Mapping the North Polar Spur Using the Hydrogen Line

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May 6, 2014

Abstract

In this report we

Introduction

One of the most important facts about the baryonic matter in our universe is that the vast majority of it consists of hydrogen atoms. Hydrogen, when excited and de-excited, produces very specific sets of emission and absorbtion lines, giving the emitted light a number of signature properties. As any large body of matter in our universe can be assumed to consist mostly of hydrogen, we can use these signature properties to construct profiles of astronomical objects.

Of particular interest to radio astronomers is radiation emitted from the a hyperfine transition of a neutral hydrogen atom. This transition, known as the hydrogen line, occurs at the 1420.4058 MHz frequency, or 21 cm wavelengths, and arises from the spin states of the electron and proton falling out of alignment. Although an extroniarily rare transition for any given hydrogen atom to undergo, the sheer abundance of neutral hydrogen dictates that our view of the sky is dominated by the hydrogen line at 21 cm wavelengths.

As seen from the atom's rest frame, hyperfine transitions have very narrow spreads in frequency. Because of this, we can reconstruct properties of objects in the sky by analyzing their spectra. Frequency peaks above 1420.4 MHz correspond to blue-shifts from atoms moving toward us; peaks below this frequency are redshifts from atoms moving away. Because neutral hydrogen is optically thin in our galaxy, it is also possible to map out the three dimensional structure of astronomical objects by analyzing different peaks originating from various depths within hydrogen clouds.

In this report we apply the above principals to mapping the structure of the North Polar Spur. The first three sections outline the overall process for gathering and preparing data. Section 1 begins with an introduction to this structure, outlining basic properties and information which we undertake to investigate. In Section 2, we describe our process and reasoning for scheduling observations and recording spectra. In section 3, we discuss the techniques we employed to remove and account for noise, interference and distortions which arose in our recorded signals.

The remaining sections summarize the results. In Section 4, we describe our method of translating spectra into temperature, velocity and column density measurements. These measurements are used to create 2D color plots of the velocity and column densities of the North Polar Spur, which are displayed and analyzed in Section 5. Finally, we offer our concluding remarks in Section 6.

1 Schedule of Observations

The North Polar Super is a massive collapsed super-nova remnant, composed of an infalling cloud of gas found at galactic longitudes $220° \leq l \leq 20°$ and latitudes $0° \leq b \leq 90°$,[1] occupying roughly one quarter of the celestial sphere. However much of it is in the Southern hemisphere, thus we were only able to see a portion of this structure. what can we see? Our axes are labelled to carve out this whole area.

For this observation, we employed a 3.7 m radio dish located atop Mount Leuchner, located just outside of Berkeley at 37° North and 122° West. At 21 cm wavelengths, this telescope possesses a half power beamwidth of 4°, making it incapable of perceiving structures with angular radius smaller than 4° on the sky. The Nyquist critereon, as applied to our object, dictates that we would require telescope pointings spaced at most 2° in each direction to extract all the information that we can given the limits of our telescope.

In order to map out where to point to on the sky, we created a grid in l and b with 45 points in lattitude going from 0° to 90°, achieving the desired spacing of 2°. While a

[1] That is 220° to 380° modulo 360°, or from 220° to 360° and wrapping around from 0° to 20°.

change of Δb in latitude always corresponds to an angular motion of Δb degrees along the celestial sphere, the angular distance between two points Δl degrees apart on the sky is latitude dependent, scaling as $\Delta l / \cos b$ for small Δl. To account for this, and avoid extraneous telescope pointings, we spaced points in our grid a distance $2^{\circ} / \cos b$ for each given b. We then added to our list of latitudes corresponding to each b until either filling out the spatial extent of our object or reaching one of the telescope pointing limits.

From there we performed a brute force calculation for each coordinate by checking whether it would be visible during any 15 minute interval for the duration of the lab. Those points which we found would be visible were marked as viewable on our reference grid, and at such times that we could observe, the telescope was directed to traverse the grid row by row so as to minimize time spent mechanically moving the telescope to track the objects. Each night we would update our grid to check off the new points which had been observed, so that our tracking software would skip them on the next observation.

Fully imaging the North Polar Spur at this resolution requires roughly 2500 pointings; i.e. the full extent of the viewable portion of the North Polar Spur consists 2500 pointings on the sky. Of those, around 1600 pointings can be made with our telescope at this time of year, so ideally we would have 1600 distinct galactic coordinate values on the sky corresponding to our object.Here goes picture from Isaac's website if possible. Unfortunately, a combination of time mismanagement on the part of ourselves and other research teams making use of the telescope, hardware and software problems which prevented use of the telescope on several occasions, and spurious system errors rendering a portion of our observations unuseable, we were only able to gather about 450 useable points of data.

In order to make best use of the time we had available, we chose to maximize coverage of the sky as opposed to taking detailed images of any given area. Our data thus covers most of the North Polar Spur's angular extent. Due to the sparsity of points our image is less detailed than desireable, and perhaps more importantly, is more difficult to use for visually removing outlier points from our data, as each point constitutes a greater portion of our image than if we had more tightly spaced data. Despite this, we have good reason to believe that our image is accurate. We describe our analysis in Sections 4 and 5.

2 Recording Spectra

The hydrogen line occurs at a frequency of 1420.4 MHz. In order to record this, the raw signal from the dish was mixed with a local oscillator running at 1270.4 ± 1.5 MHz, and then run through a filter to remove the additive components, placing line center at roughly 150 MHz. The raw data from the ADC was then processed by an FPGA which performed real time fourier transforms to return the power spectrum of the input signal over the IF range of $144 - 156$ MHz, divided into 8192 bins, giving us a frequency window of 12 MHz about line center with a frequency resolution of 1.5 kHz.

There is no source within our galaxy that we have reason to believe would be moving toward or away from us with speed greater than $250\,\mathrm{km\,s^{-1}}$. Using the Doppler shift formula for light, this is equavlent to saying $|\Delta f_{\mathrm{Doppler}}/f_{\mathrm{H\ line}}| \lesssim 8.3 \times 10^{-4}$, meaning we should see no spectra shifted more than 1.2 MHz from line center. We thus required a minimum of 3 MHz of bandwidth about line center in order to ensure that we capture all relavent parts of our signal.

In order remove the shape of the bandpass filter from our measurements, we recorded spectra with the local oscillator frequency shifted both 1.5 MHz above and below line center. This allowed us to obtain the shape of the bandpass unmodified by the hydrogen spectrum on each side. We used to divide out the noise in the manner described in the next section.

Performing this analysis required that the full frequency window of interest be contained in both the right and left-shifted spectra, and simultaneously that these two spectra do not overlap on the frequency ranges we wanted to examine. Combining these requirements with the fact that the 1 MHz boarder on each side of our spectra were unusable due to the presence of the bandpass filter was what resulted in the choice of a 12 MHz bandpass.

To determine our sampling time, we noted that the average kinetic temperature of the hydrogen atoms in these clouds is on the order of 100 K. Making use of the eponymous shorthand for the kinetic energy of a typical atom, given by

$$\frac{1}{2} m_{\mathrm{H}} \left\langle v_{\mathrm{thermal}}^2 \right\rangle = k_b T,$$

and plugging in the appropriate parameters yiels a thermal velocity of order $2\,\mathrm{km\,s^{-1}}$, meaning we should expect fluctuations in the frequency of the spectra on the order 15 kHz. Allowing for a factor of ten safety margin in our estimates of these fluctuations yields the 1.5 kHz frequency resolution used for our observations.

Prior to processing, the raw data output from the FPGA contains substantial amounts of noise, distortion, and artifacts, the causes of which are detailed in Figure . Any single recorded spectra is unuseable due to this noise. However, using the central limit theorem as guidance and assuming that the noise is in fact random, we can conclude that averaging many spectra together will tend to average out the noise and recover the desired signal.

Figure 1:

Through some experimentation we determined that an average of about two minutes per pointing was adequate to recovering our signal. Of this, one minute was spent recording the left-shifted LO frequency offset, and one minute on the right-shifted offset. Additionally, for both of these offsets, we recorded for five seconds with the equivalent of a 100 K blackbody's spectrum injected into the signal via a noise diode to be used for calibrating the light temperature of our hydrogen cloud.

The shape of the bandpass filter changes slowly over time, thus for each pointing we recorded, in order: left-shifted spectra, left-shifted calibration spectra, right-shifted calibration spectra and the right-shifted spectrum. This ensured that our noise measurements were equidistant in time from both of their respective sets of data.

3 Smoothing and Calibration

3.1 Removal of RF Spikes

One of the first problems we were required to deal with when calibrating our data were major RF spikes from overhead airplanes, depicted in Figure . In order to deal with this, we used a "minimum smoothing" method. In order to get rid of the RF spikes, we divided the 8192 data points in our spectra into 2048 sequential bins of four elements, took the minimum element in each bin, recordeding the index of that element in the original array. We then made an array of those points, and recorded the frequencies corresponding to the indices of the array.

There are several potential drawbacks to using this method. Any downward signal spikes in our data will make it into the filtered array; if these spikes are located far off line-center, they could heavily distort our derived velocity measurements since they will be used as weights for very high velocities. This method depends on there being a well defined underlying profile (well-defined bandpass shape). It also runs the risk of systematically underestimating the strength of the signal, since we are biasing toward the minimum.

There is a possibility of removing imortant information about the spectral profile from our data, since we are throwing out 3/4 of our data points. Finally, if the frequencies of the RF spikes are constant in time, we run the risk of inducing a small but systematic shift in the measured frequency of our line spectra.

In practice, after examining large numbers of our spectra, we concluded that this method worked very well. Emperically there is a very well defined shape for the signal from this telescope, and there are very few downward spikes in our data. Even if there is a systematic frequency offset in our data, there error will be of order at most 10 kHz, around 1% of the typically expected Doppler shifts in our frequency data. The effect is thus likely minimal.

3.2 Calibration of Temperatures

In order to determine the physical brightness temperature of our hydrogen clouds, we need to understand the various sources of noise and distortion in our system and sequentially eliminate them.

At the antenna itself, there are two primary sources from which our signal originates: the light from the hydrogen cloud which is at light temperature T_{sky}, and the radiation from the telescope itself, which given our narrow frequency band can be roughly treated as a blackbody emitting radiation at a temperature T_{sys}. Is this accurate? The signal originating from the telescope can be viewed as a power spectrum emitted from a source with temperature $T_{\text{sys}} + T_{\text{sky}}(\nu)$.

This signal is passed through a number of amplifiers which multiply the entire signal by a gain factor whose value is constant in frequency, or channel number Need I define this?. Ideally, our gain factors would remain the same for each pointing, however due to equipment problems we consistently measured different gains g_{left} and g_{right} when raising and lowering the local oscillator frequency.[2] These gain factors also shift our temperature measurement into arbitrary units whose values we must calibrate. Finally, the overall shape of our signal is modulated by the bandpass function $\beta(\nu)$ whose profile is a strict function of channel number. The signals we recieve are thus given by

$$S_{\text{left}} = g_{\text{left}}\beta(\nu)\left(T_{\text{sys, left}} + T_{\text{sky}}(\nu)\right)$$
$$S_{\text{right}} = g_{\text{right}}\beta(\nu)\left(T_{\text{sys, right}} + T_{\text{sky}}(\nu)\right).$$

First, we use our noise measurements to interpret our signal in units of Kelvin. Clipping off the outer parts of our frequency spectra at the edges of our bandpass filter, and excising the respective portions of our power spectra containing contributions

[2] Here g_{left} refers to the gain when our spectra was shifted left of center and g_{right} refers to the signal shifted right of center.

Figure 2: Schematic of the excized regions of our hydrogen emission spectra. The red region is removed when normalizing temperatures for the left-shifted spectra; the purple is removed when finding the sky temperatures for the right-shifted spectra. Only the blue and green regions are used when finding the gain ratio between the two spectra.

from T_{sky}, we sum over all points in our array with noise and without, to obtain that

$$\begin{aligned} Y_{\text{left}} \equiv \frac{\sum S_{\text{left cal},i}}{\sum S_{\text{left},i}} &= \frac{\sum g_{\text{left}}\beta_i \left(T_{\text{sys, left}} + T_{\text{noise}}\right)}{\sum g_{\text{left}}\beta_i T_{\text{sys, left}}} \approx \left(\frac{T_{\text{noise}}}{T_{\text{sys, left}}} + 1\right) \\ \implies T_{\text{sys, left}} &= \frac{T_{\text{noise}}}{Y_{\text{left}} - 1} = \frac{100\,\text{K}}{Y_{\text{left}} - 1}, \end{aligned}$$

with an identical equation holding for $T_{\text{sys, right}}$. Here the subscripted quantities denote values which depend on channel number.

Our gain factors are different for both the left and right shifted spectra, however we only care about their ratio. To find this, we excise any points in our array lining up with channel numbers which have contributions from hydrogen emission. Our gain ratio is thus defined by

$$R_g = \frac{\sum S_{\text{right},i}}{\sum S_{\text{left},i}},$$

where again the sum is taken over the indices corresponding to frequency channels containing neither right-shifted nor left shifted radiation from the hydrogen line, as depicted in Figure 2.