LOW FREQUENCY RADIO RECOMBINATION LINE STUDY WITH LOFAR

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ABSTRACT

Radio Recombination Lines (RRL) are important probes of physical conditions in the ISM. At very low frequencies, the electron orbital radius increases (0.07mm for principle quantum number n=766) making these atoms uniquely sensitive to density and temperature. LOFAR (Low Frequency Array) will operate from 10 to 240 MHz and straddles an important breakpoint between frequencies at which RRLs exhibit emission and absorption. LOFAR will also provide a qualitative leap in RRL detection sensitivity using a dense central array of dipole elements 2km across providing a 7' beam at 75MHz. This paper discusses scientific future investigations made possible by LOFAR and sensitivity limits of LOFAR for low frequency RRL detection.

RRL PRIMER

Radio Recombination Lines occur in regions of ionized and partially ionized gas when free electrons, captured by ions, cascade down atomic energy levels. Standard nomenclature specifies the species of atom, the ending energy level given by the principle quantum number, and the change in energy level of the transition. The line denoted by C448α, for example, is formed by an electron descending from n=449 level of a Carbon atom to the n=448 level. Greek letters β and γ correspond to downward jumps of 2 and 3 levels respectively. Most atoms can be considered 'hydrogenic' for high n, meaning the electrons in low energy levels effectively shield the outermost electron from the nucleus. In this case, the emitted line frequency differs from the Hydrogen case depending on the nuclear mass: ν_H-$\nu_Z \sim (1-1/M_Z)$; RRLs from higher mass atoms tend to blend together. RRL emission can be either spontaneous or stimulated (maser amplification) depending on the physical conditions, geometry and illuminating background. Roshi & Anantharamaiah (2000) show that along the Galactic plane, line antenna temperatures of H and C RRLs near 327MHz are well correlated with continuum antenna temperatures implying maser action. At lower frequencies, where the Galactic non-thermal background increases, this emission mechanism becomes increasingly important.

In the LOFAR frequency range corresponding to n~300-850, the atoms themselves can grow to enormous sizes. For a hydrogenic atom, the outer orbital radius is ~5×10^{-9} n^2 cm, placing the largest radius of a detected RRL (n=766, Kantharia, Anantharamaiah & Payne 1998) at around 'one thirtieth' of a millimeter: one could see a dot this size on paper from a high quality laser printer with the naked eye. Such loosely bound electrons are extremely sensitive to surrounding temperatures and densities. Pressure broadening in these lines goes as n^7 which limits the regions in the ISM they can inhabit. No RRLs in the LOFAR band will be seen, for example, from HII regions where the opacity is high and the lines will be highly broadened.

Below ~120MHz, no Hydrogen RRLs are seen and the Carbon lines which can be detected all appear in absorption. Below this frequency breakpoint, RRLs are seen towards HII regions and against bright background sources (Cas A) in absorption (Golynkin & Konovalenko 1991, Kanthria & Anantharamaiah 1998); this is because below this frequency, the excitation temperature approaches the kinetic gas temperature. Above 120MHz, the population levels are inverted and RRLs are seen in emission. The fact that only Carbon RRLs have been seen in absorption is probably due to a dielectronic electron capture mechanism which increases the probability of recombination in a multi-electron atom. This absorption mechanism means that many partially ionized and Carbon rich regions will be illuminated by the non-thermal Galactic background and be detectable by LOFAR.

ASTROPHYSICAL CONTEXTS

Figure 1 shows a schematic of an HII region taken from Roelfsma & Goss (1992). Hard UV photons ionize most of the Hydrogen near the star, but the ionization sphere boundary is relatively sharp. Photons with wavelength greater than 912 Angstroms pass through the HII region to an exterior medium in which the Hydrogen is mostly neutral and the heavier elements (Carbon, Sulfur, etc…) can be mostly ionized. In Figure 1, 'XII' refers to ionized elements heavier than Carbon. Such CII regions are characterized by RRL emission with velocities closer to the surrounding molecular cloud than to the HII region and by line widths indicative of a much cooler medium (see Pankonin 1980). Study of the

CII interface is motivated by the need to better understand energy transfer from the HII region to the parent star forming cloud.

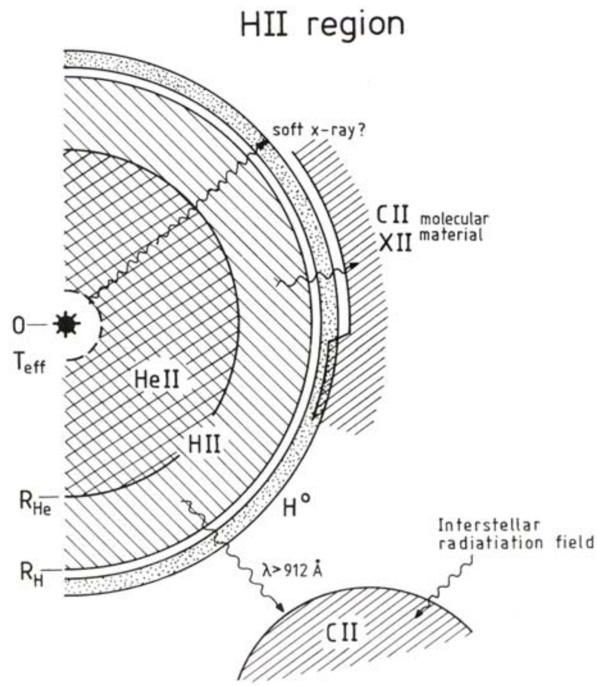

Figure 1. Schematic of HII and CII regions (Roelfsma & Goss 1992)

Wyrowski et al (1997) have used C91α observations with the VLA to show that the CII region in the Orion Bar does lie exactly at the HII/Cloud interface and matches the velocity of CO(3-2) lines which are well separated from the HII region. These authors derive a Te=200K and Ne=10/cm^3 for the CII region. An outstanding issue is to what extent the CII region is stratified and how its temperature, density and structure may change depending on distance from the exciting star. In DR21, for example, observations of the C640α RRL at 25MHz shows a broad absorption trough and a much colder Te=20K and sparse Ne=0.5/cm^3 are foundn (Golynkin & Konovalenko 1991). The caveat in this 25 MHz observation is that the beam is 20'x12deg, but clearly high resolution low frequency observations will be required to observe a spectrum of CII region physical parameters. These observations highlight the fundamental difficulty of large, asymmetric beam shapes in past low frequency RRL studies which often dilute emission from a CII region.

With a smaller beam and frequency agility below 75MHz, direct and accurate measurements of pressure broadening in CII regions are possible. In M16, Anantharamaiah et al (1988) observed the C456α line (69MHz) in absorption placing an upper limit on the density of Te<0.8/cm^3. Lower frequency spectra with pressure broadened signatures would allow a more precise determination of the density. LOFAR will be ideal for simultaneous RRL observations over a wide range of frequency.

Below ~75MHz, the Galactic background becomes brighter than an average HII region (Te~10,000K) and Carbon absorption RRLs can be identified over large sections of the Galactic plane. Erickson et al (1995) carried out an extensive survey of the Galactic plane (20<l<340, b=+-4) and found Carbon RRL absorption that varied with position. Comparison of α,β,γ lines near the same frequency imply that Ne<0.3/cm^3 over much of this region. These types of measurements are currently limited to restrictive receiver bands, but will be able to cover a wide range of frequency using the flexible LOFAR bandpass.

RRLs are also seen in both emission and absorption towards the strong background source CasA. Double peaked RRL emission (560MHz) towards this source corresponds to velocities in the Perseus spiral arm of the Galaxy. In absorption at 35MHz, pressure broadening blends these velocity components (at –37 and –48 km/s) (Kantharia, Anantharamaiah & Payne 1998). The absorption lines are Voigt profiles combining narrow Gaussian features with broad Lorentzian wings. The Lorentzian width allows one to constrain combinations of Ne, Te and the radiation background. Similar absorption observations over a wide range of frequencies can de-tangle these combinations. Combining the absorption spectra with higher frequency VLA data, they argue that the RRL gas along our line of sight to CasA is associated with HI, not molecular gas, and is characterized by Te=75K and Ne=0.02/cm^3. It is interesting to note that the 35MHz observations in (Kantharia & Anantharamaiah 1998) required an effective integration time of 400 hours, while LOFAR will be able to cut that time considerably.

SENSITIVITY AND BEAM SIZE

The types of observations described above are not feasible using current interferometers such as the VLA. The integration time required to detect a given Tl/Tc (line temperature/continuum temperature) is:

$$T_{int}=(\lambda^2/(\mathrm{BEAM}*\mathrm{AREA}*(Tl/Tc)))^2\,(1/BW)$$

where Beam is the beam size, Area is effective total area of the array, and BW is the bandwidth. Tl/Tc is typically observed to be ~ 0.003 and for a width of 15km/s (3.75 kHz) we find that in the VLA 'A' array, T_{int}=8 billion hours, and for 'D' array, T_{int}=24,000 hours for 3 sigma detections.

If we assume a 2km diameter densely packed aperture for LOFAR we find that:

$$T_{int}=((2\ \mathrm{km})^2/(\mathrm{AREA}*(Tl/Tc)))^2\,(1/BW)$$

where AREA=813λ^2 for the low frequency LOFAR dipoles and AREA=813*16*λ^2 for the 4x4 high frequency LOFAR arrays (see contribution by C. Lonsdale these proceedings). The integration times one would calculate given the LOFAR T_{int} relation above would still be prohibitive. The high spectral resolution and frequency range of LOFAR, however, will allow averaging of the RRLs to increase signal to noise ratio. The spacing between lines is given by $\Delta\nu=3\nu/n$, so one can average up to ~20 closely spaced lines depending on observing frequency. By so averaging, the integration times and beam sizes become:

At 25MHz,	T_{int}=13 hours,	Beam=21',	Number of lines = 20
At 75MHz,	T_{int}=442 hours,	Beam=7',	Number of lines = 16
At 120MHz,	T_{int}=11 hours,	Beam=4.5',	Number of lines = 10
At 200MHz,	T_{int}=52 hours,	Beam=2.5',	Number of lines = 10

CONCLUSIONS

The frequency agile, large collecting area architecture of LOFAR makes it ideal for a qualitative advance in RRL study. It will deliver high signal to noise spectra at both absorption and emission frequencies and offer mapping with resolutions at low frequencies which are an order of magnitude sharper than previously obtainable. LOFAR sensitivities may also make it possible to search for Zeeman splitting of RRLs to calculate B-fields and their dynamical importance in the cooler, rarified part of the ISM (Silvergate 1984).

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