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# Introduction to Radio Astronomy

# The Milky Way Experiment

## 1. Introduction

**Purpose of the experiment**

The aim of this experiment is to observe the effects of the differential rotation of the Milky Way and to demonstrate that the hydrogen in our galaxy is concentrated in a disc and in arm like structures.

**The HI spectral line**

The space between the stars is called the interstellar medium and consists of dust (1%) and gas (99%). The gas in its turn largely consists of hydrogen (90%) in molecular ($H_2$), atomic (HI) and ionised (HII) form. Atomic neutral hydrogen produces a spectral line in the radio part of the electromagnetic spectrum at a wavelength of about 21 cm. It originates from a transition in the alignment of the electron spin and the proton spin. The state in which both spins are aligned has a slightly higher energy level than the state in which they are not. An excited atom spontaneously attempts to regain its lowest possible energy state and emits its surplus of energy as a photon, corresponding to a wavelength of 21 cm in this case. Such a spin state transition is actually extremely rare but as hydrogen is very abundant in the interstellar medium, 21 cm radiation is produced in large amounts. A particular advantage of radio waves is that they are not obstructed by dust. We can therefore use the HI spectral line to probe into regions of space, obscured at visible wavelengths.

**Doppler shift**

Any wavelike phenomenon whose source moves with respect to an observer, is subject to an effect called doppler shift. The emitted wavelength of a receding source is stretched out and an observer measures a longer wavelength or lower frequency. The opposite occurs in case of an approaching source and an observer measures a shorter wavelength or higher frequency. The frequency shift depends on the relative velocity of the source with respect to the observer and is given by the equation:

$(f_0 - f_1) / f_0 = v / c$ (1)

In equation (1), $f_0$ is the emitted frequency, $f_1$ the observed frequency, v the relative velocity of the source with respect to the observer and c the speed of light.

**Differential rotation and structure of the Milky Way**

Our Milky Way exhibits a differential rotation, which means that the angular velocity of matter in its orbit around the galactic centre is a function of distance from the centre. Generally speaking, the angular velocity decreases with increasing distance from the centre according what is called the rotation curve of our galaxy. Observed from earth along any line of sight through the galactic plane, different regions of hydrogen therefore move at different radial velocities with respect to us. As a result, their HI spectral line shifts to longer or shorter wavelengths (lower or higher frequencies) because of the doppler effect. Outside the solar circle and to the right of the sun, one measures the HI spectral line at higher frequencies and hence negative radial velocities as the hydrogen outside the solar circle moves at a slower angular velocity than the sun.

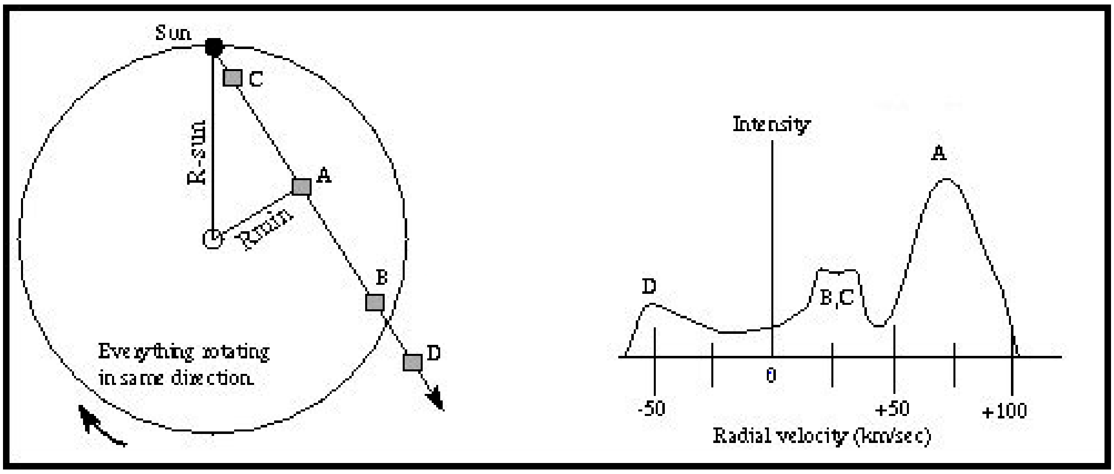


*Figure 1.1 Circular approximation of the Milky Way's rotation. Region A has the greatest angular speed and is moving fastest away from the sun. It also has a higher hydrogen density. Regions B and C are moving at about the same but higher angular speed than the sun. Region D is located outside the solar circle, has a slower angular speed and a lower hydrogen density. (Picture from Nick Strobel's "Astronomy Notes")*

In the disc of our galaxy, matter in general and hydrogen in particular is not evenly distributed in distance from the centre, and hence neither in velocity. Instead, it tends to clump together in spiral arms under the influence of a density wave. Therefore, the HI spectral line appears at several rather well defined doppler shifted positions in a spectrum, like illustrated in figure 1.1, instead of being completely smeared out. The intensity of the peaks decreases as one observes along a line of sight more and more out of the galactic plane as the amount of hydrogen one is looking through decreases due to the disc like shape of the galaxy.

# 2. Method

Using the 6.4 meter radio telescope and its 64 channel spectrometer, we carried out several observations, each with an integration time of 120 seconds, along a fixed galactic longitude of 120º but at different galactic latitudes, i.e. 0º, 5º and 15º. The galactic coordinate system defines longitude as the angle, from our point of view, subtended by the galactic centre and the projection of the target source onto the galactic plane. Galactic latitude is the angle, again from our point of view, subtended by the galactic plane and the target source.

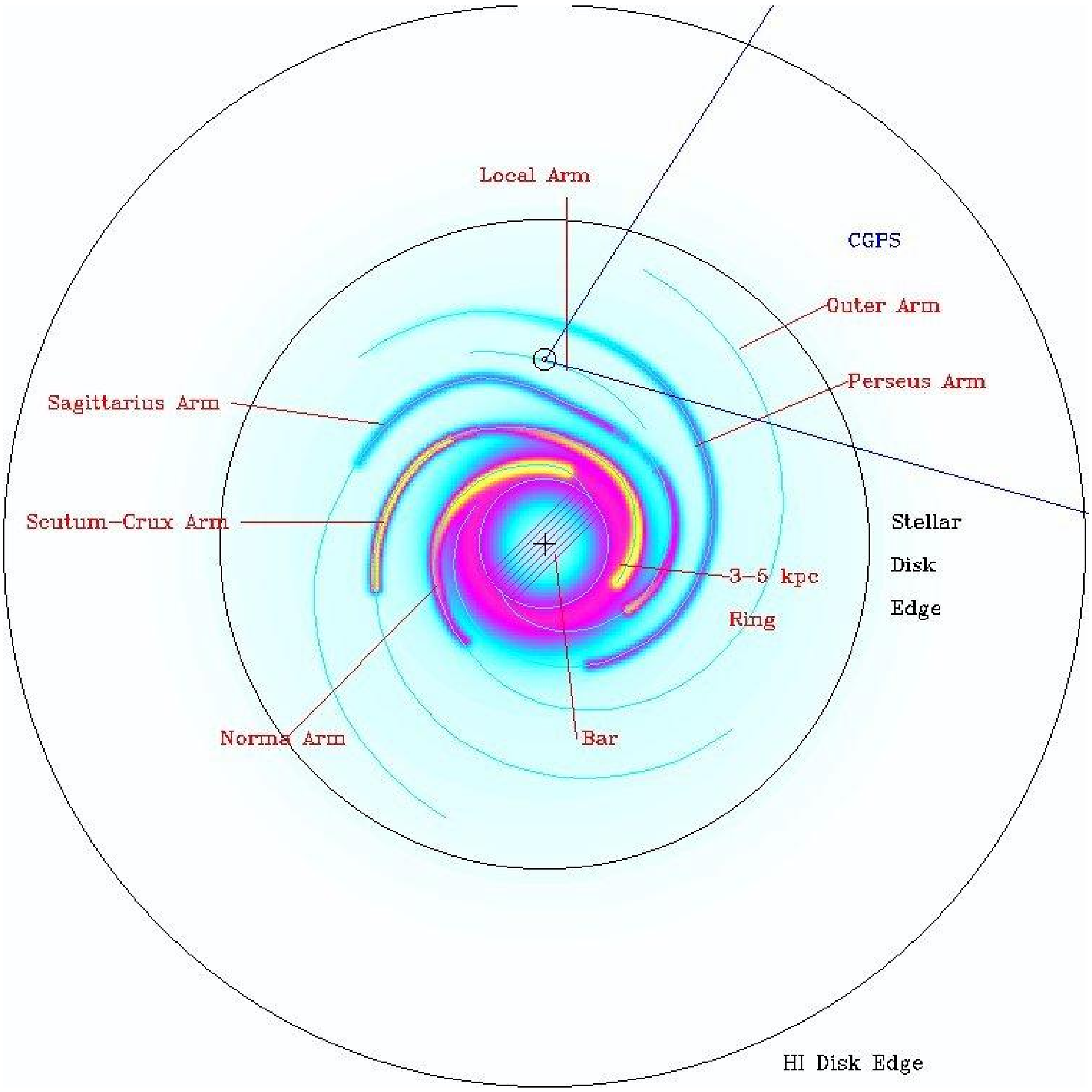


*Figure 2.1 Map of the Milky Way's disc indicating the range of galactic longitudes covered by the Canadian Galactic Plane Survey (CGPS).*

Figure 2.1 shows a map of the Milky Way in which the range of galactic longitude between 74º and 147º, covered by the Canadian Galactic Plane Survey (CGPS), is represented by two blue lines. The galactic longitude along which we observed, falls in this range.

The recorded spectrum contains radiation from the hydrogen along the line of sight as well as noise from the receiver system. In order to determine the hydrogen component, the system noise has to be subtracted from the overall spectrum. A simple way to achieve this would be to move the telescope off source, start a new integration of 120 seconds, and subtract the off source spectrum, which is then practically only due to system noise, from the overall one. However, as the interstellar medium is filled with hydrogen, there is no real off source position and this position switching procedure cannot be applied. Therefore, another technique called frequency shifting has to be used.

As the name suggests, the frequency shifting method consists of moving the observing frequency instead of the telescope. In our case, the observing frequency is set 3 MHz away from the original one, outside the bandwidth of 2 MHz on both sides of the original centre frequency. After an integration of 120 seconds, the recorded spectrum is considered to be the result of system noise and subtracted from the original one.

After each integration period, the system calibrates itself using a noise diode, to be able to return results on a temperature scale. And to convert the frequency scale of the spectra into a velocity scale, it is important to know that the telescope's receiver has a bandwidth of 4 MHz. A bandwidth of 4 MHz over 64 channels leads to a bandwidth of 0.0625 MHz per channel and a velocity step of 13.205 km/s per channel, according to the telescope's data files. It should be noted however, that for the HI spectral line frequency of 1420.406 MHz, equation (1) yields a velocity step of 13.192 km/s per frequency step of 0.0625 MHz.

It is also interesting to note that the telescope's receiver is not actually tuned to the requested HI spectral line frequency of 1420.406 MHz but to a slightly different one. The telescope's control computer sets it to 1420.427681 MHz to take the motion of our sun into account and establish a local standard of rest. The local standard of rest is determined using the average velocity for a group of stars near the sun. Knowing the frequency difference, i.e. -0.021681 MHz, we can use equation (1) to work out that the control software takes a relative velocity of -4.58 km/s into account.

# 3. Observational results and calculations

The results of our observations with the frequency scale converted into a velocity scale, are shown in figure 3.1.

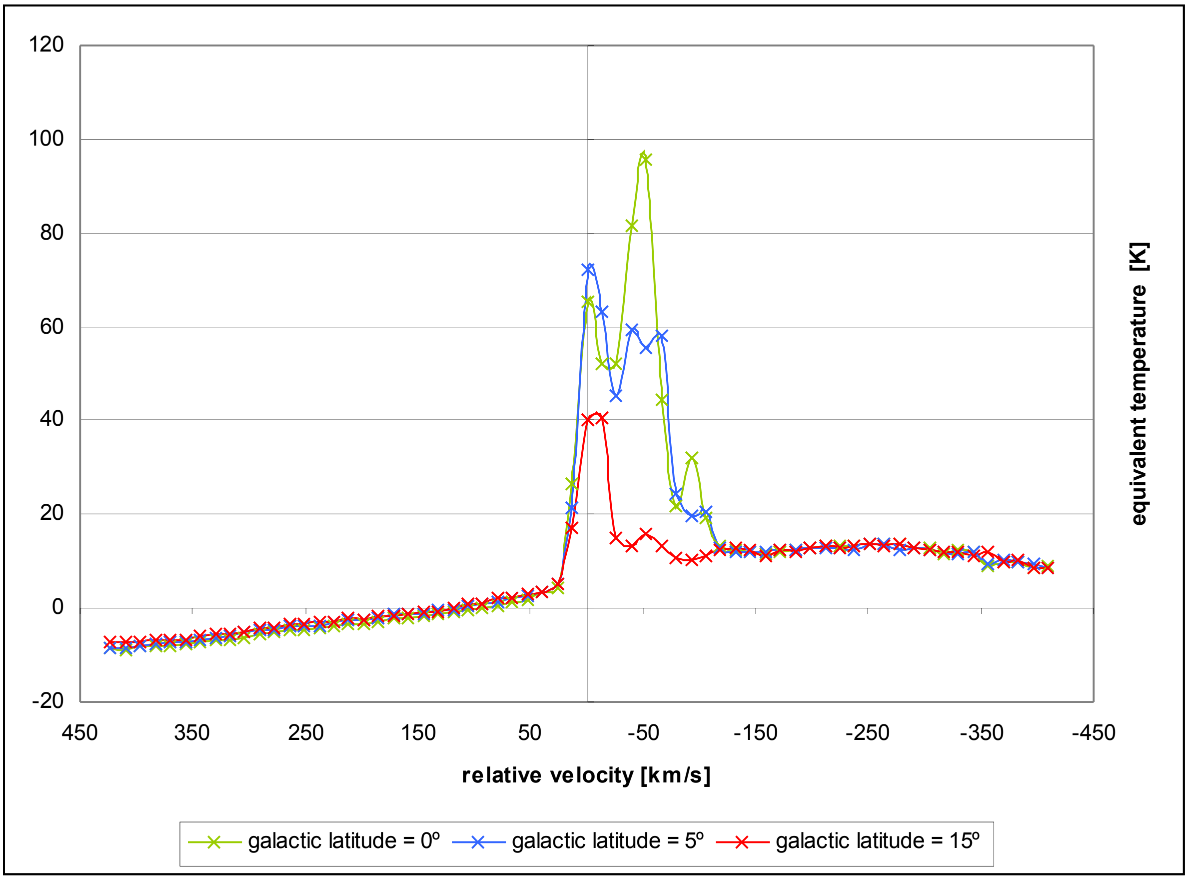


*Figure 3.1 The recorded spectra at a galactic longitude of 120° with the frequency scale converted to a velocity scale.*

The temperature integral of the spectra, i.e. the area under the curves, is proportional to the amount of hydrogen along the line of sight. In order to investigate how this amount varies as a function of galactic latitude, we integrated the area under the curves using a simple computer program. It sums the product of the width and the height for all bins, except for those with a negative temperature value (more about these negative values later). Time only permitted us to carry out three observations, which is a number too limited to make any reasonable conclusion. Therefore, the temperature integral has also been calculated for observations from other groups, made at other galactic latitudes. The result is listed in table 3.1 and graphically represented in figure 3.2.

| galactic latitude [º] | temperature integral [K km/s] |
|---|---|
| -10 | 6472.484673 |
| -5 | 7632.88018 |
| 0 | 10267.75505 |
| 5 | 9627.82001 |
| 10 | 7161.45403 |
| 15 | 6358.951659 |
| 20 | 6144.897066 |
| 30 | 5604.55125 |

*Table 3.1 Temperature integral as a function of galactic latitude for a fixed galactic longitude of 120°, bins in the spectra with negative temperature values not taken into account.*

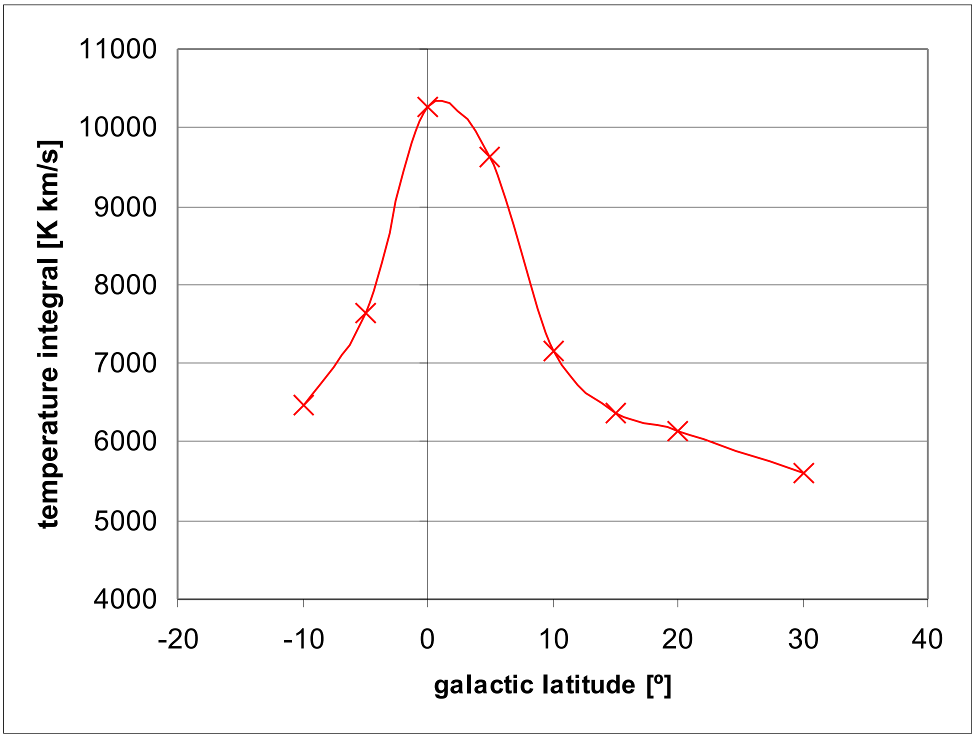

*Figure 3.2 Temperature integral as a function of galactic latitude for a fixed galactic longitude of 120°, bins in the spectra with negative temperature values not taken into account.*

# 4. Conclusion

Our first spectrum (galactic latitude = 0º) clearly shows three peaks: one at 0 km/s, one at -52.82 km/s and one at -92.435 km/s. The same peaks can be identified in our second spectrum (galactic latitude = 5°), but they are clearly less pronounced than in the first case, with an exception for the peak at 0 km/s. Our third spectrum (galactic latitude = 15°) also contains the peaks at 0 km/s and -52.82 km/s, be it even more reduced, but no longer reveals the one at -92.435 km/s.

The upward sloping profile and the negative temperature values at the beginning of our spectra can be explained in the following way. The receiver system noise was subtracted from the spectra using the frequency shifting technique. Unfortunately, the noise characteristic of a receiver system depends on frequency, which means that we might have subtracted more noise, measured at the shifted frequency, than the system actually generated at the HI spectral line frequency. The peculiarity of the negative temperature values is the reason why they were not taken into account when calculating the temperature integrals.

The shape of our spectra in figure 3.1, with distinctive peaks, is what to expect if the emitting hydrogen is concentrated in arm like structures in the galactic disc. If it would be evenly distributed, the HI spectral line would be completely smeared out over a range of frequencies. Comparing our results with the map of the Milky Way shown in figure 2.1, we can identify the peak at a relative velocity of -52.82 km/s with the Perseus Arm and the peak at a relative velocity of -92.435 km/s with the Outer Arm. The peak at a velocity of 0 km/s obviously originates from the Local Arm in which the sun resides.

The temperature integral as a function of galactic latitude in figure 3.2 shows that the amount of HI hydrogen decreases with increasing galactic latitude and tends to level at galactic latitudes above 30º. Moreover, the smoothened curve connecting the data points exhibits a symmetric shape around the galactic plane. This is what to expect if the emitting hydrogen is concentrated in a disc. If it would be concentrated in a sphere instead of a disk, the temperature integral would not decrease with increasing galactic latitude.