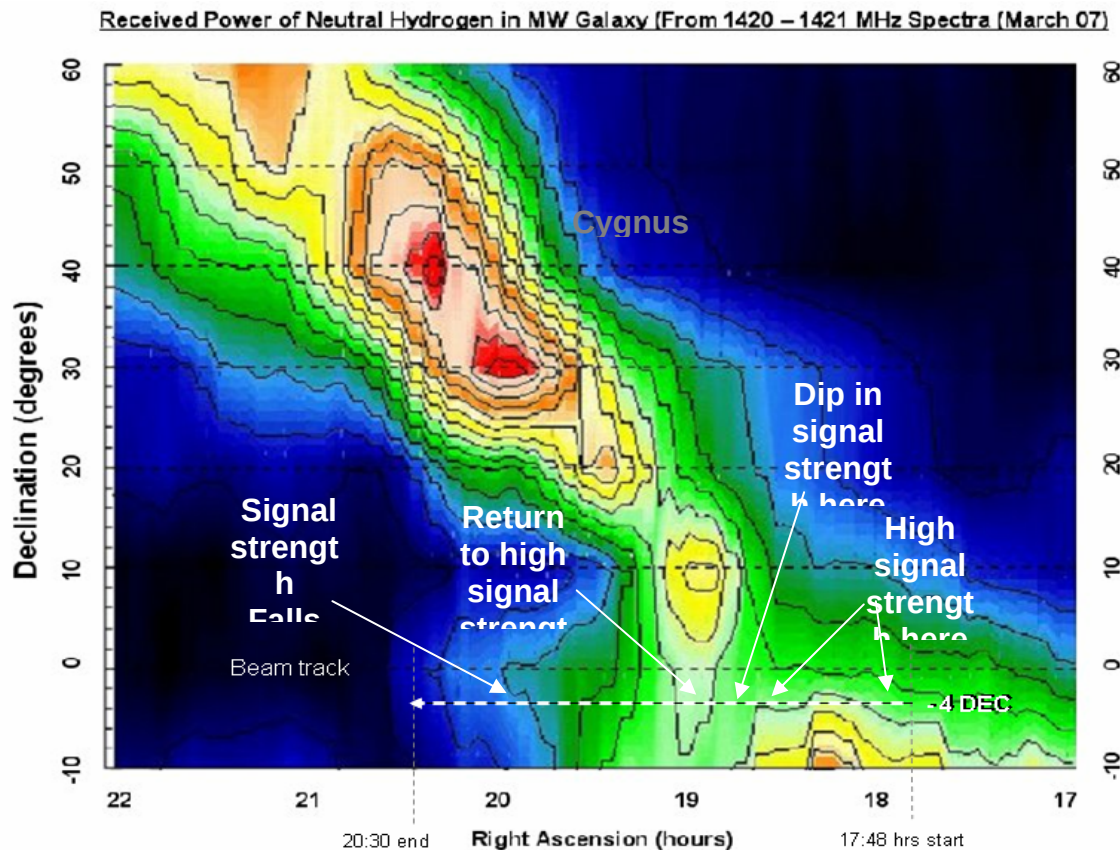


Figure 19 Hydrogen Line Intensity Map (All Frequencies)

Figure 17 shows the profile at a frequency of 1420.8MHz corresponding to a high approach velocity of $\sim +84\text{km/s}$. The overall signal strength is much smaller at this frequency, indicating that the integrated line-of-sight density of Hydrogen with this velocity is relatively small. The graph shows one peak at the location of the galactic plane with fluctuations to either side (some of which may be noise).

It is possible to visualise the whole of the Frequency / position space by creating a false colour map. This can show how the intensity of signals over the whole frequency band changes with position – and is the subject of the next section.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

8 Frequency (Velocity) as a function of Position (Right Ascension)

The data file as shown in Figure 6 can be processed in a suitable software package (eg Stanford Chart) to generate a false colour map of the frequency / position space. The result is shown in Figure 20, where we see a number of features very clearly:

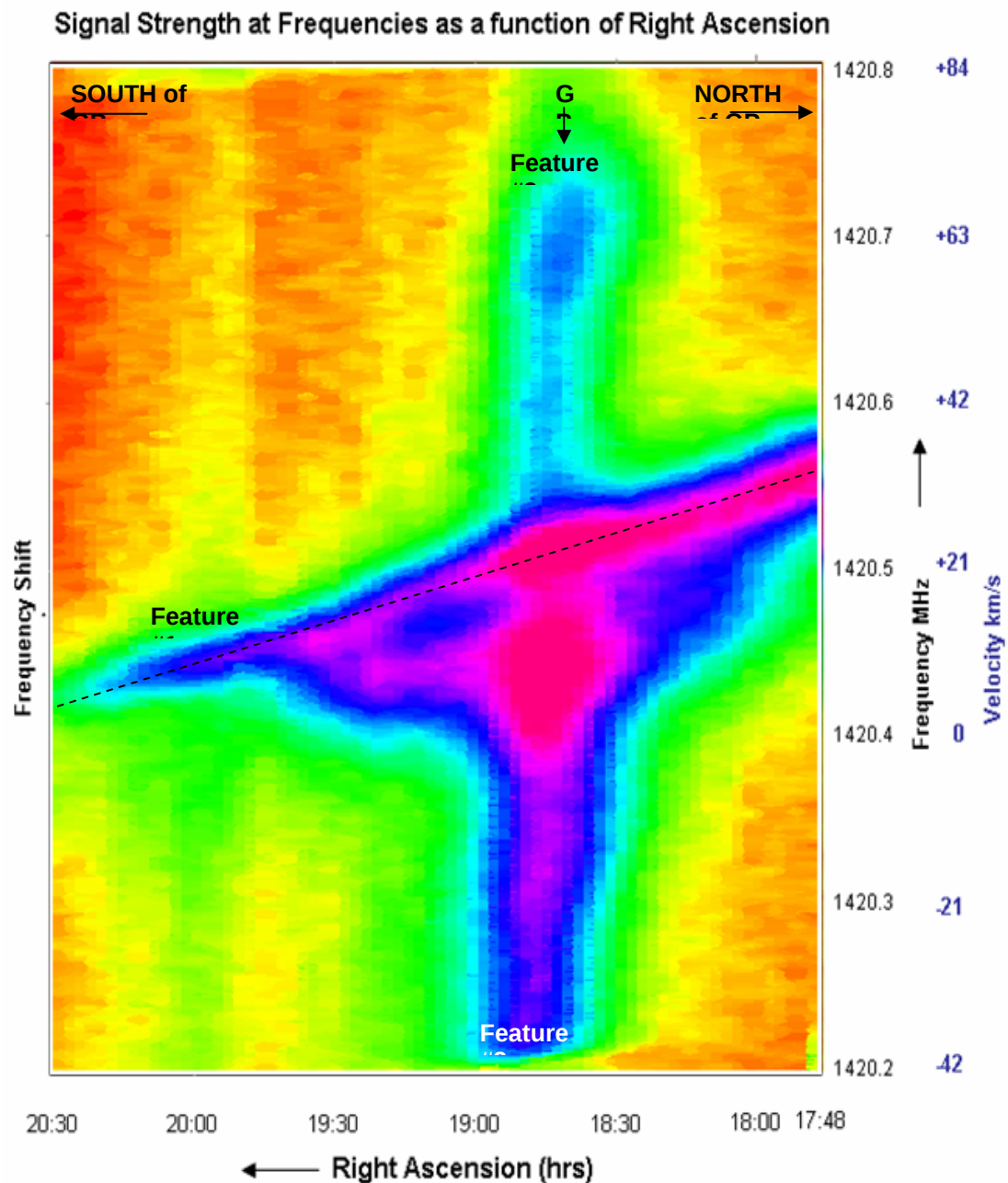
- There is a band of emissions between 1420.4 and 1420.6MHz that is not localised to the galactic plane (feature #1).
- However along the galactic plane, there is strong emission from 1420.55MHz down to 1420.2MHz (feature #2).
- There is also some weaker signal along the galactic plane at frequencies from 1420.55 to 1420.7MHz (feature #3).
- Feature #1 extends over a wide range of Right Ascension positions and is particularly strong to the north of the galactic plane
- The feature #1 signal appears to drop in frequency systematically as the position changes, moving across the galactic plane from north to south. This implies a regular change in the line of sight velocity of the emitting hydrogen which falls as the observation moves in this direction. This is a rather clear and regular feature that may arise from a simple objective physical cause related to the galactic structure of hydrogen. This has been examined further in Appendix A. However, the possibility exists that it could also be due to a small systematic effect in the frequency scanning timing, giving rise to a false picture of a falling frequency.

Currently we are not able to eliminate this possibility without improvements to the receiver system. In the future it is hoped to implement a digital frequency scanning receiver system and use this to generate data that is tied to exact frequencies at the start and end of each scan. With such a system it would also be possible to very accurately collect spectral data over the range of Right Ascension that covers the galactic plane along its equator.

It would then become possible to investigate the Doppler shifts from Hydrogen along the galactic plane rather than a 'cut' across it, as has been done in this article. One would expect very interesting and possibly complex results. Appendix A shows such results obtained by other amateur radio astronomers such as Köppen⁷ and Michlmayr⁵.

However, even a 'cut' at a single galactic longitude ($l=25^0$) shows these interesting features, as can be seen in Figure 20 below.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane



Note Velocity in this diagram does not follow convention: -ve is receding & +ve is approaching

Figure 20 Frequency / Position space - False Colour Map

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

9 CONCLUSIONS

- This article shows that it is possible for amateur radio astronomers with relatively simple equipment to detect, measure and map the Hydrogen Line signal strength and the relative velocity of source regions in the Milky Way.
- The receiver used in this exercise was programmed to automatically and repeatedly scan the frequency range from 1420.2MHz to 1420.8MHz over a period of several hours during a transit scan across the galactic plane at -4° declination.
- The data stream was broken down into blocks representing one scan of the frequency range in a time period of 4 minutes and 24 seconds. During this time the 8° wide HPBW beam moved only 1.1° across the sky.
- There were 37 spectrum blocks from which various graphs were plotted.
- The spectrum was seen to change markedly during the scan from north of the galactic plane to the south of the plane. The most complex spectra, suggesting up to four Doppler shifted signal sources, were evident when the beam was in the galactic plane.
- Outside the plane, the spectra were from simple single sources emitting frequencies close to the H Line rest frequency – indicating relatively low line-of-sight velocities.
- The 'Frequency / Position space' false colour map showed up some interesting features:
 - Along the galactic plane there was a broad band of signals from 1420.55MHz to 1420.2MHz (feature #2) indicating a predominantly receding LOS source or sources.
 - There was a weak band of emission at frequencies from 1420.55MHz to 1420.8MHz (feature 3), indicating a source or sources approaching the observer with LOS velocities up to $\sim +60\text{km/s}$. It is possible that the strong receding signal sources are local to us and that the weaker signal from the approaching sources may have travelled some distance across the galaxy – possibly from another spiral arm? It is also possible that this band of weak signals may be due to Synchrotron emission and is only visible where the stronger H line emissions do not mask it.
- The most interesting feature is number 1. In order to resolve the issue of the cause of this steadily falling frequency feature in the false colour map, it is necessary to remove any possibility of an instrumental artefact by improving the accuracy in timing the start /end of the spectrum data blocks. The steady change in frequency with Right Ascension of feature #1 has been explored in data generated by other amateur radio astronomers and is discussed in Appendix A.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

APPENDIX A FURTHER INTERESTING H LINE SPECTRAL DATA

Information on Hydrogen line spectra has been produced by other amateur radio astronomers. Some of their data are presented in this Appendix and can be compared with data produced in the main article.

The spectra shown in this section have all been obtained at different galactic latitudes and these can be seen plotted in Figure A1.

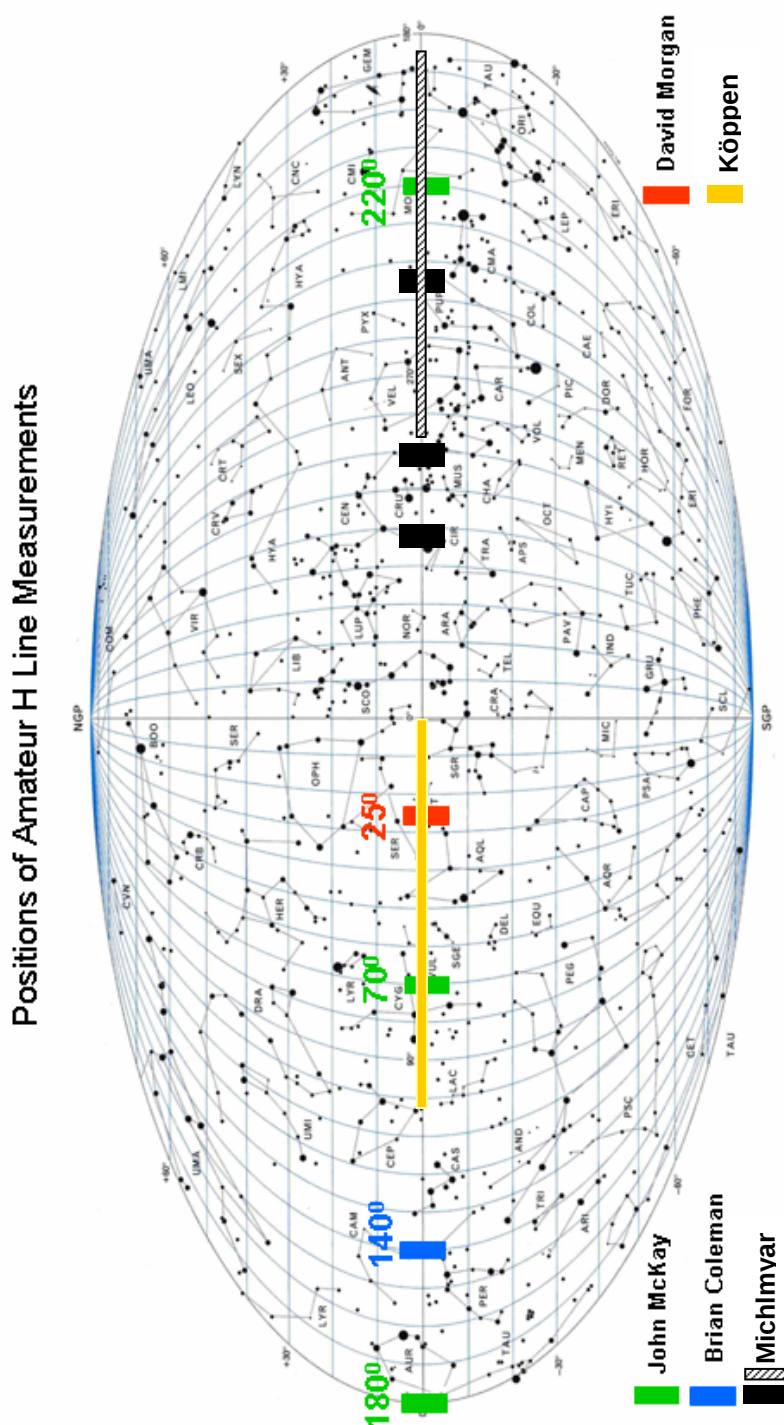
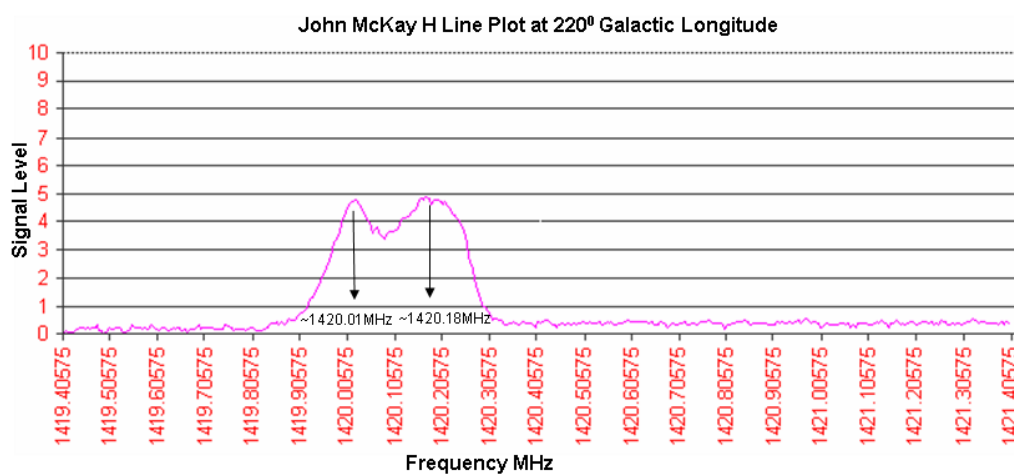
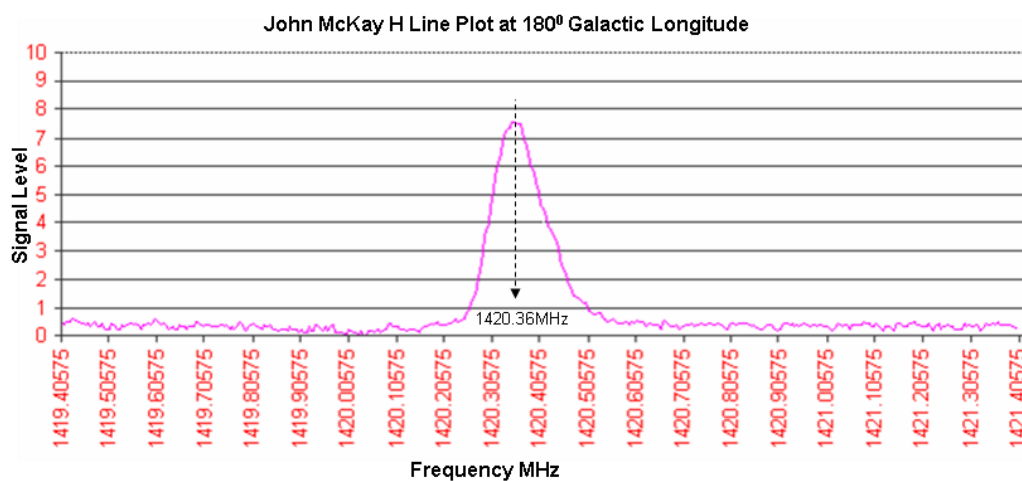
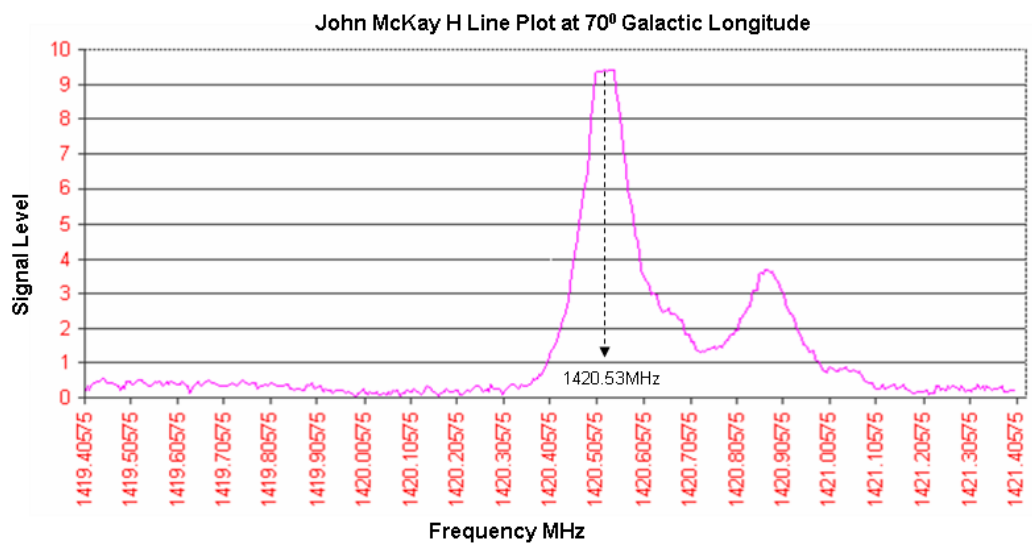


Figure A1 Positions of H Line Measurements

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

The spectra shown below are produced by John McKay³ at $l = 70^\circ, 180^\circ$ & 220° .



Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

This sample spectrum has been measured by Brian Coleman ⁴ at 140⁰ galactic longitude.

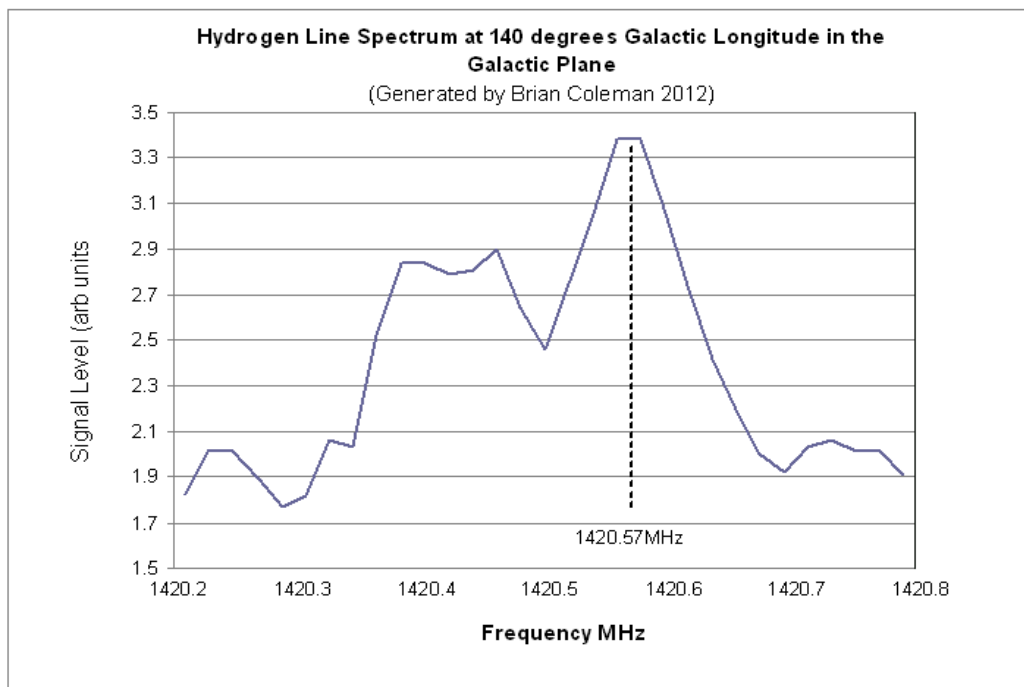


Figure A3 H Line Spectrum measured by Brian Coleman

The collection of spectra shown below were measured by the author.

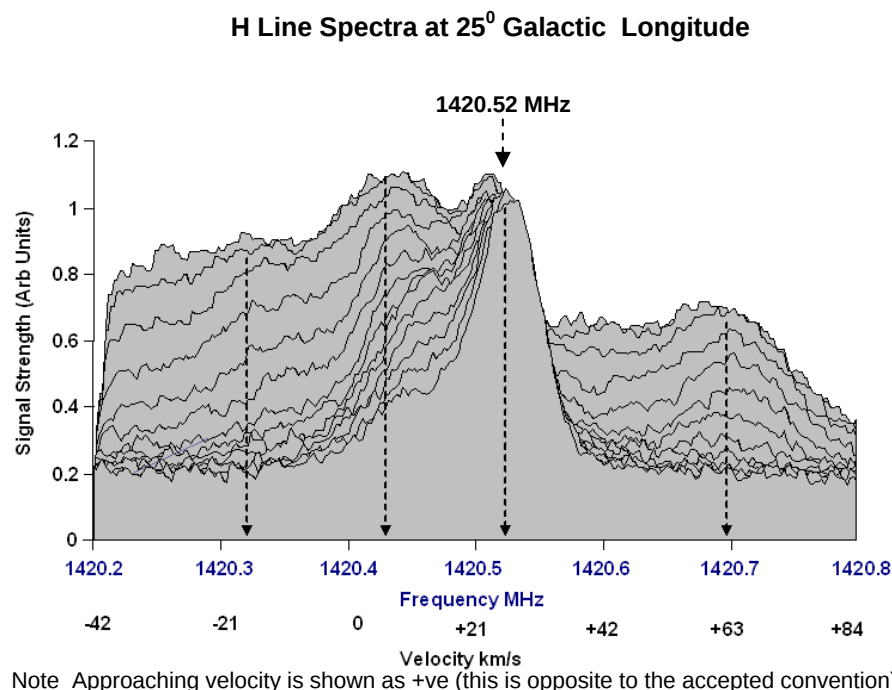


Figure A4 Typical H Line Spectra shown in this article (D Morgan)

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

An excellent set of H Line measurements has been made by Hans Michlmayr⁵ from the southern hemisphere, covering the range of galactic longitude from 186° to 319° . Typical example spectra are given in Figure A5 (a,b,c).

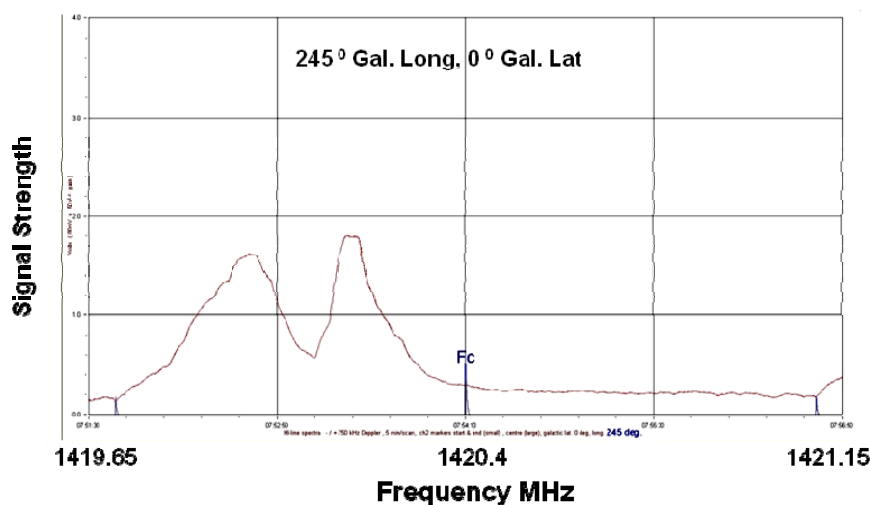


Figure A5a H Line Spectrum at $l = 245^{\circ}$, $b = 0^{\circ}$

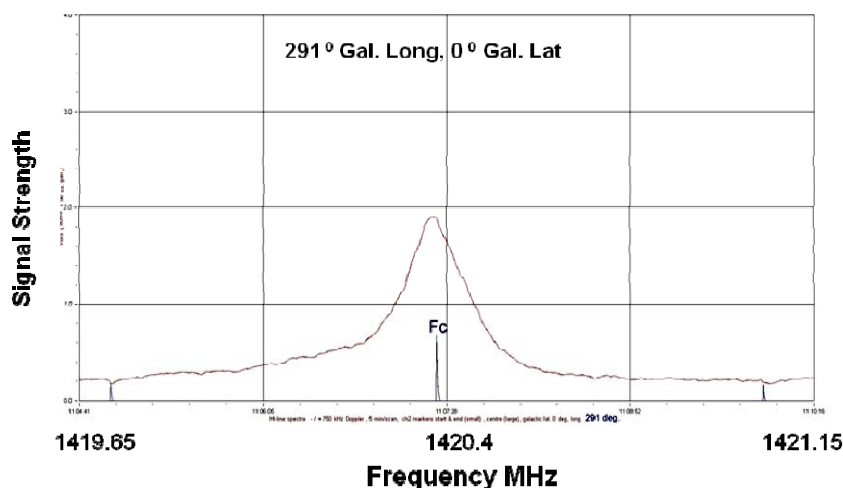


Figure A5b H Line Spectrum at $l = 291^{\circ}$, $b = 0^{\circ}$

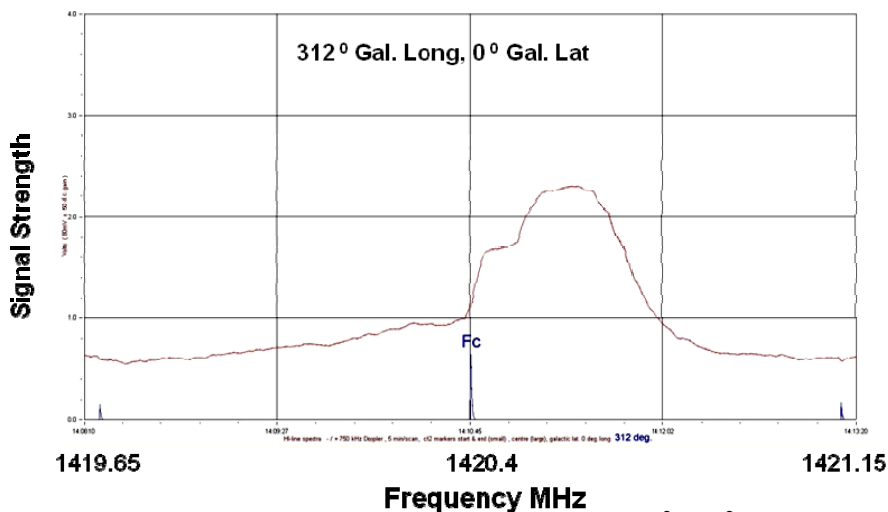


Figure A5c H Line Spectrum at $l = 312^{\circ}$, $b = 0^{\circ}$

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Michlmayr has scanned the galactic plane from 185° to 285° along the galactic equator, using a continuous scan method producing the sequence of spectra shown in Figure A6. This the same technique used by the author to produce Figure 7 in the main document and Figure B1 in Appendix B.

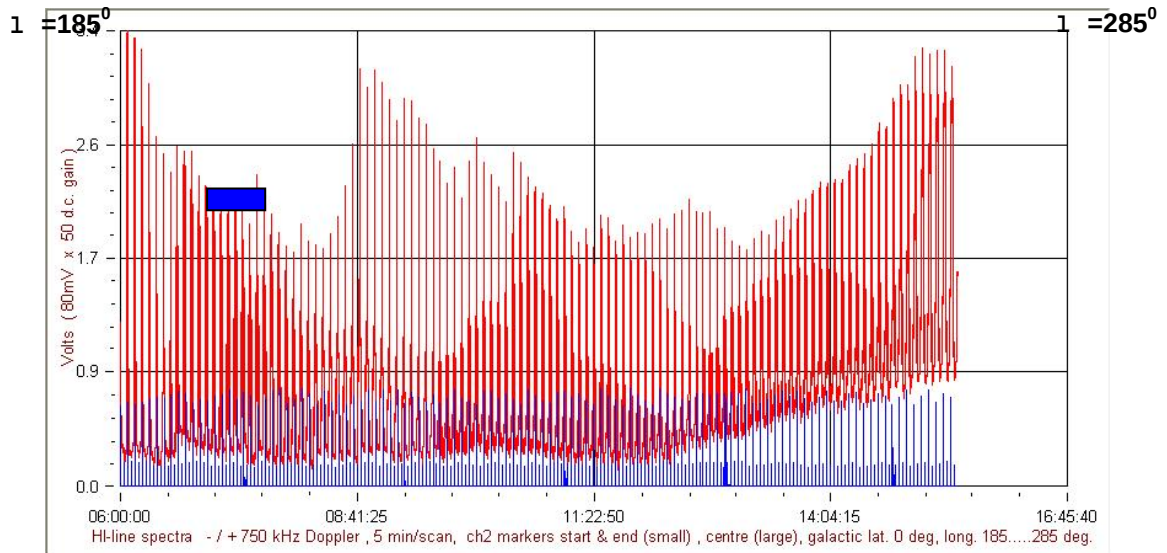


Figure A6 Michlmayr's scan of Galactic Plane from 185° to 285°

The section below the blue box in Figure A6 has been expanded in Figure A7 to show the individual spectra with two clear H Line components from hydrogen regions with different velocities.

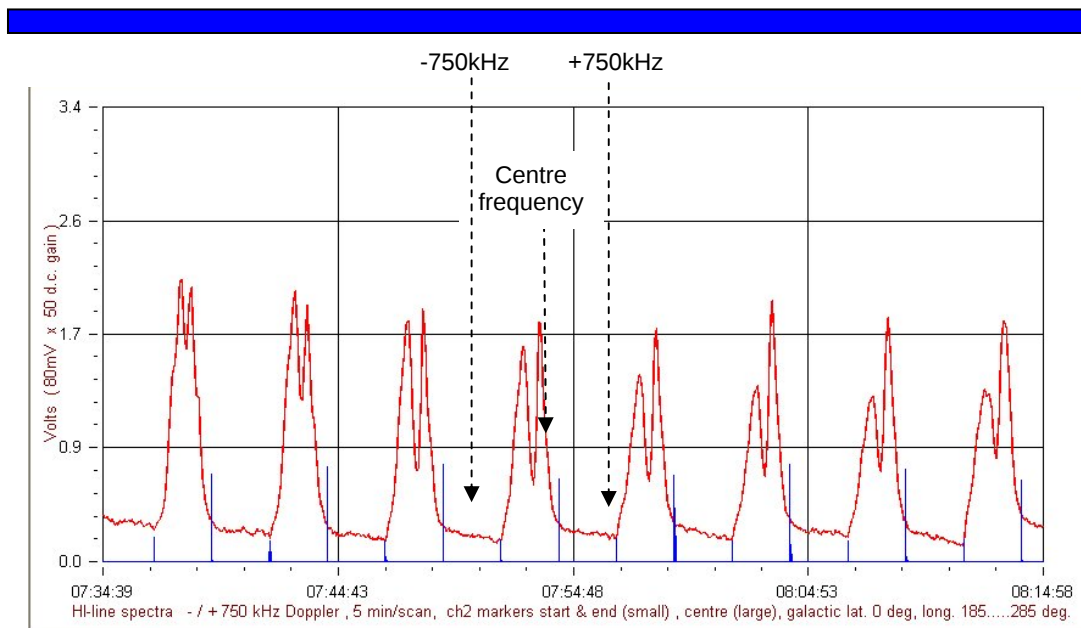


Figure A7 Michlmayr scans showing individual spectra

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

It is possible to process Michlmayr's data file - which can be found on his web site ⁵ - to yield a frequency / velocity vs position map similar to that of Figure 20 in the main document. The basic data file is ~ 10MB in size and was written using Sky Pipe software ⁶. The author has converted this file to a Microsoft Excel file and processed the data into the format shown in Figure 5 of the main document. This is quite a laborious task but can be completed accurately, as Michlmayr has also recorded markers at the start, middle and end of each 5 minute frequency scan.

The spectra in the section of Figure A8, marked with a green line have been processed to give the frequency / velocity vs position map over the range 185⁰ to 218⁰ galactic longitude. This section was chosen because one can see, by observing the spectra, that the shape of the spectrum changes from a simple single peak to multiple peaks and returns to a single peak again. This indicates more than one mass of hydrogen moving with different velocities at different galactic longitudes in the galactic plane.

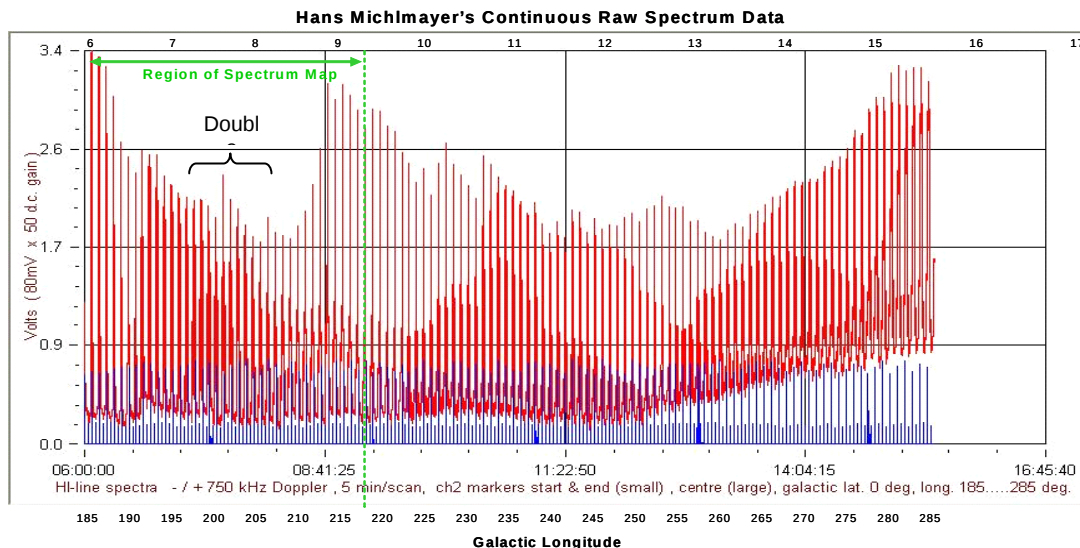


Figure A8 Selection of Spectra for Velocity / position map

The resulting map can be seen in Figure A9 and clearly show the single H line splitting into two components at around 202⁰. The feature marked 'A' then fades away, whereas the branch marked 'B' strengthens and returns to its original velocity at 'C'. This map confirms that regular frequency drifts of a few hundred kilohertz as a function of position, can exist - and lends credence to the Feature #1 shown in Figure 20 of the main document.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

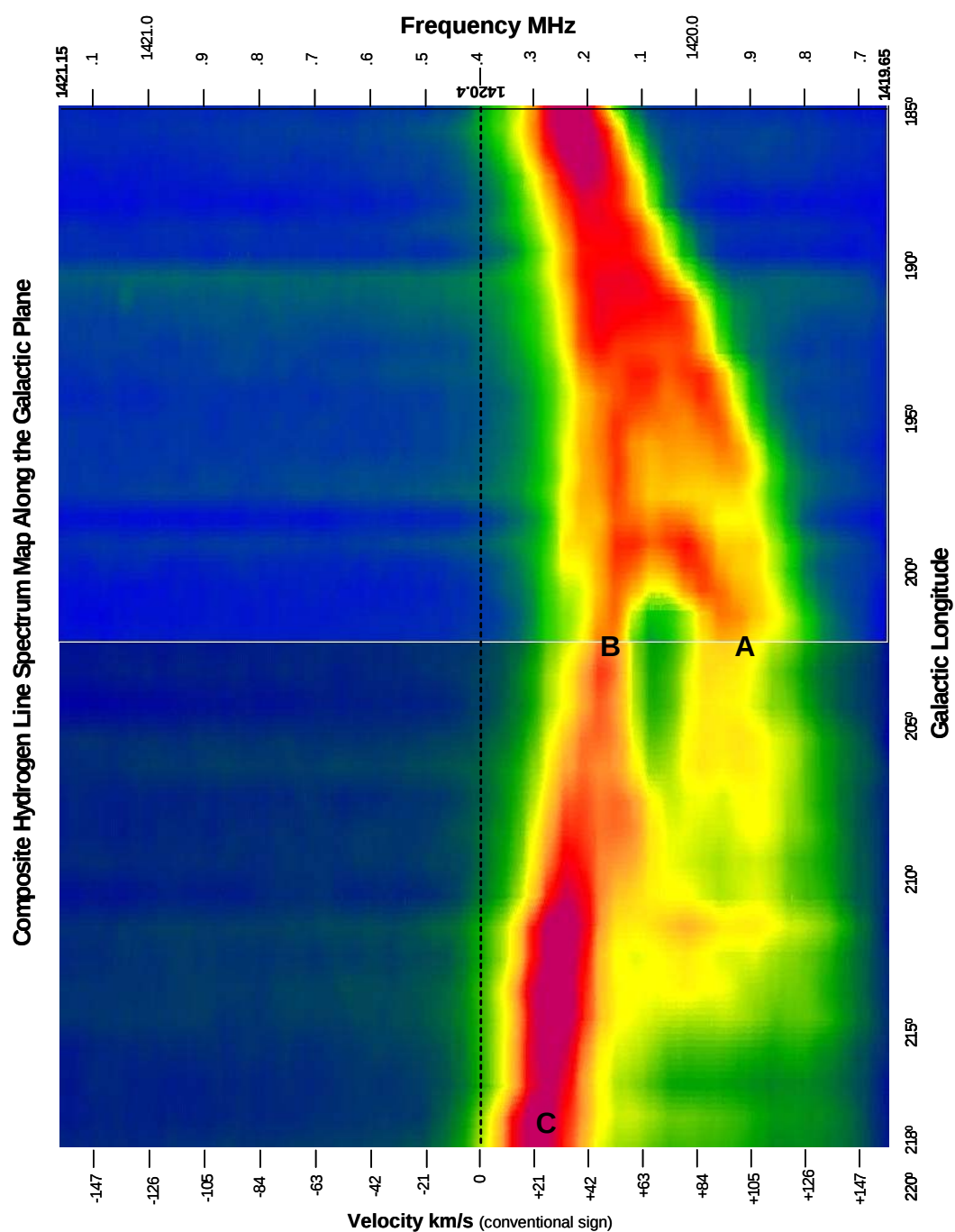


Figure A9 Velocity/ Position Map

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

The H Line velocity map in Figure A9 (above) has been located on the sky in Figure A10 to indicate its position and extent. Almost all the Hydrogen in this region is moving away from us with velocities from zero up to 130km/s.

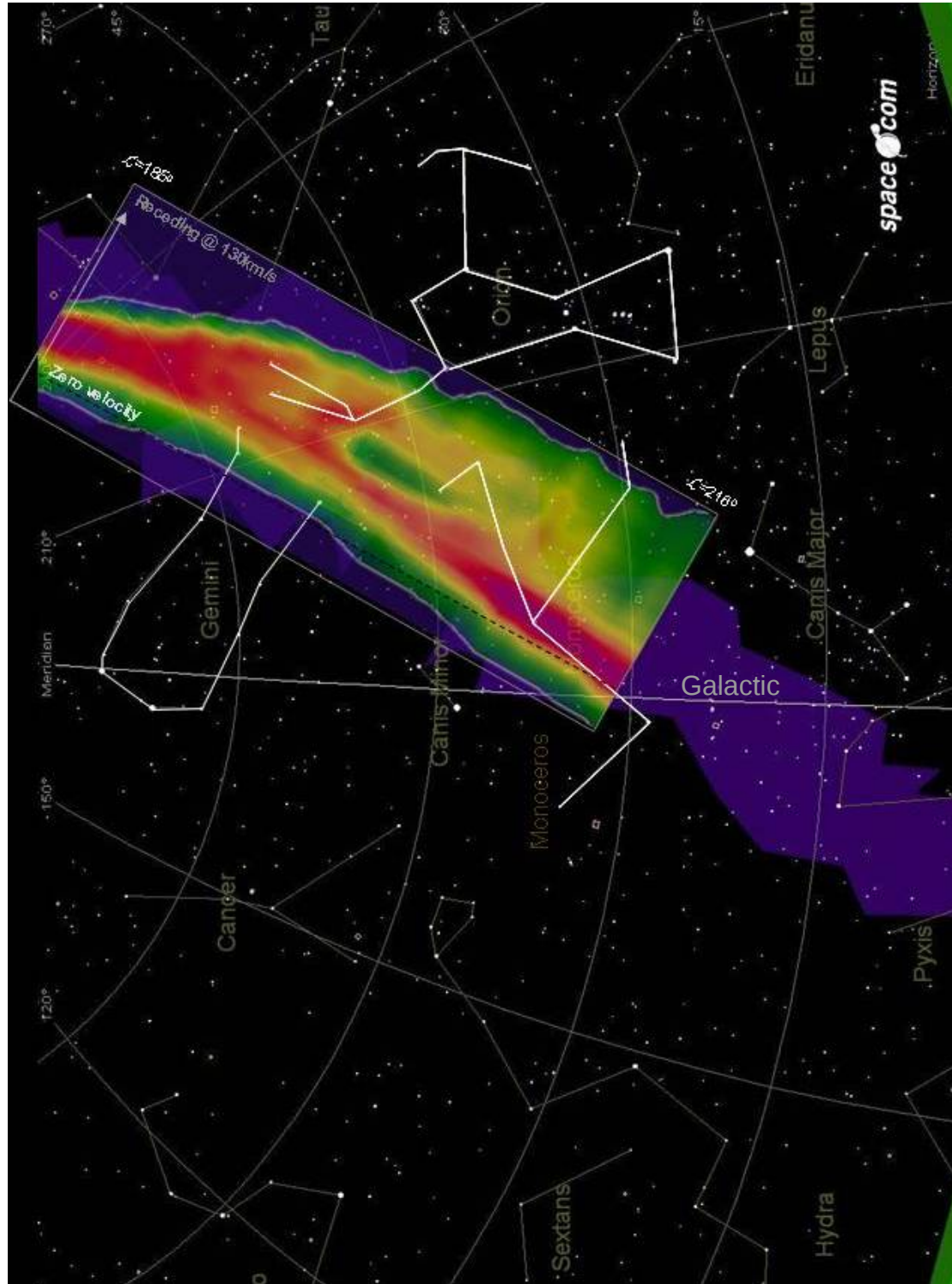


Figure A10 Velocity Map on the Sky

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

It is also interesting to look at the double emission region spectra at the position of the white line in Figure A9 in more detail. In Figure A11 below, we have identified the features A, B and C and shown them in the form of 'spectral slices' at each galactic longitude.

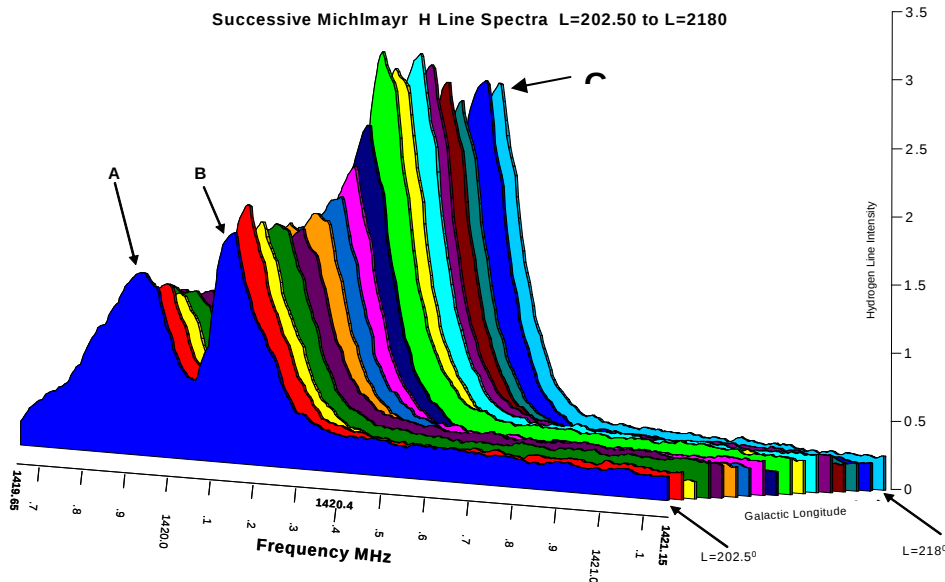


Figure A 11 'Slices' of Spectra from $l = 202^{\circ}$ to $l = 218^{\circ}$

In the author's opinion, the velocity / position maps (Figures A9 and Figure 20) are particularly useful in differentiating and visualising the multiple sources of hydrogen emissions that are captured in the beam of an antenna pointing in a particular direction. This is the case when scans are made across the galactic plane (as in the main document – Figure 20) or along the plane as described in this Appendix.

It would make the basis of a very interesting project for a group of amateur radio astronomers to collect data along the whole of the galactic plane and pool the information to generate a velocity / position map of the kind in Figure A9 for the whole Milky Way.

Finally we have a spectrum measured by Joachim Köppen⁷ from Strasbourg University. He is a professional astronomer, but is also very involved in amateur radio astronomy.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

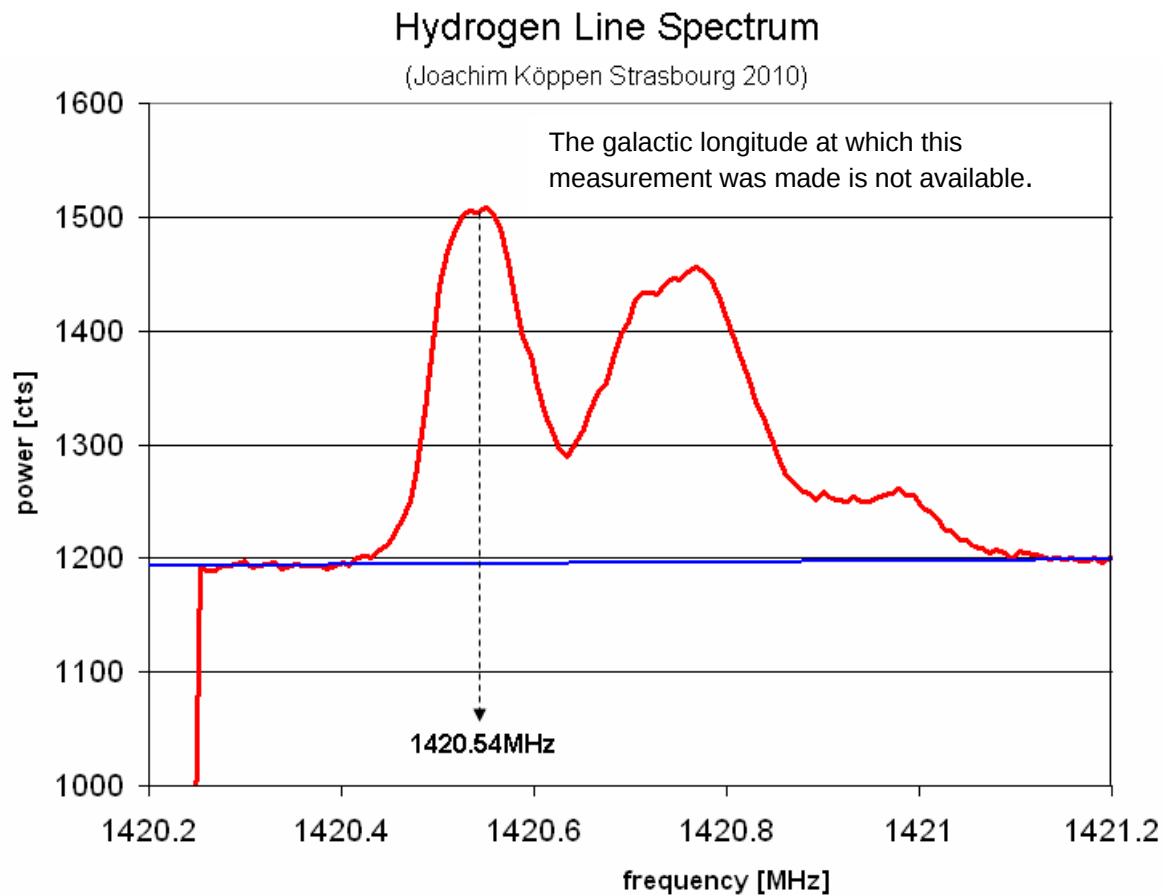


Figure A12 H Line Spectrum produced by Köppen

This information can be found at reference 7

These spectral peaks all need to be related to specific features in the galaxy. Whilst this is a somewhat complex problem of geometry, perhaps amateur radio astronomers working together within the British Astronomical Association (BAA) Radio Astronomy Group could produce a suitable model.

A very good guide to understanding the galactic rotation model has already been produced by Joachim Köppen², some extracts of which have been enhanced and reproduced below.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Précis of Joachim Köppen's observations along the Galactic Equator

Köppen has made systematic observations of H Line spectra taken in the Galactic Plane at Longitudes between $l = 0^\circ$ and $l = 250^\circ$ which is almost 70% of the Galactic Longitude.

An example of accumulated spectra from observations during the night of 15th July 2009 is shown in Figure A13, where a spectrum is recorded 25 times for every 1° in longitude from $l = 0^\circ$ to 110° .

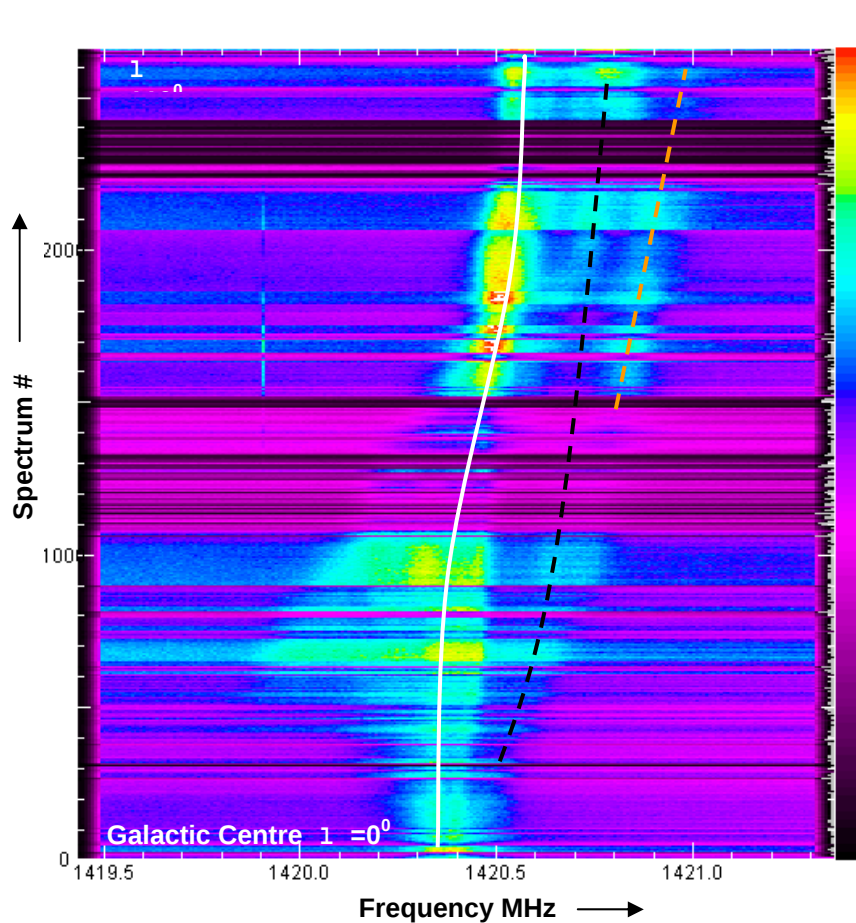


Figure A13 Spectral Waterfall plot from Galactic Longitude $l = 0^\circ$ to 110°

Looking at Figure A13, the structure of the Milky Way's gas disk becomes apparent. We notice that the emission components seen at one longitude can be traced to the others as well. (See the white, black and orange lines). It is probable that each of the velocity components constitutes a separate spiral arm.

The strong component near to 0 km/s (white line) is the Orion-Cygnus spiral arm in which our Sun is located. The two further components seen distinctly at

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

$l = 90^\circ$ at positive Doppler frequencies (black & orange) may indicate the presence of two more distant arms.

The spectrum waterfall plot has been re-cast as a radial or Line of Sight (LOS) velocity map against galactic longitude as seen in Figure A14.

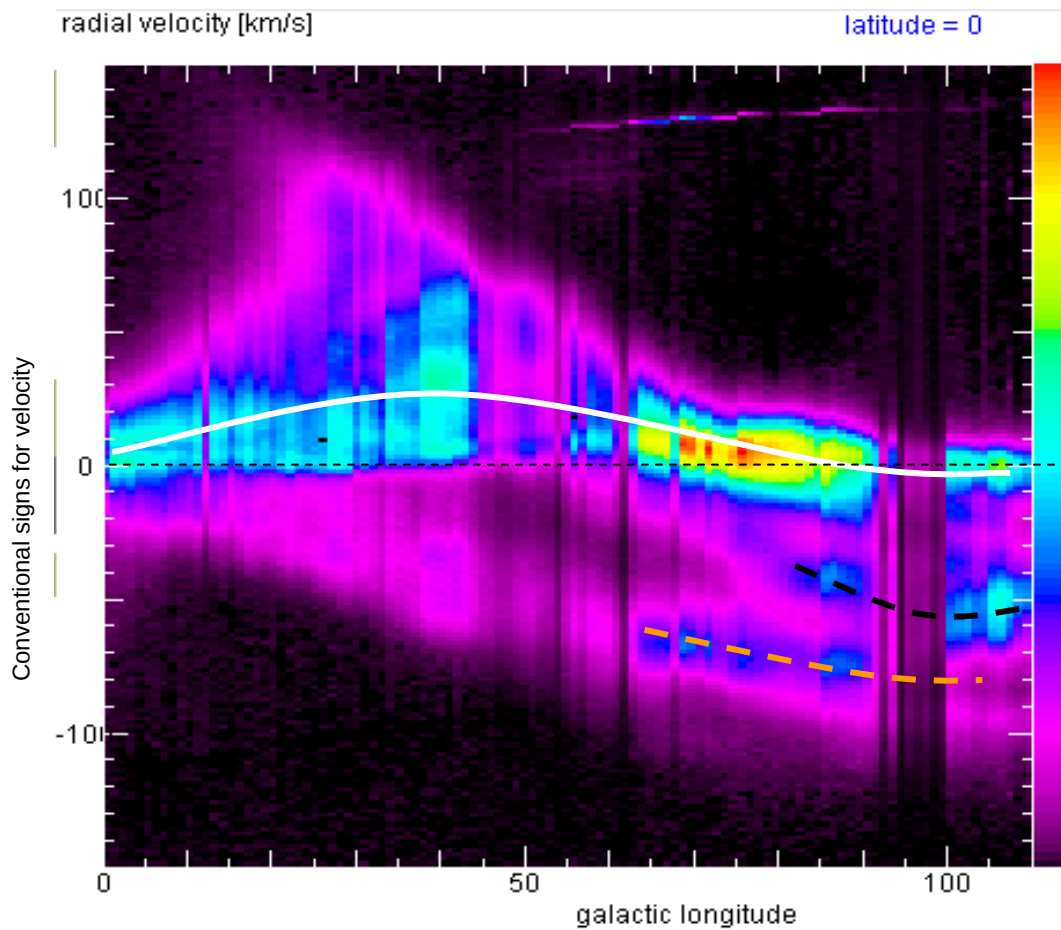


Figure A14 H line velocity map as a function of Galactic Longitude

The velocity of the local Hydrogen (white line) varies by +30km/s (receding) to <-10km/s (approaching). The spiral arm represented by the black dotted line is approaching at 40 to 60km/s - and that represented by the orange dotted line is approaching at 60 to 80 km/s.

Köppen suggests that for longitudes below 90° , one can use the 'maximal radial velocities' to derive the rotation curve of the Milky Way.

This is achieved by determining for each of the observed longitude positions the maximum radial velocity. These values permit one to derive the rotational speed in the Milky Way at various distances from the Centre.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

A typical spectrum is given in Figure A15 and the maximum velocity is marked with a black bar. This velocity is defined for each spectrum over the range of galactic longitudes being investigated.

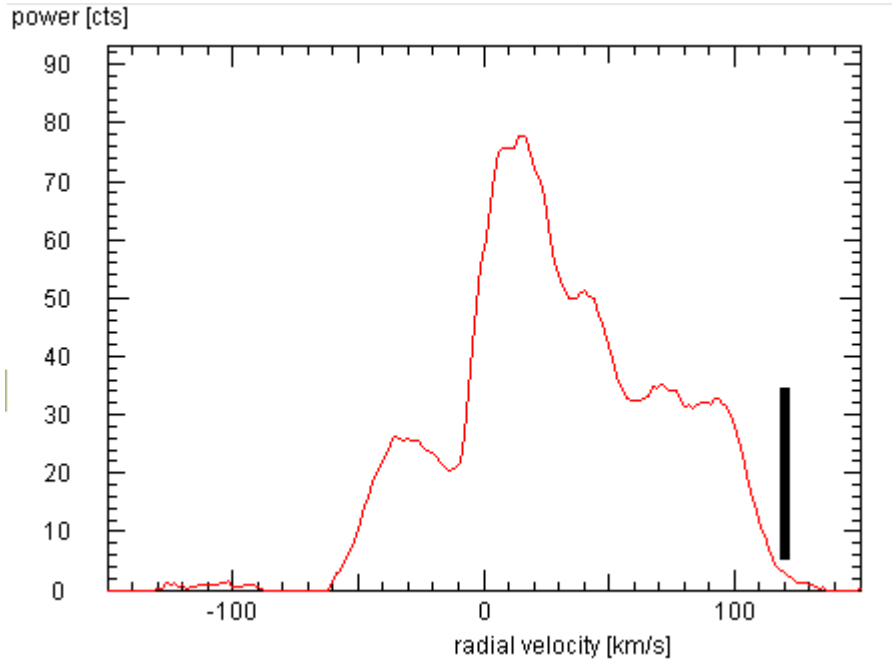


Figure A15 Defining the maximum radial velocity from a spectrum

Let us assume that all parts in the Galactic Disk are moving in circular motion around the Galactic Centre, and that the rotational speed depends in some way on the distance from the centre. If we look from the Sun into the direction of galactic plane, we observe on our line of sight a parcel of gas with radius R from the centre. We measure its radial velocity with its circular velocity $v(R)$ projected on the line of sight, with the projected velocity of the Sun subtracted. The Geometry is shown in Figure A16.

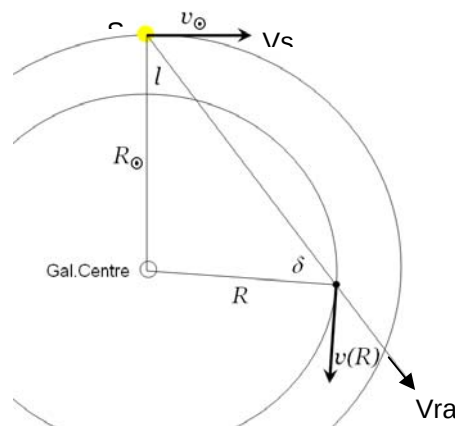


Figure A16 The Geometry of Galactic Rotational Model

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Now Köppen shows that $V_{rad} = v(R) * \sin \delta - v_{sun} * \sin l \dots\dots\dots(1)$

The maximum radial velocity is measured when the line of sight is tangential to the circular orbit: $R = R_{sun} * \sin l \dots\dots\dots(2)$ which gives

$$V_{max} = (v(R) * R_{sun}/R - v_{sun}) * \sin l = v(R) - v_{sun} * \sin l \dots\dots\dots(3)$$

Leading to $v(R) = V_{max} + v_{sun} * \sin l \dots\dots\dots(4)$

The parameter values for the Sun are $R_{sun} = 8.5$ kpc and $v_{sun} = 210$ km/s and these have been used by Köppen, with the values of V_{max} derived from the spectra, to calculate the Galactic Rotation curve shown in Figure A17.

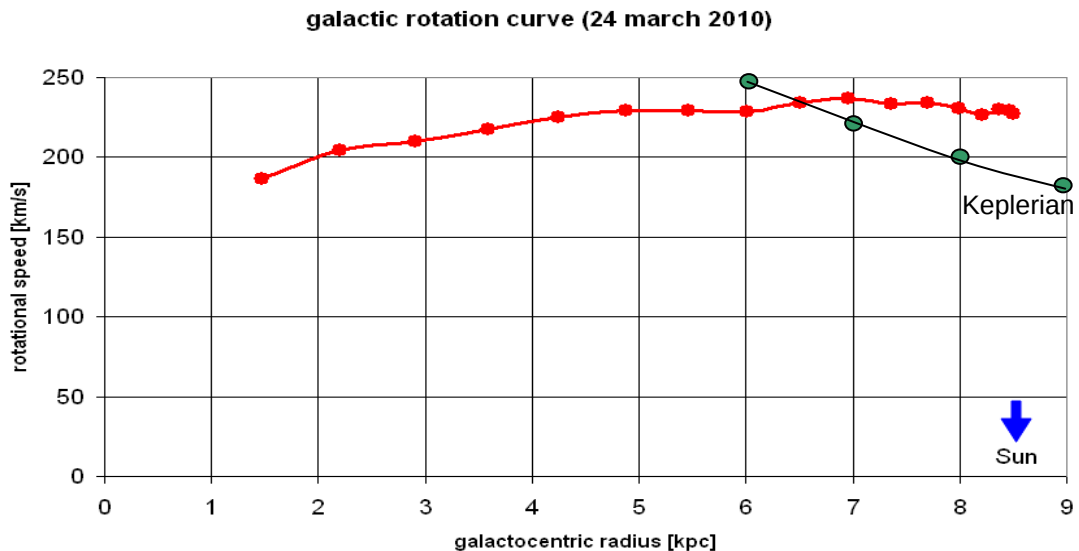


Figure A17 The Galactic Rotation Curve

In order to explain the constancy of the rotational velocity, which is quite different from the Keplerian form, the amount of visible matter (stars, gas, and dust) in a galaxy does not suffice.

It is postulated that the existence of invisible Dark Matter, whose presence is only evident by its gravitational attraction, is the responsible agent. However, to account for the rotation curve of the Milky Way one needs about ten times more dark matter than there is visible matter!

Köppen shows that with sufficient, organised spectral data and an assumed rotational model is possible for amateur radio astronomers to determine these interesting facts about our galaxy.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

APPENDIX B HYDROGEN LINE MAP OF GALACTIC PLANE

As we have seen in this article, the signal strength of the narrow neutral Hydrogen spectral line varies considerably with frequency in the range 1420MHz to 1421MHz as various sources within the galaxy move with a range of line-of-sight velocities.

If a map is to be made of the intensity of Hydrogen emissions as a function of Right Ascension and Declination, then the contributions at all frequencies in the range 1420 – 1421MHz must be included. To simply plot the signal strength at one frequency with a receiver bandwidth of <1 MHz would result in an erroneous map, as emissions at other Doppler shifted frequencies would be missed.

Without a receiver with a 1MHz wide bandwidth, another strategy must be employed. In what follows, a receiver was set to automatically scan the 1MHz wide band with a bandwidth of 6kHz and the resulting digitised spectra stored in a computer. An example of the continuous stream of spectra produced during a transit scan can be seen in Figure B1.

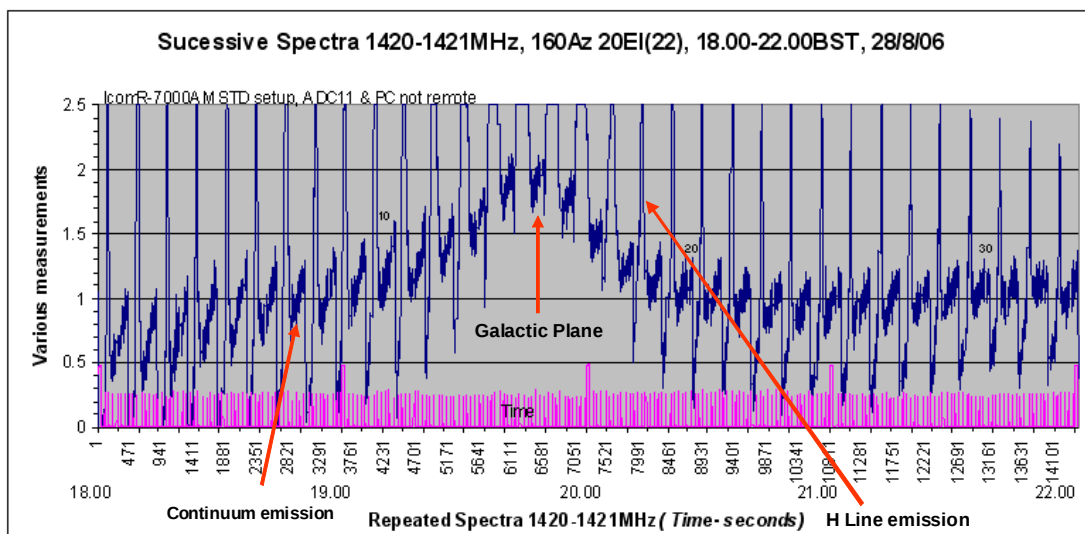


Figure B1 A succession of 1420 – 1421MHz receiver scans as the galactic plane transits the antenna beam

It is easy to see the position of the galactic plane where both the H Line signal (sharp peaks) and the background continuum – probably the Synchrotron emission signal - rise towards the middle of the plot.

In order to produce a 'true' H line intensity map we must measure the peak signal level of the sharply defined hydrogen line at whatever frequency it presents itself during each of the spectral scans.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

This can be done within software such as Microsoft Excel without difficulty. What results is an 'envelope trace' capturing the maximum signal strength in every spectrum as shown by the yellow line in Figure B2.

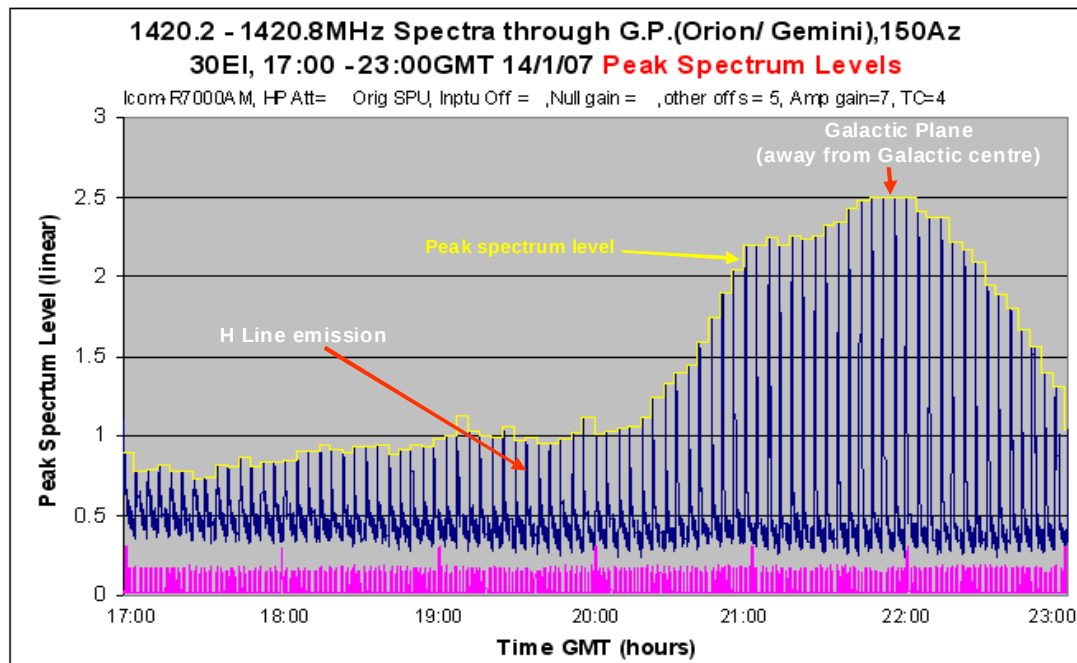


Figure B2 Calculated envelope of maximum H Line emission at all Doppler shifted frequencies in the range 1420 to 1421MHz.

These 'envelope' traces are produced and assembled for a number of transit scans at various Declinations and Right Ascensions measured on different days. From these data, a false colour map of the Hydrogen line emission – irrespective of Doppler frequency - can be generated, in this case using Stanford Chart software.

From this process we have produced a map of the maximum intensity of Galactic Hydrogen (at any Doppler shift / velocity) over the range -10° to $+60^{\circ}$ Declination and 17 to 22hours Right Ascension) – limited by what was visible from the observatory location⁸. It can be seen in Figure B3 below, that the emission is strong along the Galactic plane and increases in intensity toward the Galactic centre and the Cygnus Spiral arm.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Received Power of Neutral Hydrogen in MW Galaxy (From 1420 – 1421 MHz Spectra (March 07)

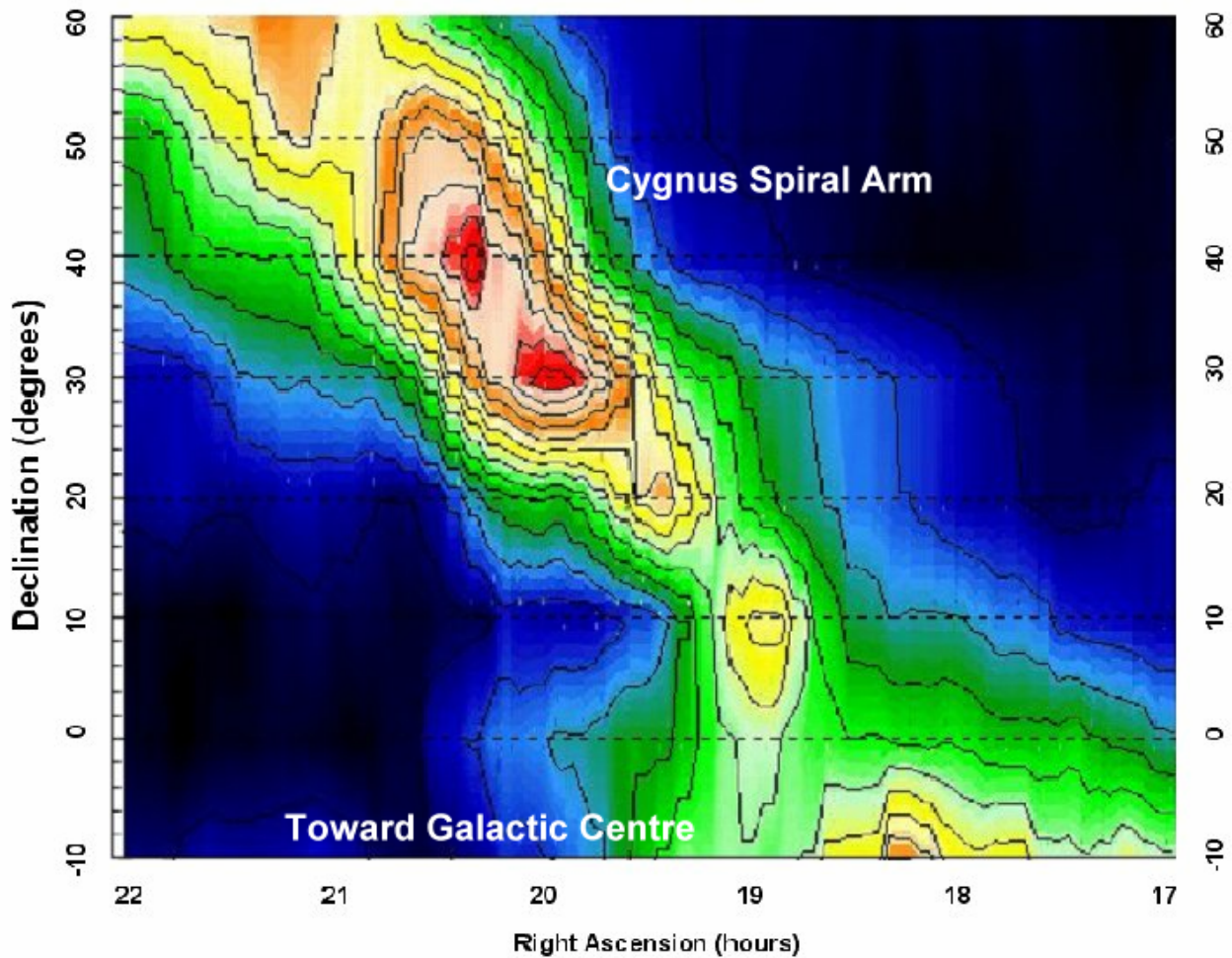


Figure B3
Map of intensity of Galactic Hydrogen
(including components from all Doppler shifted sources
with signals in the range 1420 to 1421MHz)

The map in Figure B3 can be converted from Right Ascension and Declination to Galactic coordinates using equations available on the internet ⁹.

This enables the generation of Figure B4 showing the radio plot superimposed on an optical picture of the Milky Way from galactic longitude $l=20^{\circ}$ to 100° .

There is a good correlation of the radio features with the optical image.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Received Power in H Line Spectra (1420 to 1421MHz) 17 -22hrs RA, -10 - +60Dec (March 07)

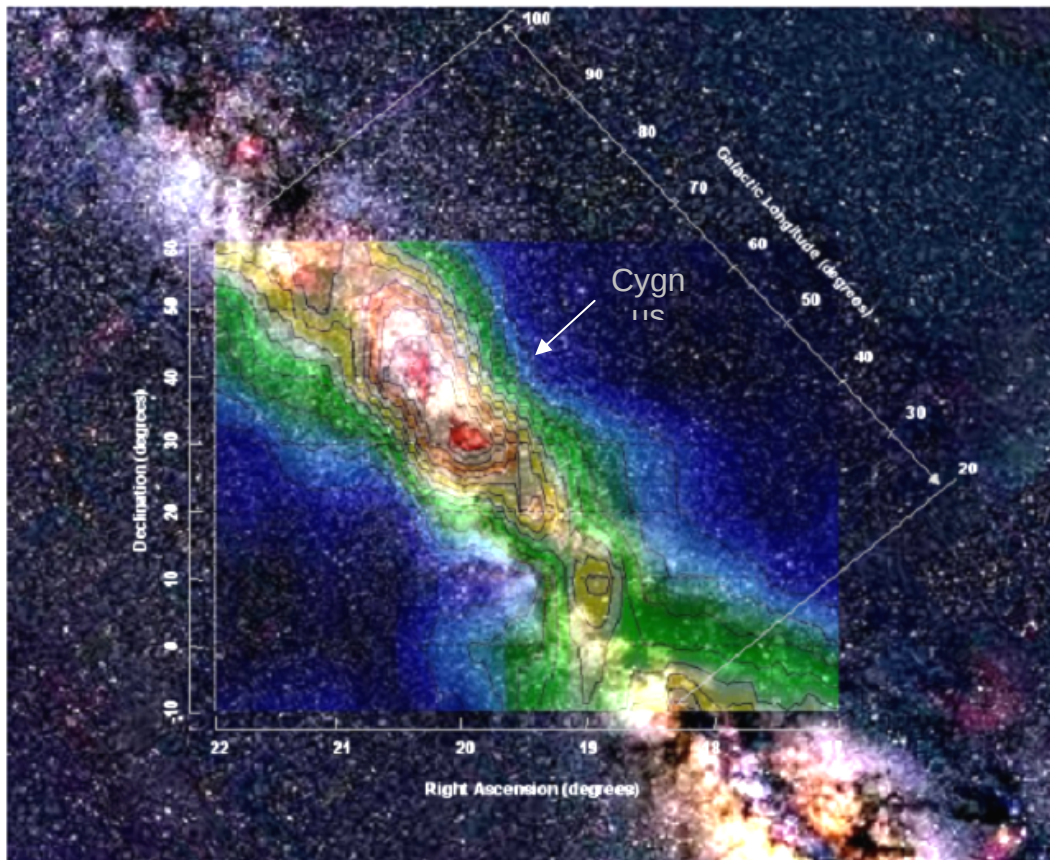


Figure B4 Overlay of Hydrogen Line Radio image and Optical image of the Milky Way

In Figures B5 and B6 we are able to see similarities in the amateur Radio Map above and professional measurements shown below.

The expanded cut out section of the professional map shows similar features to those found in this amateur one.

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

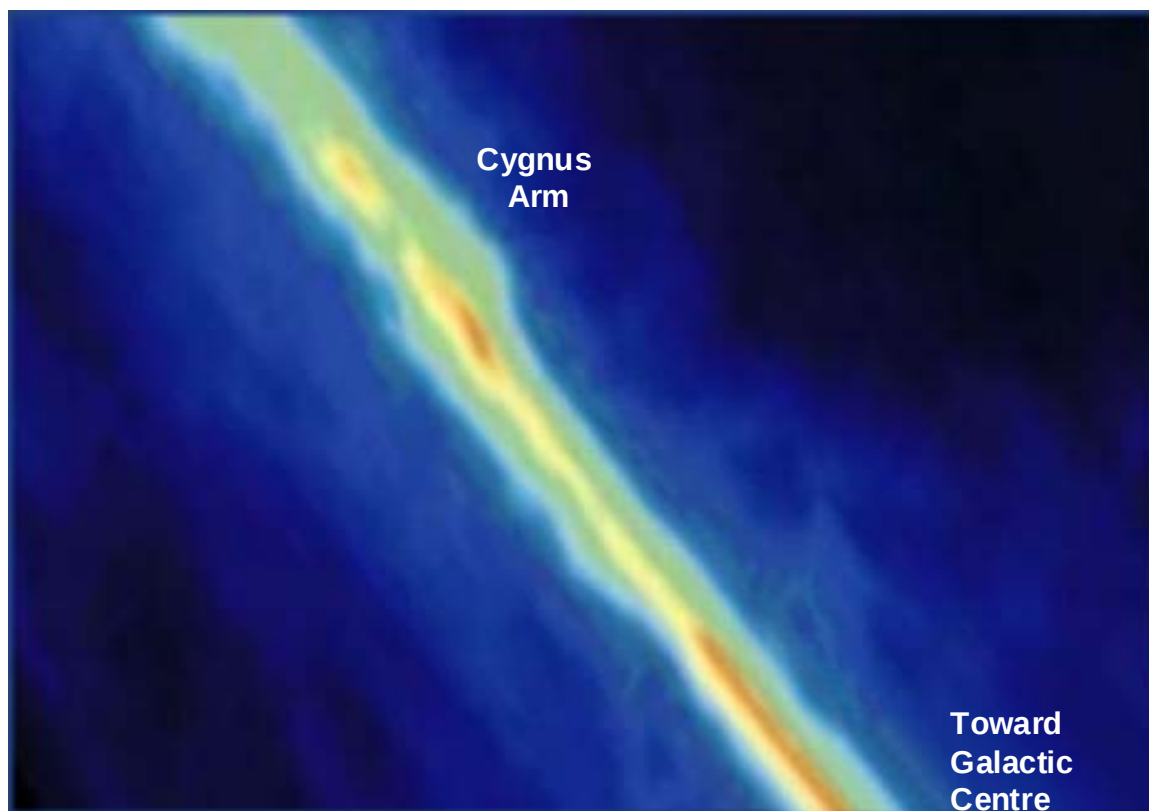
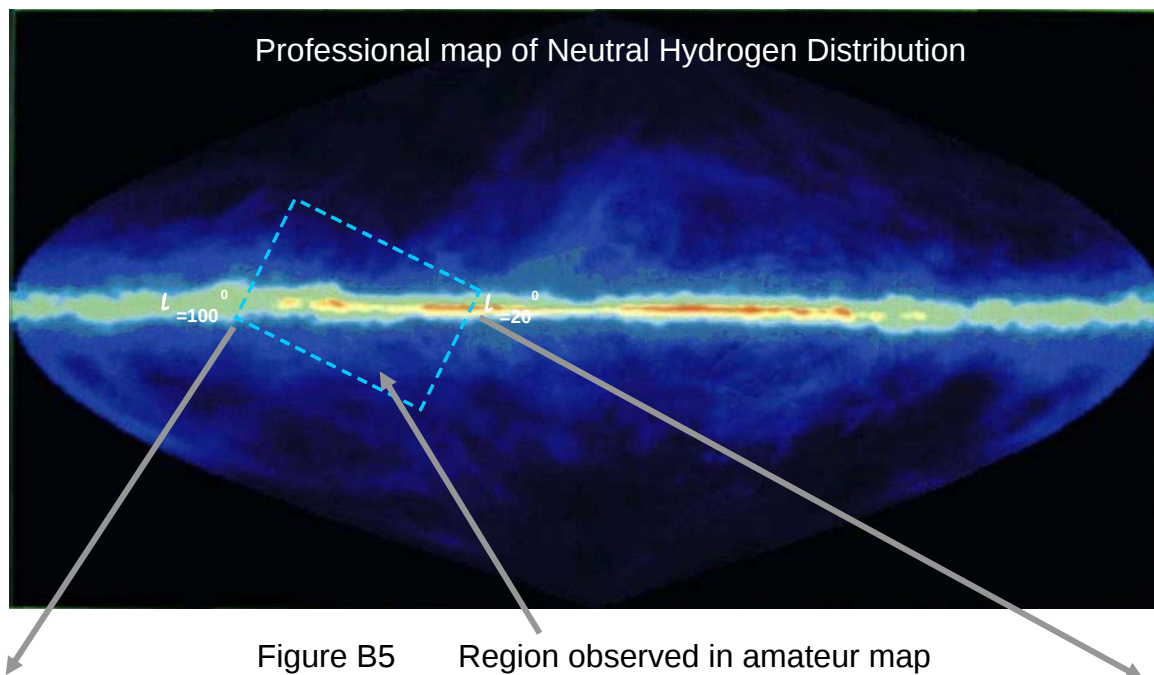


Figure B6 Expanded section of professional H Line map

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

Finally, to put this information in the context of the Milky Way structure, we can see that the most intense Hydrogen line signal occurs at a galactic longitude of around 60° to 70° . This is when the antenna beam is looking in the direction of Cygnus and along the line of sight of the local Orion - Cygnus spiral arm giving a high value of integrated hydrogen emission.

This can be seen in Figure B7 which shows the location of the Solar System in our local spiral arm

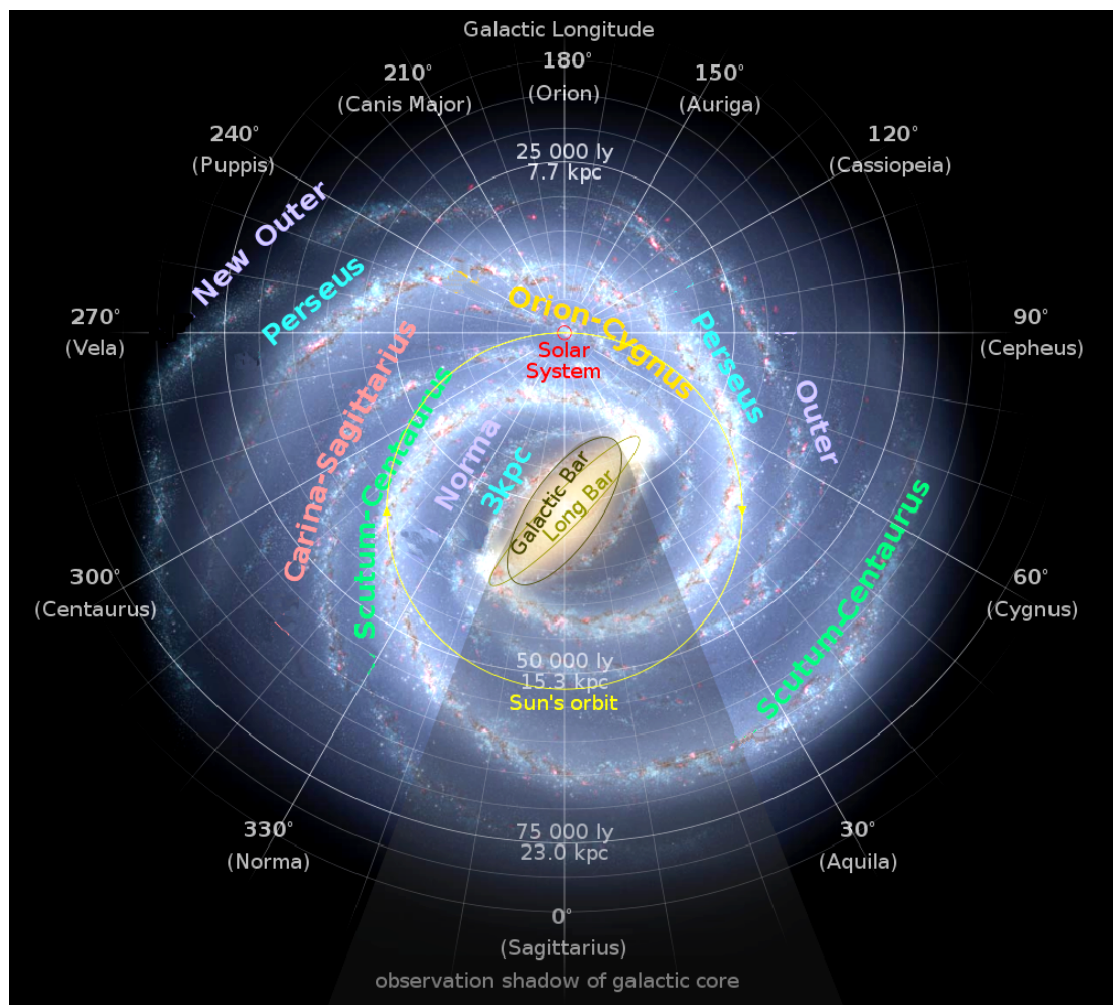


Figure B7 The Solar System located in the Orion – Cygnus Spiral Arm

Measurement and Analysis of Neutral Hydrogen Velocities across and along the Galactic Plane

References

- 1 Radio Eyes software <http://www.radiosky.com/radioeyesishere.html>
- 2 Rotation curve <http://astro.u-strasbg.fr/~koppen/Haystack/rotation.html>
- 3 John McKay <http://www.britastro.org/radio/h-line.html>
- 4 Brian Coleman Spectrum Private communication
- 5 Hans Michlmayr <http://wavelab.homestead.com/hydrogen2.html>
- 6 Sky Pipe Software
- 7 H Line Spectrum <http://astro.u-strasbg.fr/~koppen/Haystack/spectro.html>
- 8 Hydrogen Line map www.dmradas.co.uk
- 9 Coordinate transform
<http://scienceworld.wolfram.com/astronomy/GalacticCoordinates.html>