Radio Recombination Lines with the Arecibo Observatory

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1 Introduction

Ionized gas, composed of atoms that have lost electrons, is the most massive component of matter in the Universe. Almost a quarter of the gas mass of the Milky Way is ionized, and it is therefore important that we understand the physics and distribution of ionized gas.

Ionized gas with characteristic temperatures of 10^4 K produces radio recombination lines (RRLs), which have been studied extensively with the Arecibo Observatory. The brightest RRLs are from Hydrogen, the most abundant element in the Universe, but helium and carbon RRLs are also routinely detected (Figure 1). Advances in instrumentation have greatly aided the study of RRLs, making them a powerful and under-utilized tool for understanding massive star formation, Galactic structure, and the physical properties of the most massive component of matter in the Universe.

RRLs are produced by phenomena energetic enough to remove an electron from atoms. There are two main sources of RRLs: H II regions and the diffuse, warm ionized medium (WIM) that pervades the disk of spiral galaxies like the Milky Way. H II regions are the ionized zones surrounding massive stars. Massive stars emit most of their energy in the ultra-violet regime, and these high-energy photons create and maintain these zones of plasma by ionizing atoms. An example of the RRL emission from the H II region S88 is shown in Figure 1. The WIM is also created primarily by the ionizing radiation from massive stars (Reynolds, 1984). Not all of the photons created by massive stars remain in H II regions, and some fraction escape into the interstellar medium (ISM). To the best of our knowledge, the escaped ultraviolet photons ionize elements in the ISM, creating the WIM.

To determine the structure of the ionized gas in our Galaxy, we require velocity information – i.e. how fast something is moving toward or away from us. These velocities are caused by the rotation of matter in our Galaxy, and with a model of Galactic rotation we can learn where the emitting gas is in the Galaxy. Recombination lines naturally provide this velocity information, for the entire volume of the ionized ISM, in much the same way that the

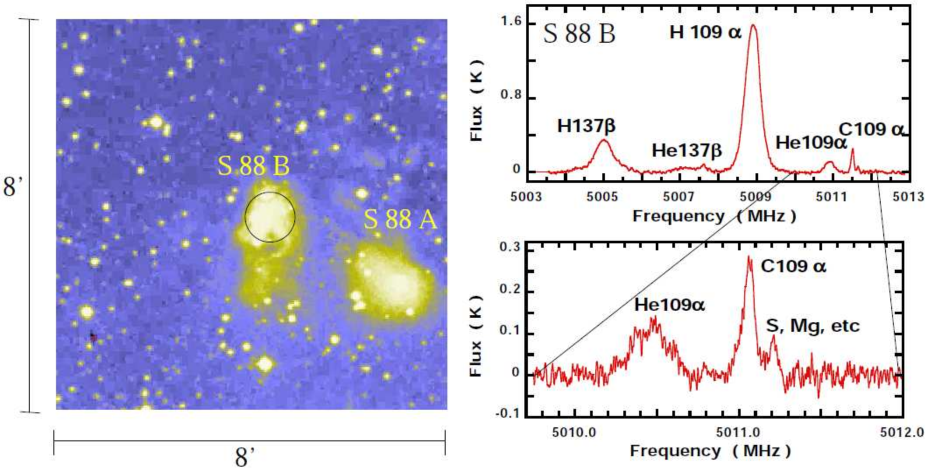

Figure 1: *Left:* Optical image of the massive star forming H II region S88. *Right*: RRL observations at 5 GHz toward S88 from Arecibo. The circle on the left panel shows the nominal pointing. Hydrogen, helium, and carbon lines are clearly detected. This spectrum was taken in 45 minutes of integration time (Y. Terzian, private communication).

21 cm line does for atomic gas. Most of the ionized gas traced by RRLs is from ongoing massive star formation. Studying the kinematics and dynamics of this component of the interstellar medium is key to understanding the interstellar medium and massive star formation.

Recent advances in technology have made the simultaeous observation of many RRLs possible, greatly increasing the efficiency of observations. There are 190 hydrogen RRLs in the frequency range observable with Arecibo ($\sim 0.3 - 10$ GHz, Figure 2). Thus, RRLs are a flexible tool that can be used to study the ionized universe, across the entire radio spectrum.

2 Background

Most future cm-wave single-dish RRLs observations will rely on line-stacking. This technique has long been used at optical wavelengths, but only recently has it been extended to RRLs using many (> 5) lines. Balser (2006) showed the utility of line-stacking at X-band with the GBT, and the same technique

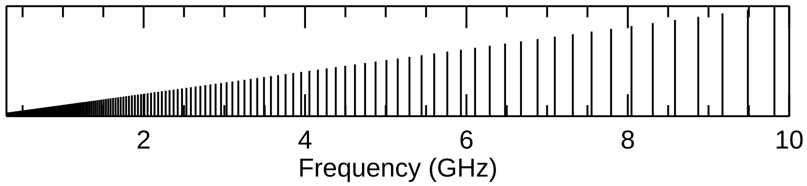

Figure 2: Frequencies of the 190 hydrogen RRLs within the frequency range observable with Arecibo. The heights approximate the line strength, under some simplifying assumptions.

has since been used in large subsequent surveys (Anderson et al., 2011). The increased use of line-stacking today is due to advances in instrumentation, but is only possible due to the RRL physics described below.

Recombination lines can be observed from the ultraviolet through the radio regime. The most commonly observed and strongest lines are of Hydrogen, but carbon and helium RRLs are also routinely observed. The strongest lines are from changes of electronic level n of 1. These are known as α-lines, $\Delta n = 1$, whereas β-lines have $\Delta n = 2$, etc.

RRL transition frequencies follow the relation:

$$\nu = R_{\rm M} c \left(\frac{1}{n^2} - \frac{1}{(n + \Delta n)^2} \right) , \tag{1}$$

where $R_{\rm M}$ is the Rydberg constant for atoms of mass M. The dependence of $R_{\rm M}$ on M reduces the observed frequency of the helium and carbon RRLs relative to hydrogen. For $n > 40$ in the radio regime and $\Delta n \ll n$, Equation 1 becomes:

$$\nu_0 \approx \frac{2(R_{\rm M} c)\Delta n}{n^3} . \tag{2}$$

The spacing between adjacent transitions is therefore,

$$\nu_0(n) - \nu_0(n-1) \approx 2R_{\rm M} c \frac{1}{n^3 - (n-1)^3} \approx \frac{3\nu}{n} . \tag{3}$$

Equation 3 shows that lines are spaced closer together at lower frequencies (Figure 2). A rough rule of thumb found by combining Equations 2 and 3 is that there are $70\nu^{-4/3}$ H$n\alpha$ RRLs falling within one GHz, so there are ~ 4 RRLs per GHz of bandwidth at X-band, ~ 8 at C-band, and ~ 40 at L-band.

Rohlfs & Wilson (2000) show that the line strength of RRLs, T_L follows

$$T_{\rm L} \approx 1.92 \times 10^3 \left(\frac{T_{\rm e}}{\rm K}\right)^{-3/2} \left(\frac{\rm EM}{\rm cm^{-6}\,pc}\right) \left(\frac{\Delta\nu}{\rm kHz}\right)^{-1} (\Delta n)^{-2}\,, \tag{4}$$

where T_e is the electron temperature of the plasma, EM is the emission measure (the integrated squared electron density along the line of sight), and $\Delta\nu$ is the line width. Neglecting pressure broadening, RRLs have approximately the same line width in units of $\rm km\,s^{-1}$, so $\Delta\nu \propto \nu$, and

$$T_L \propto \nu^{-1}(\Delta n)^{-2}\,. \tag{5}$$

Equation 5 neglects the effects of the changing telescope beam with frequency. In the radio regime, the difference in adjacent RRL strengths with the same Δn is therefore minimal (Figure 2). For example, the intensities of the $n = 100$ and $n = 101$ α-lines only differ by 3%. Stacking lines widely-spaced in frequency, however, does require some care if accurate line fluxes are desired.

Because they are closely spaced and of similar intensities, multiple lines from a single wide bandpass observation can be stacked together to greatly increase the efficiency of the observations. With its large collecting area, RRLs at Arecibo are a powerful tool for studying the ionized universe. High-bandpass receivers and back-ends will greatly increase the efficiency of these observations, because they will allow for more lines to be observed simultaneously.

3 RRL Astrophysics

3.1 Studies of Discrete HII Regions

Historically, RRLs have largely been used for surveys of discrete Galactic H II regions. Such studies have been essential for understanding the structure of the Milky Way. With Arecibo, there have been a number of such studies (Araya et al., 2002; Watson et al., 2003; Bania et al., 2012). Arecibo's SIGGMA survey (Liu et al., 2013) is mapping the Galactic plane visible to Arecibo in RRLs with ALFA at L-band, and will presumably detect numerous discrete Galactic H II regions as well. Recently Anderson et al. (2011) used to GBT to observe 448 new Galactic H II regions and the same team completed a second survey of ~ 300 more (Anderson et al., 2015, in prep.). The current census of Galactic H II regions numbers nearly 2000 (Anderson et al., 2014), most of which have been discovered from the RRL emission.

3.2 The HII Region Electron Temperature Gradient

The electron temperature of H II regions depends on the RRL intensity to radio continuum intensity ratio, the strength of the helium RRL, and the hydrogen RRL line width. Churchwell & Walmsley (1975) first used RRLs to study the relationship between the electron temperature of Galactic H II regions, T_e, and Galactocentric distance, R_{gal}. They found that T_e increases with increasing R_{gal}, as result consistent with studies in external spiral galaxies (Searle, 1971; Rubin et al., 1972). Metals are the main coolants of H II regions, and therefore a high electron temperature is the result of a low metal abundance. The low electron temperatures found in the inner Galaxy result from the large amount of stellar processing there.

The basic form of the abundance gradient is well-known, but questions remain. For instance, there may be azimuthal structure in the H II region T_e distribution, as found by Balser et al. (2011). This would imply that the Galactic disk is not well-mixed, a very important result for models of Galactic chemical evolution. The number of H II regions with accurately determined T_e values is still only ~ 100. Arecibo could make significant improvements in this area with very sensitive RRL and continuum measurements.

3.3 The Warm Ionized Medium

The diffuse ionized gas of the warm ionized medium (WIM), also known as the extended low density medium, pervades the disk of star forming galaxies. It is this component of the ISM that causes pulsar dispersion measures. The main tools for studying the WIM have been Hα (see Haffner et al., 2009, and references therein) (with other optical lines for comparison) and low frequency RRLs (e.g. Roshi & Anantharamaiah, 2001). Hα measurements can be extremely sensitive, but they suffer from severe attenuation in the Galactic plane. Low frequency radio observations have coarse angular resolution. Much progress can be made in understanding the origin and structure of the WIM using arcminute-resolution RRL observations with Arecibo.

In their study of the WIM using RRLs at L-band with 0.25° resolution, Alves et al. (2010) list 11 radio surveys that have observed diffuse ionized gas using RRLs. Among these only one, that of Cersosimo et al. (2009), was a fully sampled survey; the others only sampled grids of non-overlapping beams. Thus, the currently available data are largely inadequate for a comprehensive study of the properties and distribution of the ionized hydrogen found in different environments of the Galactic plane. Alves et al. (2010) did not have the resolution to separate the WIM emission from that of compact H II regions. While low frequency observations can more easily detect the WIM rather than higher density discrete H II regions, in part due to stimulated emission, a detailed study of the WIM must have sufficient angular resolution to exclude compact sources.

The WIM is surprisingly easy to detect in stacked RRL observations. Anderson et al. (2011) measured the RRL emission from 448 H II regions using the GBT at X-band with an $82''$ beam. They found that 130 ($\sim 30\%$) of their targets have multiple RRL velocity components, one of which is likely from the WIM. Their observations averaged just 10 minutes per position. In followup observations with the GBT, Anderson et al. 2014, in prep. traced the distribution of the WIM. The additional components come from the most active star forming regions in the disk, indicating that they are due to leaked photons from H II regions. This interpretation, however, does not completely agree with the lack of detected helium (Roshi et al., 2012), long known from optical line measurements.

Ionized gas above the Galactic plane seems to exist in long plumes. (Heiles et al., 1996) observed RRLs and found ionized "worms" extending out of the Galactic plane. These features are likely blown out by supernova remnants or successive generations of O-stars. The connection between these features and star formation below in the disk needs to be investigated at high resolution and sensitivity. Arecibo is the idea instrument to further studies of the distribution of the WIM, and its connection to star formation. The large aperture makes for relatively high angular resolution observations, even at low frequencies.

3.4 Carbon RRLs

Carbon RRLs are emitted from the outer transition zone of molecular clouds and from H II region PDRs. Photons with wavelengths long-ward of the Lyman limit can escape the PDRs of H II regions to ionize carbon, which has an ionization potential 2.3 eV below that of hydrogen. Carbon RRLs are therefore excellent probes of the physical conditions in H II region PDRs and their line strengths are important inputs to PDR models. They were first detected by Palmer et al. (1967) and have been studied by Pankonin et al. (1977).

Carbon RRLs can also be used to estimate the magnetic field strength in

H II region PDRs. Roshi (2007) used Arecibo data from Roshi et al. (2005) to estimate the magnetic contribution to the non-thermal carbon RRL line width. To expand such work to a larger sample of H II regions requires high sensitivity and a velocity resolution sufficient to resolve the few $\mathrm{km\,s^{-1}}$ lines. The lines in Roshi et al. (2005), for example, are typically $\sim 10\,\mathrm{mJy}$. Given the usual difficulties in estimating cosmic magnetic field strengths, expanding this work to a larger sample of H II regions with Arecibo is important.

3.5 Extragalactic Star Formation

Extragalactic RRLs directly trace the emission of Lyman continuum photons from all OB stars. This emission can therefore be used as a star formation rate (SRF) indicator. In contrast to optical SFR tracers , RRLs of course need no correction for dust atenuation. Because RRLs are quite faint, the line stacking method will be especially useful for studies of external galaxies.

There have been only four galaxies with RRL detections using single-dish telescopes: M82 (Shaver et al., 1978), NGC 253 (Puxley et al., 1997), Arp 220 Anantharamaiah et al. (2000), and NGC 2146 (Puxley et al., 1991). These are all galaxies with extremely active star formation, and therefore more normal galaxies need to be studied for RRLs to be a useful SFR indicator. Most successful RRL studies of external galaxies have used the VLA. While the VLA has the benefit of angular resolution, the sensitivity of Arecibo can easily exceed that of the VLA. Furthermore, Arecibo's arcminute-sized beam is well-matched to the size of many nearby galaxies.

Interpretation of RRL detections requires some modeling to account for stimulated emission and pressure broadening, collectively referred to as non-LTE effects. The so-called "departure coefficients" due to stimulated emission are well-known (Salem & Brocklehurst, 1979), and depend on the electron density. They were shown to largely be unimportant for a sample of Galactic H II regions observed at X-band by (Quireza et al., 2006). Detecting the β lines or comparing the intensity of α lines separated in frequency can greatly aid the modeling.

4 The Future

There are five projects outlined above: discrete H II regions, the H II region electron temperature gradient, the warm ionized medium, carbon RRLs, and extragalactic star formation. Of these, the latter four hold the most promise for work with Arecibo in the near fugure. Adding significantly to the number of known discrete H II regions in the part of the sky seen by Arecibo (project # 1) will take a lot of telescope time, and may not pay large scientific dividends. For example, Bania et al. (2012) recently used 50 hours on Arecibo to get 37 RRL detections of discrete H II regions at X-band. Performing electron temperature followup observations of discrete H II regions (project #2), however, could be very fruitful.

The latter three projects deserve more dedicated study. The warm ionized medium in particular can be mapped at high resolution and sensitivity with Arecibo. This work is essential for understanding the energy balance in the interstellar medium, and in determining how exactly this gas is ionized. Using RRLs as an extragalactic star formation rate indicator is similarly a project with great potential. These projects will benefit from the continuing development of wide bandwidth frontends, so we can observe many RRLs simultaneously.

5 Collaborators on this research

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