Observing Galactic Hydrogen

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The Spin Flip Transition

Quantum particles have a property known as 'spin' which can either be 'up' or 'down'. In a Hydrogen atom, the electron and proton can either have spins aligned 'parallel' or 'anti-parallel' to each other. The configuration with anti-parallel spins is more stable than that with parallel spins. It is possible for the electron in the parallel configuration to change its spin by radiating energy. This is known as the 'spin flip' transition. During this transition, the atom emits electromagnetic radiation at 1420.4 MHz ($\lambda = 21$cm) known as HI emission.

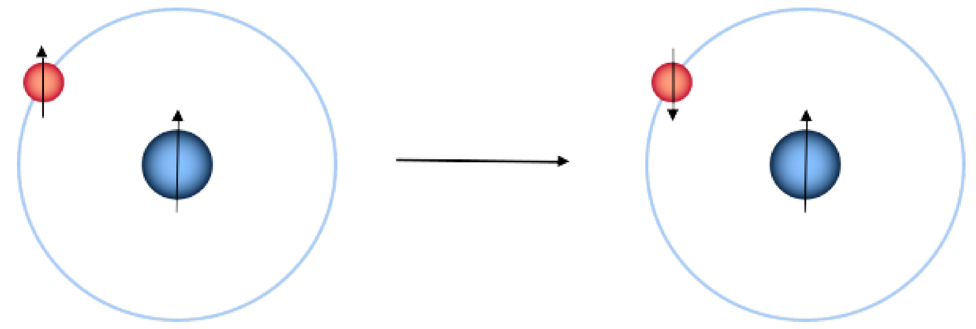


Figure 1. The spin flip transition in atomic Hydrogen.

A single Hydrogen atom in the parallel configuration will, on average, only undergo this transition after 11 million years. However, due to the large abundance of Hydrogen in our galaxy, we find that the HI signal from the galactic plane is very strong.

What does radio data look like?

Data from an optical telescope is fairly intuitive- a camera can record light intensities as we see them. The camera sensor here uses the particle nature of light to detect photons. A radio telescope, on the other hand, leverages the wave nature of light. The incoming electromagnetic radiation excites a frequency-dependent voltage in the telescope probe. The rawest form of radio data consists of a time series of such voltages. To obtain frequency information from this data, we perform a Fourier transform. This gives us a power spectrum which essentially contains information about the 'amount' of each frequency present in the original signal.

The Radio Telescope

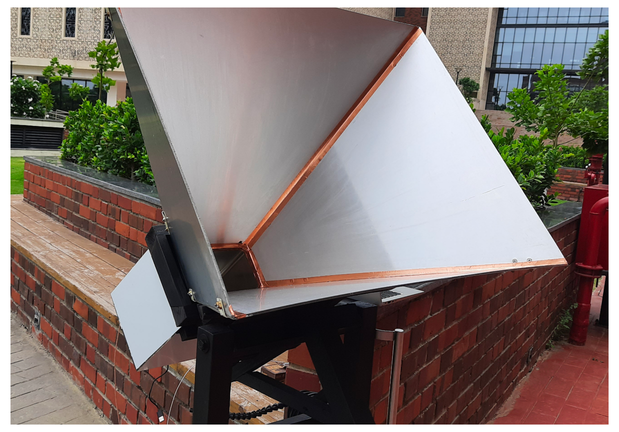


Figure 2. The Radio Telescope used for this project fabricated by Pradip Chaudhari in the Physics Laboratory at Ashoka University.

The radio telescope consists of a flaring horn, a waveguide box, and a unipole antenna. The flaring horn directs incoming electromagnetic radiation to the waveguide box containing the antenna which in turn is connected to a series of electronics designed to filter out the frequencies of interest.

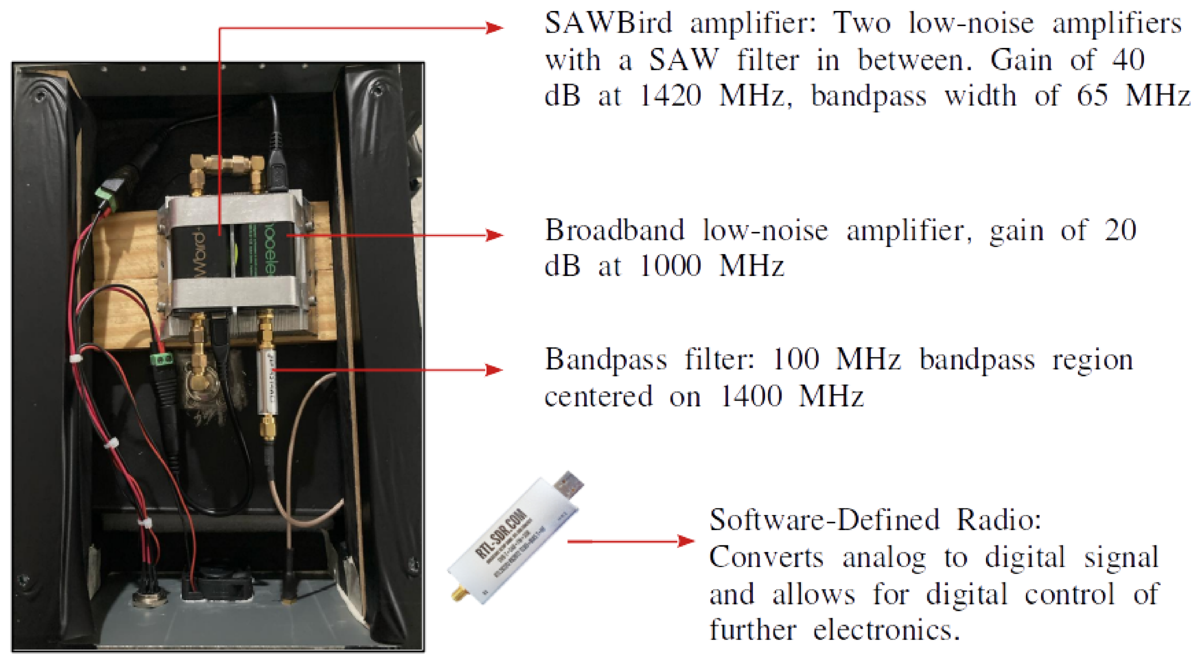
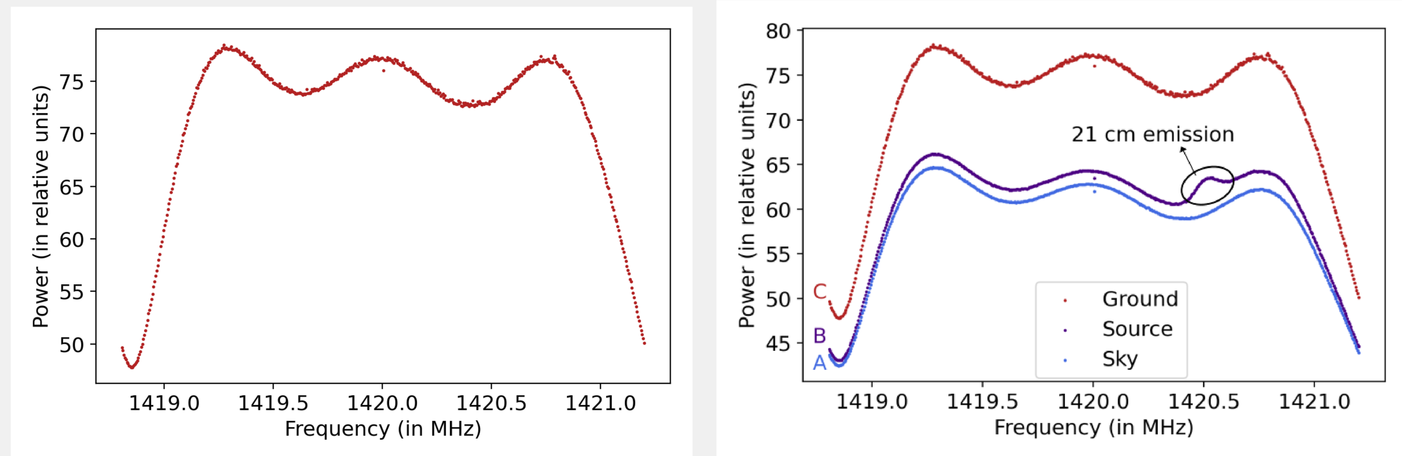


Figure 3. The electronics connected to the antenna of the radio telescope which amplify and filter the incoming radiation.

Interpreting the Power Spectrum

It turns out that even when we point the telescope at nothing (say, an empty patch of the ground), we obtain a power spectrum like the one shown on the left below. This 'M'-shape characterises the response of the instrument itself, and thus underlies any signal we collect using the telescope. On the right, we see that the HI signal is embedded within this shape. To study this signal, we need to 'subtract' the spectrum on the left from the spectrum labelled 'B' on the right.



(a) Power spectrum showing the power levels recorded across the frequency band when the telescope is pointed at a Hydrogen-free region at room temperature.

(b) Power spectrum showing the power levels recorded across the frequency band for the HI source as well as the calibration readings at known temperatures.

Figure 4. Various power spectra showing the power spectra obtained when the telescope is pointed at different regions. On the right, 'A' corresponds to the telescope pointing at a Hydrogen-free region of sky, 'B' corresponds to pointing at an HI source and 'C' corresponds to pointing at the ground.

Now, we model the antenna as a 1-D blackbody such that we can associate an equivalent temperature with each measured power. This allows us to transform our power axis into a temperature axis using the power spectra at two known temperatures: the ground (at $T_g \sim$300K), and the (HI-free) sky (at $T_{\text{sky}} \sim$5K). Using $P \propto T$ for a 1-D blackbody, we can find the temperature of the emission source as,

$$T_{\text{source}} = \frac{P_{\text{source}}}{P_g}(T_g + T_r) - T_r; \quad T_r = \frac{T_{\text{sky}}P_g - T_g P_{\text{sky}}}{P_{\text{sky}} - P_g} \tag{1}$$

where T_r is the receiver temperature and P_g, P_{sky} are the power spectra of the ground and the sky respectively. It is important to note that the temperature thus obtained is **not** a thermal temperature.

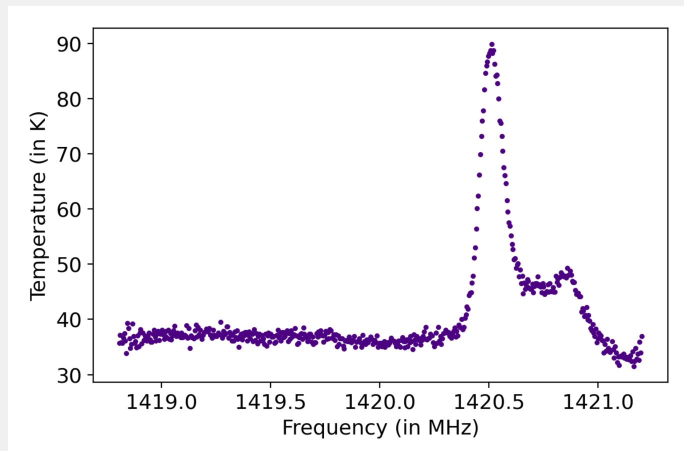


Figure 5. The source signal after temperature calibration. We find that the 'M'-shape of the spectrum has been eliminated, allowing us to isolate and study the 21-cm emission.

Frequencies and Velocities

The Milky Way is a spiral galaxy and different parts of the galaxy move at different velocities relative to its centre. The Hydrogen clouds in the galaxy also have some velocity relative to us, leading us to expect that the observed HI emission will be Doppler shifted. For emission frequency $f_0 = 1420.4$MHz and observed frequency f, we can find the velocity v of the source as,

$$v = c\left(1 - \frac{f}{f_0}\right), \tag{2}$$

where c is the speed of light. It is important to note, however, that we can only measure the radial component of the velocity of the source. We can most meaningfully associate a velocity and distance to a source that is tangential to our line of sight since its entire velocity is along the radial direction.

The Milky Way

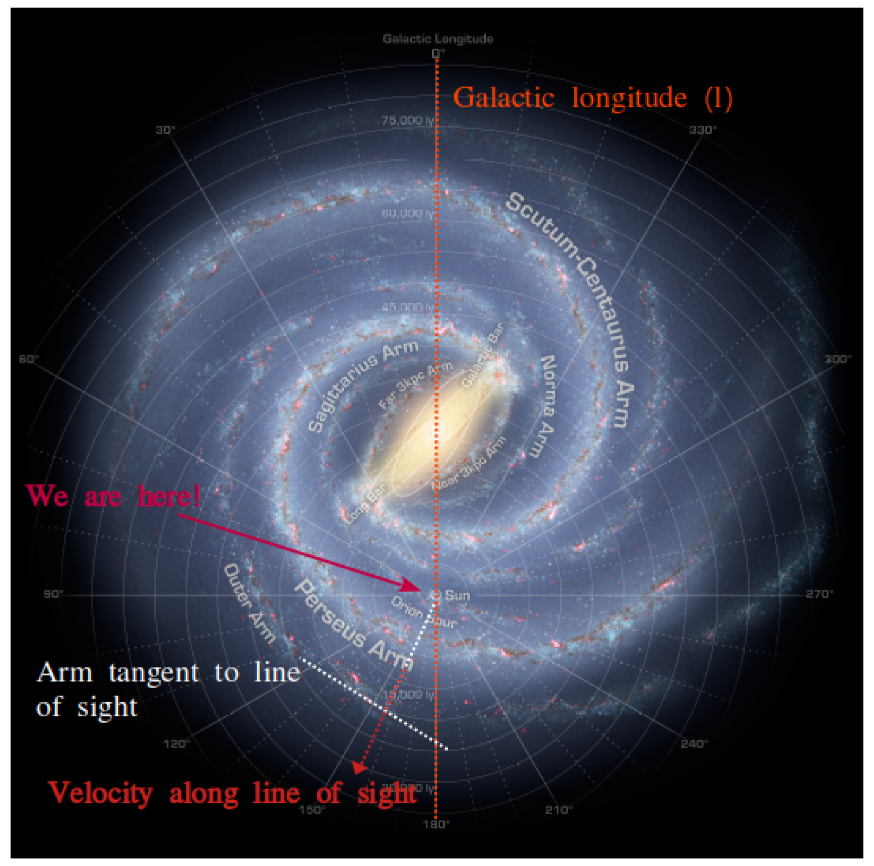


Figure 6. The galactic coordinate system is defined with the Sun at its centre and provides two coordinates- longitude (l) and latitude (b). Since we can only measure radial velocities, the points tangential to our line of sight will have the largest measured velocities.

Results

Once we convert all the frequencies in the band to the associated velocities, we convert to a standard frame of reference known as the Local Standard of Rest (LSR). We can then plot the velocity-temperature profiles for different parts of the galaxy. To verify our data, we have plotted it alongside the results of the Leiden-Argentine-Bonn (LAB) survey of galactic Hydrogen.

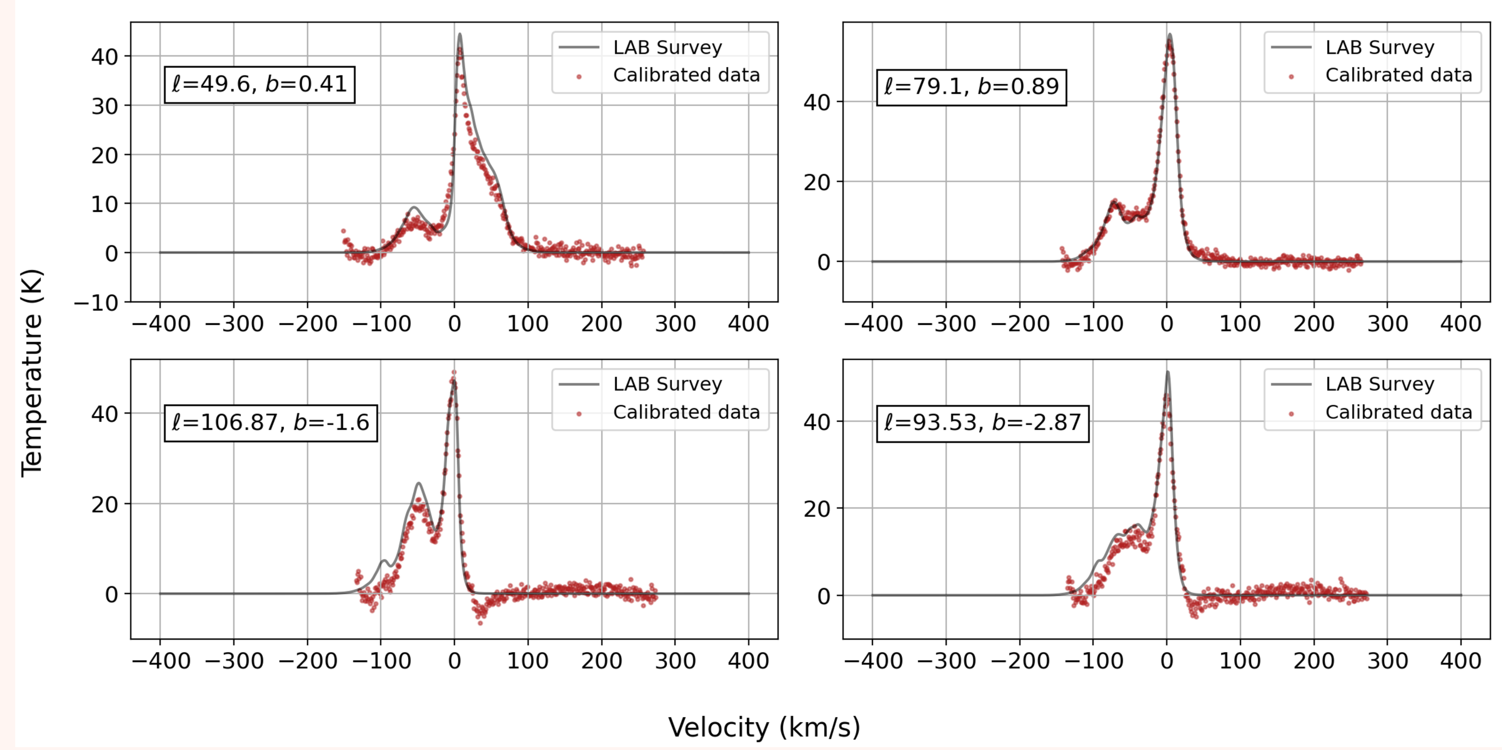


Figure 7. Velocity-temperature profiles for various regions in the galactic plane plotted alongside the results of the LAB survey showing good agreement between the two.

What Next?

- Explore ways to optimize temperature calibration procedure.
- Use multiple Gaussian fitting to identify the various velocity components of the velocity-temperature profile.
- Survey a larger range of points along the galactic plane in order to plot a rotation curve for the galaxy.

References

1. 'HI experiment with horn antenna: Student Manual' by Ashish A. Mhaske, IUCAA.
2. 'Lightwork Memo 29' by Eric Trumbauer, Sahar Khashayar.
3. HI profile search: LAB Survey
4. Wikipedia: Milky Way