**RRLs and the Warm Ionized Medium: the Role of ALPACA**

Carl Heiles; February 6, 2022

## 1. ABSTRACT

ALPACA can map the brighter portions of the Warm Ionized Medium, which is the least well-known component of the Interstellar Medium. Maps containing thousands of ALPACA central positions would revolutionize our understanding of the WIM.

## 2. Introduction

The warm ionized medium (WIM) is one of the four major components of the diffuse interstellar medium. It amounts to about 25% of the total interstellar gas mass in the solar neighborhood. In the Galactic interior, it becomes a much larger fraction. It is best studied using its recombination radiation: continuum ('free-free' radiation), from free electrons captured by bare protons, and spectral lines, as the electron successively drops down from one electronic state with quantum number $n$ to a lower one with number $n - \Delta n$. These 'recombination lines' with $\Delta n = (1, 2, 3...)$ are called $(\alpha, \beta, \gamma...)$ lines. All the WIM emission lines are weak, and of the four ISM phases the one we know least about is the WIM.

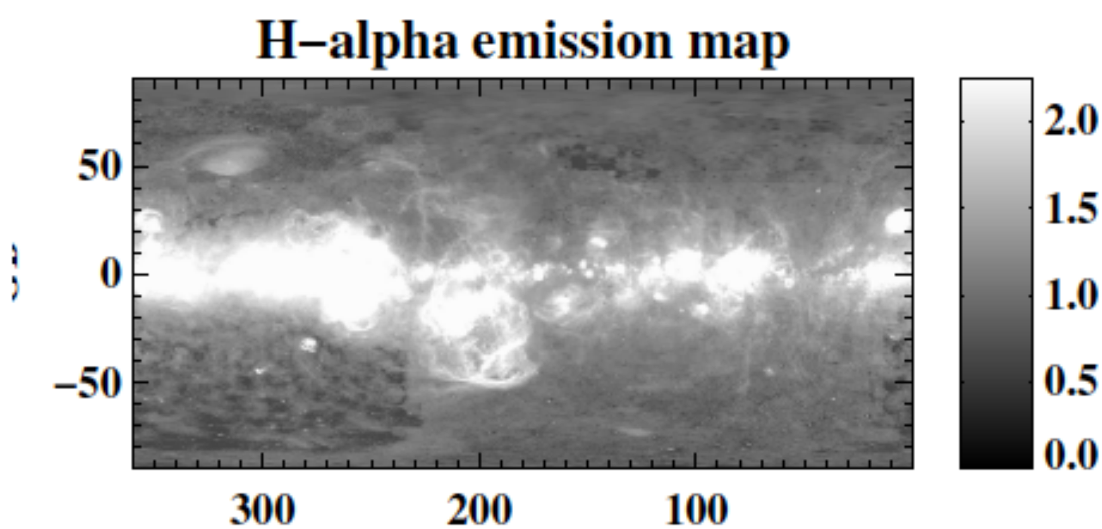


Fig. 1.— The WIM as seen with the Hα line. The saturated bright patches have $EM \gtrsim 20$ cm$^{-6}$ pc

The H-$\alpha$ optical recombination line, $(n = 3 \rightarrow n = 2)$, is the easiest to observe and most of our information regarding the physical state of the WIM comes from the H$\alpha$ line and some other non-Hydrogen and non-recombination optical lines. The optical lines are subject to absorption by interstellar dust, which limits their use to nearby gas. WIM in the Galactic interior can only be seen with recombination lines in the IR and radio. It's the radio lines that first revealed the enhanced abundance of WIM in the Galactic interior.

The only all-sky WIM map comes from the optical H$\alpha$ line. Figure 1 is the 20-year old best picture of the WIM. It's an agglomeration of three separate surveys, one (the Wisconsin H-Alpha Mapper—WHAM) with spectral resolution, allowing the H$\alpha$ line to be spectrally resolved and studied independently, and the other two (SHASSA, VTSS) using the free-free continuum radiation. The angular resolutions differ greatly: the continuum data have angular resolution of arc-seconds, while the WHAM survey has resolution $\sim 1$ degree.

## 3. Radio Recombination Lines (RRLs)

### 3.1. RRL Basics

Radio recombination lines reveal the WIM, but they are very weak. For alpha lines, we have (Gordon & Cato 1972, equation (1))

$$T_B \Delta f = 2.05 \times 10^3 b_n T_e^{-1.5}\, EM \tag{1}$$

or, for a line width of 10 km/s ($\Delta f = 50$ kHz) and $T_e = 10^4$, we have

$$T_B \approx 4 \times 10^{-5} EM \tag{2}$$

where $EM$ is the emission measure $n_H n_e L$ with units cm$^{-6}$ pc. This puts the saturated bright regions on Figure 1 within observational reach. For the brighter regions, we can see not only the Hydrogen alpha lines, but also the beta lines and also the Helium alpha lines. These provide information on excitation rates, the Helium abundance, and (for doubly-ionized Helium) the spectrum of the WIM ionizing photons.

### 3.2. That $b_n$ factor...

Note that $b_n$ factor buried in equation (1). $b_n$ is known as the departure coefficient, and specifies the departure of the electron population from its LTE vale. With high electron densities, $b_n \to 1.000$. When collisional rates can't keep up with radiative rates, $b_n$ becomes smaller than unity. This directly affects the line intensities by reducing the number of recombinations. But it can do more: the rate of change of $b_n$ with $n$ ($d \ln b_n / dn$) can lead to weak maser emission, or enhanced absorption. Comparing beta and alpha llnes gives a direct handle $d \ln b_n / dn$. Studies of this effect are rare, few, and far-between.

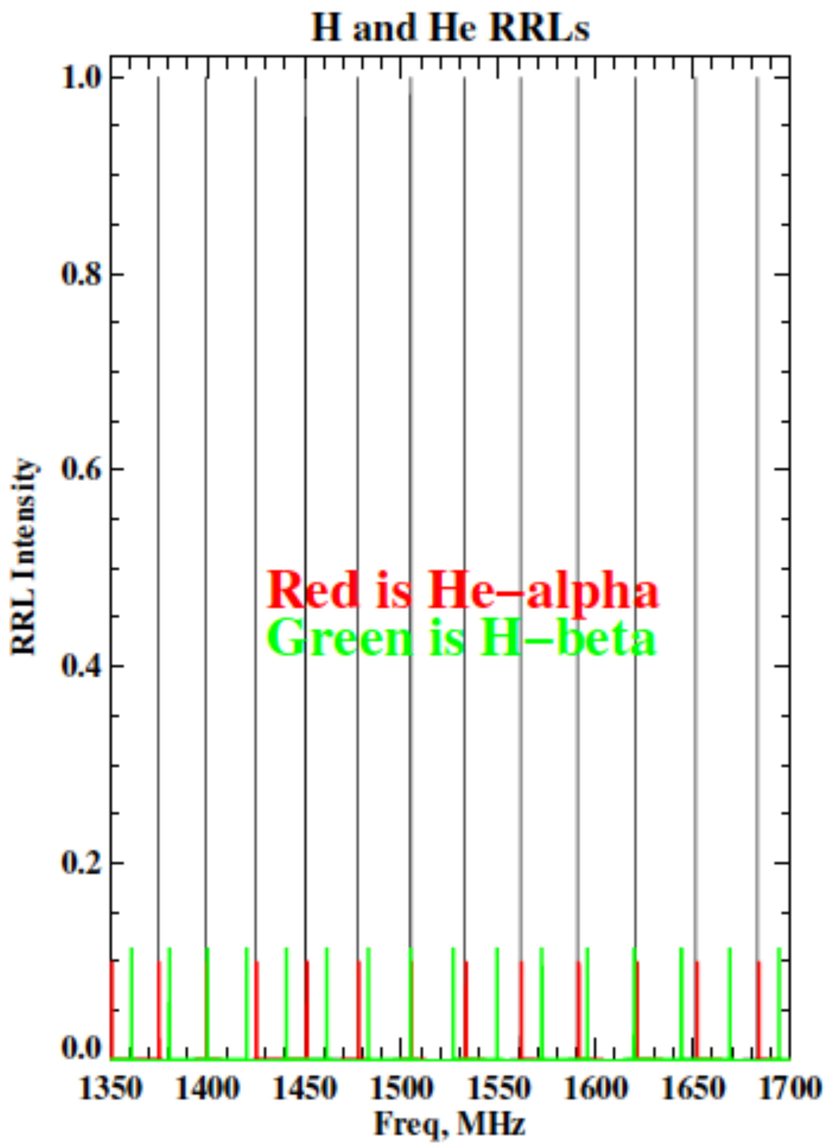


Fig. 2.— Recombination lines near 1500 MHz. Black is Hydrogen $\alpha$ lines, red is Helium $\alpha$ lines, green is Hydrogen $\beta$ lines.

## 4. How does all this relate to ALPACA?

For a 1-hour integration on a 10 km/s wide RRL we have a time-bandwidth product $Bt = 1.8 \times 10^8$, so for a system temperature of 30 K we reach noise $\Delta T_B = 2 \times 10^{-3}$ K, which corresponds to $EM \sim 60$. This is for a single H-recombination line. In fact, from figure 2 we see that in a 300 MHz band we observe 11 lines simultaneously, which reduces the noise level by a factor 3.3, meaning that we reach $EM = 18$.

With the 39 beams of alpaca, each of which sees 11 H$\alpha$ lines simultaneously, it makes sense to map all of the saturated bright regions in Figure 1. This amounts to thousands of ALPACA central positions. This would be a quantum leap in our observational understanding of the WIM.

## 5. REFERENCES

Gordon, M.A. & Cato, T. 1972 ApJ 176, 587

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