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INTRODUCTION

1.1. THE INTERSTELLAR MEDIUM

The interstellar medium (ISM) contains the gas, dust, radiation and charged particles that lie between the stars in a galaxy. The gas in the ISM is composed of hydrogen (70.4 % by mass), helium (28.1 % by mass) and heavier elements (1.5 % by mass). In our Galaxy, the Milky Way, gas and dust are $\approx 10\text{--}15\%$ of the stellar mass (e.g., Ferrière, 2001). Gas, dust and radiation interact with each other. This coupling between gas, dust and radiation gives rise to an ecosystem (e.g., Burton, 2004). In this ecosystem stars are formed out of interstellar gas. Stars process interstellar gas through nucleosynthesis, which is then returned to the Galaxy through stellar winds and supernova explosions. There, it will repeat the process, forming new stars, planets and life. An overly simplified cartoon of this cycle is presented in Figure 1.1. Stars are formed in the densest portions of the ISM, molecular clouds, where gravity compresses the gas to densities high enough that it can form stars (e.g., Blitz & Rosolowsky, 2006). Once stars are formed, these will interact with the surrounding gas. This interaction, through radiation, winds and supernovae explosions, might trigger new rounds of star formation or render the surrounding gas incapable of forming new stars (e.g., Walch, 2014). The exact details of how this cycle develops, how gas transitions from being hot and diffuse to cold and dense, are part of the recipe that determines how galaxies evolve over time, and it is one of the main missing pieces in our understanding of galaxy evolution (e.g., Schaye et al., 2015).

A color composite image of part of the Galactic ecosystem is shown in Figure 1.2. This is Cygnus X (Piddington & Minnett, 1952), a region of massive star formation located at a distance of ≈ 1.4 kpc (Rygl et al., 2012; Kiminki et al., 2015). In Cygnus OB2 it is estimated that there are around 2600 OB stars (Knödlseeder, 2000), and between DR21 and W75N 40 massive protostars (Beerer et al., 2010). There, the extreme-ultraviolet (EUV) photons (energies ≥ 13.6 eV) from massive stars ionize the gas creating HII regions. The free electrons produced in the process heat the gas through collisions to temperatures $\sim 10^4$ K. This results in HII regions having high thermal pressures and

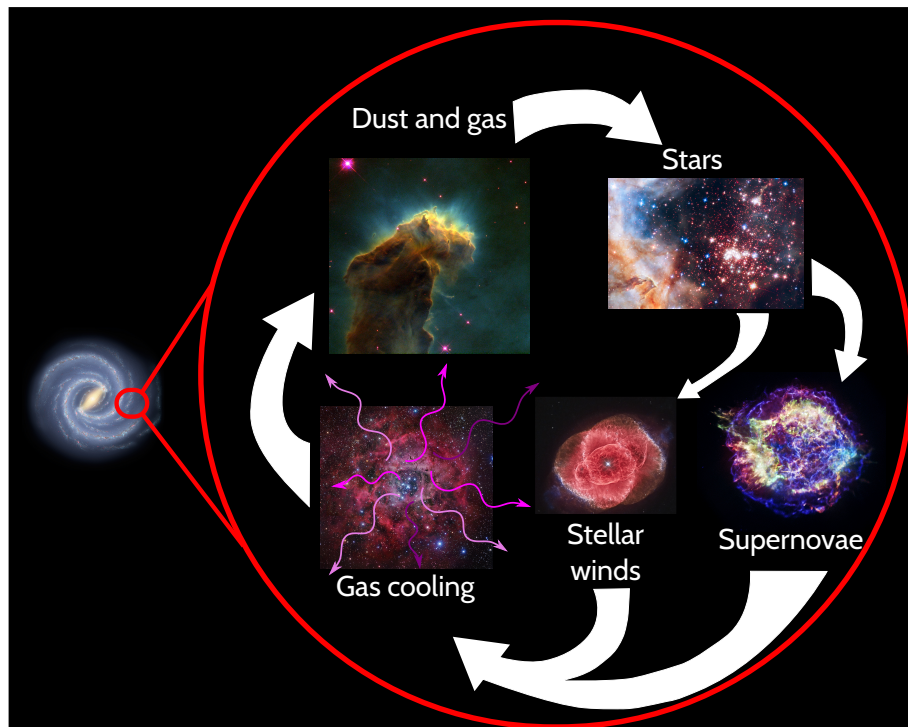


Figure 1.1.: A simplified schematic of the Galactic ecosystem. In a galaxy, like the Milky Way, stars are constantly being born out of dust and gas. These in turn return dust and gas to the galaxy when they go out. Then the hot gas returned by the stars cools down in spectacular displays. Once it has cooled enough it can become the material from which new stars are born. Images credit: NASA/ESA/Hubble/HLA/Robert Gendler/Raul Villaverde.

large thermal velocities, which causes them to expand against the colder material from which the ionizing stars formed. Moreover, the ionizing radiation will drive a ionization front into the surrounding gas. This will cause the gas to compress, forming dense structures which might become gravitationally unstable and hence, new sites of star formation (Elmegreen & Lada, 1977). However, in the long run the ionizing radiation will photoevaporate the parent molecular cloud, shutting down star formation (e.g., Elmegreen, 2007; Murray, 2011). This is one of the ways in which stellar feedback regulates star formation in a galaxy (e.g., McKee & Ostriker, 2007).

The influence of stellar radiation, winds and supernovae explosions gives rise to a turbulent ISM where the gas is found in different states. Depending on its temperature and the dominant form of hydrogen (molecular, atomic or ionized), ISM gas can be grouped into; molecular, cold neutral medium, lukewarm neutral medium, warm neutral medium, warm ionized medium and hot ionized medium (CNM, LNM, WNM, WIM and HIM, respectively). For molecular gas the temperatures are ~ 10 K, and, as its name suggests, hydrogen is molecular. The WNM consists of gas in which hydrogen is atomic

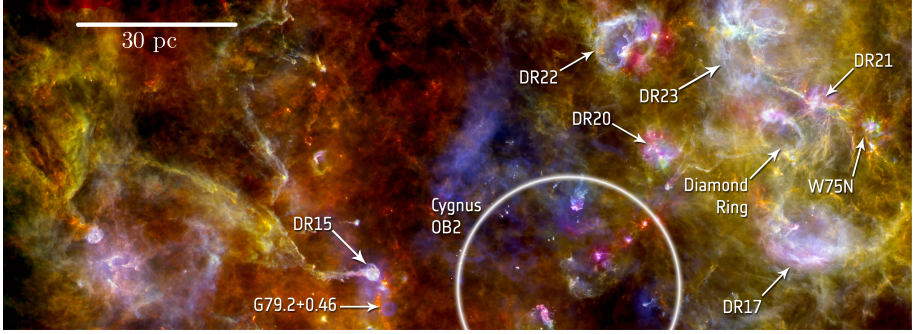


Figure 1.2.: The Cygnus X star forming region in the Milky Way as seen by the Herschel space observatory. In blue 70 μm , in green 160 μm and in red 250 μm . Image credit: ESA/Herschel/PACS/SPIRE/HOBYS Consortium.

with a temperature of $\sim 10^4$ K. In the CNM hydrogen is also atomic, but it has a lower temperature, ~ 100 K (e.g., Wolfire et al., 2003). By mass, most of the gas in the ISM is in the WNM and CNM (e.g., Tielens, 2010). The lukewarm neutral medium is gas where hydrogen is atomic with a temperature between that of the WNM and CNM. In the WIM the temperatures are similar to those in the WNM, $\sim 10^4$ K, but hydrogen is ionized. The density in the WIM is $\sim 0.1 \text{ cm}^{-3}$ and has a volume filling fraction of 0.4–0.2 (e.g., Haffner et al., 2009). The hot ionized medium comprises gas in which hydrogen is ionized and the temperatures are $\sim 10^6$ K. The high temperatures in the HIM are maintained through shock waves driven by supernovae. As seen in Figure 1.2, all these types of gas coexist and interact with each other. For example, part of the ionizing photons emitted by massive stars are able to leak from HII regions into the neutral ISM. These escaping photons are part of what determines the energy balance of the ISM, and they are responsible for maintaining the ionization of the gas in the WIM (e.g., Haffner et al., 2009). How ionizing photons are able to transverse the large distances required to keep the ionization of the WIM is related to how the CNM is distributed. Thus, to understand the WIM we also need to understand the properties of the CNM.

Observations of different types of gas in our Galaxy are performed using diverse tracers. An example of some of these observations is presented in Figure 1.3. In these maps only regions close to the Galactic plane are shown (Galactic latitudes $|b| < 10^\circ$). The CNM and WNM are traced by the 21 cm line of atomic hydrogen (HI, top panel in Figure 1.3). The distribution of atomic gas peaks close to the Galactic plane and extends over most of the sky (e.g., Kalberla & Kerp, 2009). The CNM has a scale height of ≈ 100 pc, while that of the WNM is ≈ 400 pc (e.g., Kalberla & Kerp, 2009). Molecular gas is usually traced by the first rotational transition of carbon monoxide (CO) at 2.6 mm, the $^{12}\text{CO}(1-0)$ line (second panel, from top to bottom, in Figure 1.3). Most of the molecular gas is concentrated in the Galactic plane, $b \approx 0^\circ$. Molecular gas has higher densities and column densities than atomic gas. For this reason, the radiation field that impinges into molecular gas is softer and less intense than that bathing atomic

gas. Visible light traces the stellar component and the dark regions are produced by absorption and scattering by dust. X-Rays trace regions where the gas is hot and ionized, the HIM. This is mostly in regions of massive star formation, such as Cygnus-X or the Galactic center, or in supernova remnants, like Vela.

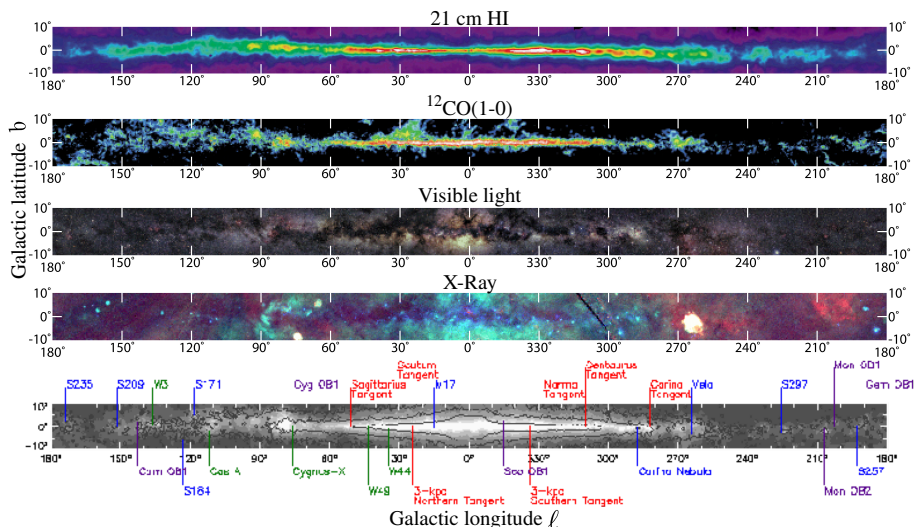


Figure 1.3.: Maps of the Milky Way as seen at different wavelengths. The *top panel* shows the distribution of atomic gas, cold and warm, as seen through the 21 cm line of HI. The next panel shows the distribution of molecular gas as traced by the $^{12}\text{CO}(1-0)$ line at 2.6 mm. The *middle panel* shows the Milky Way as seen in optical light between $0.4-0.6 \mu\text{m}$. The next panel shows the X-ray emission from the Milky Way. X-rays trace mostly hot ionized gas. The *bottom panel* is a finder chart showing some regions and their names. The HI-21 cm map is from the Leiden-Argentina-Bonn (LAB) survey (Kalberla et al., 2005). The $^{12}\text{CO}(1-0)$ map is from the Harvard Center for Astrophysics (CfA) survey (Dame et al., 2001). The visible light image was produced by A. Mellinger, and it is an earlier version of the one presented in Mellinger (2009). The X-ray image is from the Position-Sensitive Proportional Counter (PSPC) instrument on the Röntgen Satellite (ROSAT, Snowden et al., 1997). Image credit: NASA.

Observations like the ones presented in Figure 1.3 have helped us describe the Galactic ecosystem. However, it has also become clear that in order to reach a deeper understanding of the physics that drive galaxy evolution we require a quantitative assessment of the gas physical properties (e.g., temperature and density). The distribution of temperature and density of interstellar gas is determined by the effects of different physical mechanisms (e.g., Vázquez-Semadeni, 2012). An extension of this is that it should be possible to determine the relative importance of different physical mechanisms by measuring the temperature and density distribution of the ISM. An example of such analysis is that performed using the 21 cm line of HI. Observations of 21 cm-HI reveal the existence of a broad range of physical conditions for atomic gas (e.g., Kalberla et al., 1985; Heiles, 2001; Heiles & Troland, 2003; Kalberla & Haud, 2018). If the gas is in pressure and thermal equilibrium, then the phase structure is set by the gas

heating and cooling. Under these equilibrium conditions the gas will arrange itself into cold dense clouds (CNM) and a warm diffuse medium (WNM). Gas with conditions between those of the CNM and WNM, e.g., the LNM, is thermally unstable, so it will cool down or heat up to the CNM and WNM, respectively (e.g., Field et al., 1969; Wolfire et al., 1995, 2003). If we consider mechanical energy input by massive stars, then, the constant energy transfer will stir and shock the gas. The pressure fluctuations caused by these shocks and turbulence will drive gas between the CNM and WNM, resulting in the presence of significant quantities of thermally unstable gas (e.g., Kim et al., 2013). Supernovae explosions are one of the main driving mechanism of shocks and turbulence in the ISM (e.g., Mac Low & Klessen, 2004; Gazol et al., 2005; Kim & Ostriker, 2017).

One of the main issues regarding the use of the gas physical conditions to determine the relative importance of different physical mechanisms in setting the phase structure of the ISM is the lack of probes for the physical conditions. The most widely used method to study cold gas in the ISM is through the 21 cm-HI line. When HI is observed in absorption against a continuum source, the absorption feature will be stronger the colder the gas is. This makes the absorption features of the 21 cm-HI line a reliable tracer of cold gas in the ISM. In order to estimate the gas temperature using the 21 cm-HI line observations of both emission and absorption profiles are required (e.g., Heiles & Troland, 2003; Murray et al., 2015). However, observations of 21 cm-HI in absorption are only possible against a background source and the line is not sensitive to the gas density.

Another limitation of the bright 21 cm-HI and $^{12}\text{CO}(1-0)$ lines for the study of the cold ISM, is that they do not trace a large fraction of the molecular gas mass. Dust and γ -ray observations have revealed that close to 50% of the molecular gas mass in the Solar neighbourhood is not traced by these lines (e.g., Grenier et al., 2005; Planck Collaboration et al., 2011). This *CO-dark* molecular gas is in regions where hydrogen is mainly molecular, so HI is not detected, and CO has not been formed or it has been destroyed (e.g., van Dishoeck & Black, 1986; Visser et al., 2009; Wolfire et al., 2010). This has led to the use of other lines to determine the gas physical conditions and to probe *CO-dark* molecular gas (e.g., the 18 cm line of OH, Allen et al., 2015; Engelke & Allen, 2019).

For the conditions typical of *CO-dark* molecular gas, most of the hydrogen will be in molecular form, and carbon will be ionized, C^+ . This makes the far-infrared (FIR) fine structure line of C^+ at $158\ \mu\text{m}$ ([CII]) a prime tracer of *CO-dark* molecular gas (e.g., Langer et al., 2014; Tang et al., 2016; Goldsmith et al., 2018). However, since the energy difference between the fine structure states of [CII] is 91.2 K, and that [CII] can be easily excited through collisions with electrons, atomic or molecular hydrogen, [CII] emission traces a variety of gas states. Some of these include the WIM, the extended low density WIM (ELDWIM, e.g., Heiles, 1994), extended low density HII regions (e.g., Goldsmith et al., 2015), as well as *CO-dark* molecular gas (e.g., Visser et al., 2009; Wolfire et al., 2010) and photodissociation regions (PDRs). Hence, to study *CO-dark* molecular gas using [CII] we must be able to separate the contribution from different gas states to its excitation (e.g., Pineda et al., 2013; Pabst et al., 2017). An alternative is to use lines from C^+ at radio frequencies, which, as we will see, only trace cold gas.

The radiation from massive stars exposes most of the interstellar gas to ultraviolet (UV) photons creating PDRs in the surfaces of atomic and molecular clouds. PDRs are regions where UV photons (with energies between 6 and 13.6 eV), determine the chemistry, structure and thermal balance (for a review see Hollenbach & Tielens, 1999). Photons with energies less than 13.6 eV are not capable of ionizing hydrogen, but they can ionize other elements, such as carbon (ionization potential 11.2 eV, e.g., Emsley, 1998), and dissociate molecules, such as molecular hydrogen (e.g., Stecher & Williams, 1967). As UV photons penetrate into a PDR, the radiation field will lose energy and hardness due to dust extinction and absorption by molecular hydrogen. This will give rise to a layered structure, where hydrogen is atomic close to the source of photons and molecular far from it (Tielens & Hollenbach, 1985).

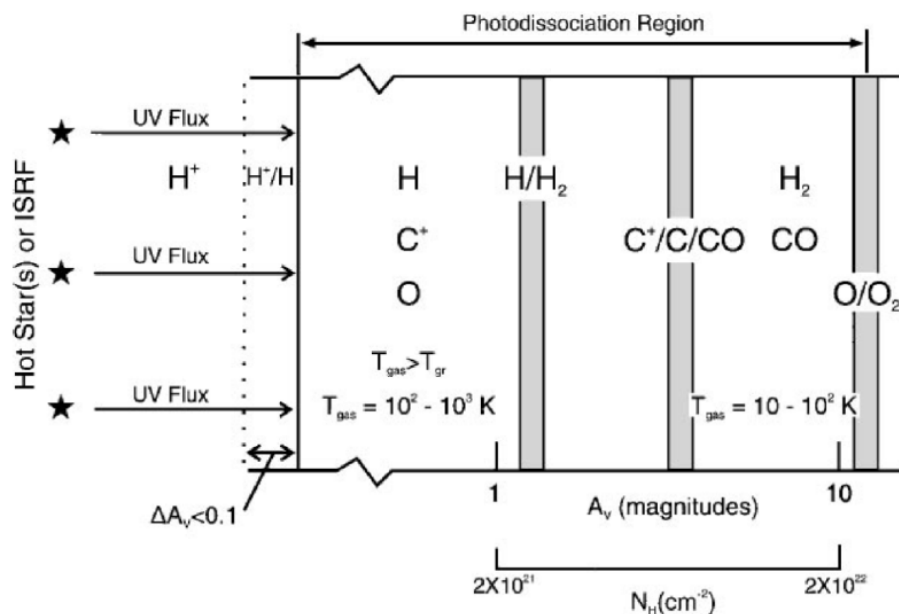


Figure 1.4.: Diagram showing the structure found in a PDR. At the edge of the PDR, on the left, hydrogen is ionized by UV photons with energies above 13.6 eV. As we move to the right, deeper into the PDR, hydrogen becomes atomic and then molecular. Image taken from Hollenbach & Tielens (1999).

An example of the layered structure found in a PDR is presented in Figure 1.4. There the source of radiation is on the left. Close to the source of radiation we have an HII region (labelled H^+ in Figure 1.4). At the interface between the HII region and the neutral gas we have the H^+/H interface (the ionization front). Only photons with energies less than 13.6 eV pass the ionization front. As we move to the right we have two other important regions, these are: the dissociation front, where the transition between atomic and molecular gas takes place (H/H_2 interface) and the $C^+/C/CO$ interface. Between the H^+/H and $C^+/C/CO$ interfaces, the C^+ layer, most of the free electrons are provided

by the ionization of carbon. Because of this, we have that $x_e \approx x_{C^+} \approx 1.6 \times 10^{-4}$ (Sofia et al., 2004), where $x(X)$ is the abundance of X with respect to hydrogen. Also, in the C^+ layer we have that most of the gas heating is through the photoelectric effect (e.g., Spitzer, 1948; Watson, 1972; de Jong, 1977; Draine, 1978; Bakes & Tielens, 1994; Weingartner & Draine, 2001), and the gas cooling is through the FIR lines of oxygen and ionized carbon. In the denser layers of the PDR the gas heating is through collisional de-excitation of UV pumped H_2 (Sternberg & Dalgarno, 1989; Burton et al., 1990; Röllig et al., 2006).

The picture described above represents a *classical* PDR, i.e., the interface between an HII region and a molecular cloud. For the PDRs exposed to the mean interstellar radiation field (ISRF, e.g., Mathis et al., 1983) the relevant physical and chemical processes, as well as the layered structure, are similar to those found in a *classical* PDRs. The PDRs in atomic clouds have been studied using absorption line studies in the UV (e.g., van Dishoeck & Black, 1986). UV absorption studies provide important observational constraints on the physics of the ISM, however, they lack spatial information and only sample local gas, as they can only be performed against a UV bright background source. Given that most of the mass in the ISM is in neutral atomic gas (WNM and CNM), understanding the properties of this gas is a central piece in our understanding of the galactic ecosystem.

1.2. CARBON RADIO RECOMBINATION LINES

A powerful tool for the study of the cold ISM is through observations of carbon radio recombination lines (CRRLs). The cold gas in the ISM, atomic clouds and the surfaces of molecular clouds, is teeming with ionized carbon. Thanks to the capabilities of new and upgraded telescopes it is now possible to observe these faint lines with unprecedented detail. This was the main motivation for this thesis.

CRRLs, as their name suggests, are spectral lines of ionized carbon observed at radio frequencies. When a carbon ion recombines with an electron to a large principal quantum number n it will result in a Rydberg atom. As the Rydberg atom of carbon transitions between different principal quantum numbers it will produce CRRLs, from GHz to MHz frequencies depending on the n levels involved. For example, a transition from $n' = 31$ to $n = 30$ will produce a line at 232 GHz, and it is called a $C30\alpha$ line. α lines involve a change in principal quantum number $\Delta n = 1$. Transitions involving larger changes in n are called β , γ , δ and so on, for $\Delta n = n' - n = 2, 3, 4$ and larger.

Ionized carbon can also be found in e.g., HII regions, the WNM, the CNM and the surfaces of molecular clouds. However, given the strong dependence of the CRRL optical depth on temperature ($\tau \propto T^{-5/2}$), these lines predominantly arise in cold gas (~ 100 K, e.g., Gordon & Sorooshenko, 2009). This means that they are tracers of the CNM and the surfaces of molecular clouds. Moreover, CRRLs provide independent probes of the gas physical conditions (temperature and density, e.g., Payne et al., 1994). This makes CRRLs particularly interesting tools for the study of cold gas, since the physical conditions of the CNM and *CO-dark* molecular gas are hard to determine by other means.

The first reported detection of CRRLs was that of Palmer, Zuckerman, Penfield, & Lilley (1967). These were quickly followed by the suggestion that departures from local thermodynamical equilibrium (LTE) could help explain the observations (Goldberg & Dupree, 1967). The discovered CRRLs were then interpreted as coming from high density atomic regions surrounding HII regions under LTE (Zuckerman & Palmer, 1968). An alternative explanation was that the lines were stimulated due to the presence of a background source of continuum (Dupree & Goldberg, 1969). The observations of Palmer et al. (1967) and Zuckerman & Palmer (1968) targeted C109 α lines at ≈ 5 GHz. Observations of the C134 α and C166 α lines at lower frequencies confirmed that CRRLs were not coming from the HII regions themselves, and that departures from LTE were necessary to explain the observed line strengths (Pedlar, 1970; Zuckerman & Palmer, 1970). Observations of narrow hydrogen RRLs (HRRLs) at the velocity of the corresponding CRRL provided additional evidence supporting that the lines are not produced in the HII region, but in colder gas (Ball et al., 1970; Chaisson, 1971).

Departures in the population of ionized carbon atoms with respect to their LTE values are characterized by the departure coefficients b_n and $\beta_{nn'}$. The factor b_n describes how the number of ions at a particular n deviates from its LTE value, while the factor $\beta_{nn'}$ characterizes the effect of absorption and stimulated emission. The first calculations of departure coefficients for CRRLs were those of Dupree & Goldberg (1969). These calculations were performed for conditions typical of HII regions, as at the time which type of gas the CRRLs were tracing was not clear and the relevant collisional rates were not available at low temperatures. After these rates became available, and observational evidence in favor of a cold gas origin of CRRLs accumulated, Dupree (1972) computed departure coefficients for CNM-like conditions. These calculations were then applied to the interpretation of CRRL observations (e.g., Hoang-Binh & Walmsley, 1974; Dupree, 1974).

The combined use of CRRL observations and calculations of the departure coefficients lead to a picture in which high frequency (frequencies $\gtrsim 2$ GHz) CRRLs trace the dense interfaces between HII regions and molecular gas (e.g., Zuckerman & Palmer, 1968; Zuckerman & Ball, 1974) –regions now generally recognized as PDRs– while at lower frequencies the lines can be observed thanks to the effect of stimulated emission (e.g., Dupree & Goldberg, 1969; Dupree, 1974).

The first detection of a CRRL in absorption was that of C631 α (Konovalenko & Sodin, 1980). This line was first identified as the hyperfine transition of atomic nitrogen (Konovalenko & Sodin, 1980), but it was quickly suggested that the line could be due to a recombination line of carbon (Blake et al., 1980). This was confirmed by the detection of the C630 α and C640 α lines (Konovalenko & Sodin, 1981). The detection of C631 α implied that highly excited states of ionized carbon can be found in our Galaxy. The observations of C631 α were performed against Cassiopeia A (Cas A), and led to many more observations of CRRLs towards this source (e.g., Ershov et al., 1982; Konovalenko, 1984; Ershov et al., 1984; Anantharamaiah et al., 1985; Lekht et al., 1989; Payne et al., 1989; Anantharamaiah et al., 1994; Payne et al., 1994; Kantharia et al., 1998; Stepkin et al., 2007; Asgekar et al., 2013; Oonk et al., 2015, 2017; Salas et al., 2017, 2018). There, the largest bound atoms in space have been found ($n = 1009$, corresponding to an atom with a classical diameter of $\approx 50 \mu\text{m}$, Stepkin et al., 2007), and the lowest

frequency detection of a spectral line at 11 MHz was achieved (Salas et al., 2017). Moreover, these observations showed that low-frequency (frequencies below 1 GHz) CRRLs originate in cold diffuse gas. However, it was not possible to determine whether CRRLs are associated with atomic or molecular gas (e.g., Anantharamaiah et al., 1994).

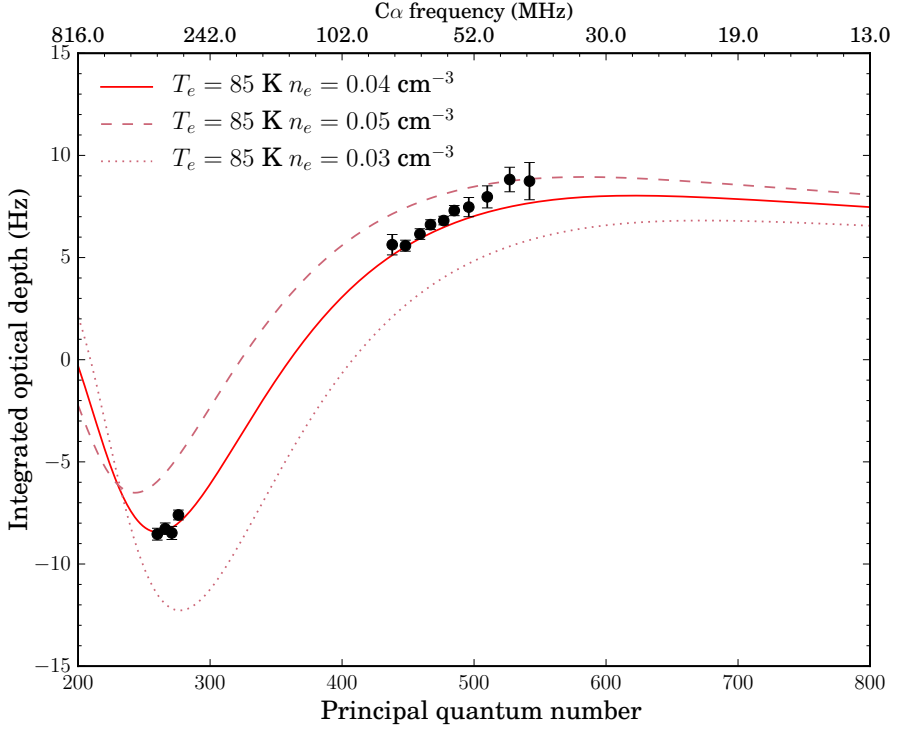


Figure 1.5: Comparison between the predicted integrated optical depth (*red lines*) and the observed values (*black circles*). The CRRL observations were carried out towards Cas A, one of the brightest low-frequency continuum sources, using LOFAR. The predicted integrated optical depth was computed using the departure coefficient calculations of Salgado et al. (2017). The departure coefficients were evaluated for different values of electron temperature, T_e , and density, n_e . Adapted from Oonk et al. (2017).

A couple of years before the first detection of CRRLs in absorption, it was realized that dielectronic capture plays an important role in setting the level population of ionized carbon (Watson et al., 1980). Dielectronic capture is the process in which a carbon ion recombines with a free electron, exciting the carbon ion core in the process. This led to new calculations of the departure coefficients (e.g., Walmsley & Watson, 1982; Ponomarev & Sorochenko, 1992; Payne et al., 1994; Roshi & Kantharia, 2011). However, with these calculations it was not possible to explain the observed variations in line properties as a function of principal quantum number with one set of physical conditions (e.g., Payne et al., 1994). Recently, Salgado et al. (2017) have updated the calculation of

the departure coefficients. These updated calculations used the semi-classical angular momentum changing collisional rates of Vranceanu et al. (2012), and solve the level population problem explicitly considering the role of angular momentum, l , in the dielectronic capture process. Previous calculations had to assume some distribution for the departure coefficient b_{nl} as a function of l , largely due to the lack of computing power available. Using the departure coefficient calculations of Salgado et al. (2017) it has been possible to explain the change in CRRL properties as a function of principal quantum number (Oonk et al., 2017). This is illustrated in Figure 1.5, where we show a comparison between predictions for the CRRL integrated optical depth as a function of principal quantum number and the observed values.

Other studies of low-frequency CRRLs have focused on surveying the Galaxy (e.g., Erickson et al., 1995; Kantharia & Anantharamaiah, 2001; Roshi et al., 2002). These surveys studied large portions of the Galaxy using coarse angular resolution observations ($\gtrsim 1^\circ$). This enabled the study of large regions, establishing that low-frequency CRRLs are ubiquitous, but it also limited the interpretation of the results (e.g., Kantharia & Anantharamaiah, 2001). One of the main issues faced in the interpretation was posed by the unknown size of the emitting regions, and the unknown origin of the regions to which the CRRLs were associated with. In the large beams used for these surveys, it was easy to find HII regions, supernova remnants and diffuse regions under the beam. These types of sources have very different continuum spectra, and the gas associated with them can be very different as well. Besides, it was also possible to establish an association between low-frequency CRRLs and HI self absorption (HISA, Roshi & Kantharia, 2011). This association confirmed that low-frequency CRRLs trace cold gas.

With modern radio telescopes, it is now possible to observe low-frequency CRRLs at a much better angular resolution. For example, the Murchison Widefield Array (MWA, Tingay et al., 2013) is able to reach an angular resolution of $2'.1$ at 150 MHz and a spectral resolution of 17 km s^{-1} . Additionally, observations of low-frequency CRRLs have benefited from upgrades in receiver technology, particularly the introduction of wideband receivers. Given that the separation between adjacent energy states decreases at large n , the frequency separation between CRRLs decreases at lower frequencies. This means that many CRRLs, corresponding to different values of n , can be observed simultaneously. Since the frequencies at which these lines appear are known, and when they trace the same gas, the lines can be stacked together to increase the signal-to-noise ratio of the observations (e.g., Stepkin et al., 2007; Oonk et al., 2014). These upgrades have motivated a re-flourishing of low-frequency CRRL studies, the main topic of this thesis.

1.2.1. OBSERVATIONS OF CARBON RADIO RECOMBINATION LINES POWERED BY THE LOW FREQUENCY ARRAY

The Low Frequency Array (LOFAR van Haarlem et al., 2013) is an interferometer operating at frequencies between 10 MHz and 250 MHz. This frequency range is covered by two different types of dipoles: low band antennas (LBA, 10–90 MHz) and high band antennas (HBA, 120–250 MHz). The HBA dipoles are combined in a 4×4 tile with



Figure 1.6.: The innermost stations of LOFAR. The stations located in the central circular region, a *terp*, are known as the *superterp* stations. The LBA and HBA dipoles can be identified by their arrangement in the field. The LBA dipoles are distributed in a non-uniform way, while the HBA dipoles are arranged into compact groups.

an analog beamformer. The dipoles and tiles, with no moving parts, are grouped into stations, each one forming an independent phased array. Stations are further combined to form an array, and are distributed all over Europe, resulting in baselines of up to 1900 km. For the core stations of LOFAR (located in the Netherlands), the LBA stations consist of 96 dipoles, while the HBA stations have 48 tiles split into two fields. Of the 96 dipoles in a core LBA station 48 can be actively beamformed (Broekema et al., 2018). There are 24 stations in the core of LOFAR. The core stations are connected via fiber to a central clock, thus their signals can be added coherently to form a telescope with a maximum baseline of 3.5 km. The stations in the innermost 350 m are known as the *superterp*. An aerial view of the innermost stations of LOFAR is presented in Figure 1.6.

The characteristics of LOFAR make it a great instrument for the study of CRRLs at low frequencies. In particular, it has a dense core with baselines of up to 3.5 km and a large fractional bandwidth ($\Delta\nu/\nu \sim 0.5$). Its dense core gives it a good sensitivity to large scale structures (the largest angular scales recoverable by the array are 1.6° at 240 MHz and 2° at 90 MHz), while reaching an angular resolution of $10'$ at 30 MHz. And, its large fractional bandwidth enables observations of hundreds of CRRL transitions simultaneously. These capabilities have been exploited to produce the first detections of low-frequency CRRLs on sub-arcmin scales (Asgekar et al., 2013), in extragalactic sources (Morabito et al., 2014; Emig et al., 2018) and using extragalactic

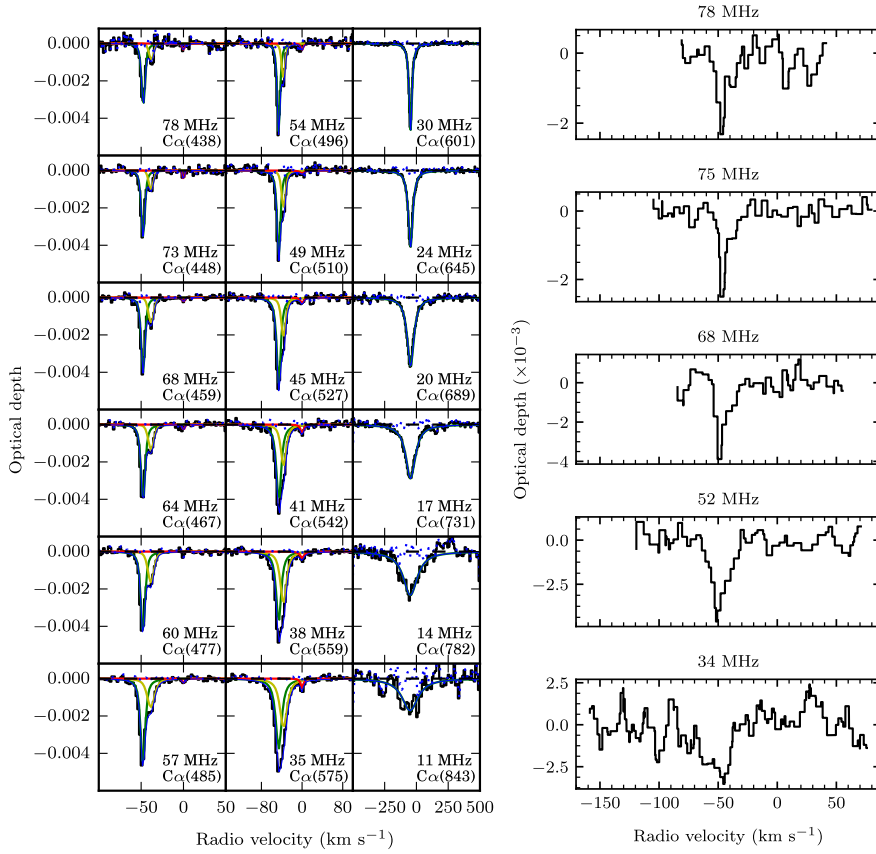


Figure 1.7.: Comparison between low-frequency CRRLs obtained with LOFAR (*left*) and previous telescopes (*right*). Both sets of CRRLs were observed against Cas A. The LOFAR observations were presented in Oonk et al. (2017) and in Chapter II of this thesis. The principal quantum number shown is the effective value for the stack. Previous observations were presented by Payne et al. (1989).

sources as background for Galactic studies (Oonk et al., 2014).

Figure 1.7 shows how LOFAR observations of CRRLs compare with previous observations. In this case the LOFAR observations were performed during three different periods to cover the full bandwidth of the LBA antennas with a spectral resolution of 3.5 km s $^{-1}$ at 33 MHz (Oonk et al., 2017). The increased spectral resolution of these observations with respect to previous ones (e.g., Payne et al., 1989) enables the study of different velocity components along the line of sight. The high signal-to-noise ratio of the CRRLs observed with LOFAR (Figure 1.7) was achieved by stacking multiple transitions (20 per stack on average). This highlights the importance of having a large fractional bandwidth for radio recombination line studies. During the stacking process,

an iterative procedure was used in order to remove the instrumental bandpass response of the telescope (e.g., Stepkin et al., 2007; Salas et al., 2017).

Observations of CRRLs in our Galaxy using LOFAR have focused on a couple of regions so far: Cassiopeia A (Asgekar et al., 2013; Oonk et al., 2017; Salas et al., 2017, 2018), Orion A (Chapter IV, Salas et al. submitted) and the line of sight towards Cygnus A (Oonk et al., 2014). In order to fully exploit the capabilities of LOFAR and the potential of low-frequency CRRLs as tools to study the ISM, observations of larger portions of the Galaxy are required (e.g., Oonk et al., 2015). LOFAR has a field of view (FoV) of 2.4° at 240 MHz (for the core stations) and 90 MHz (using the outer dipole layout in the LBA stations). If we wanted to cover the Galactic plane observable from the northern hemisphere (roughly 180° along the plane) it would require 75 pointings separated by one FoV. For an integration time per pointing of eight hours, sufficient to detect the CNM down to a column density of $3 \times 10^{20} \text{ cm}^{-2}$, it would take 1200 hours to cover the northern Galactic plane using the LBA (between 30 MHz and 90 MHz) and the HBA (between 120 MHz and 170 MHz).

A first attempt at obtaining large scale maps of low-frequency radio recombination lines in our Galaxy targeted the star forming region Cygnus X (Oonk et al. in prep.). In order to avoid the artifacts introduced during the inversion of the observed visibilities, caused by the lack of a zero spacing when observing the Galactic plane, and to limit the data volume, these maps were produced using the tied-array mode of LOFAR. In the tied-array mode the signals from the stations are added together coherently (this is the same as a phased array) instead of cross-correlating the signals (imaging mode). This reduces the amount of data considerably, as only one real valued output is produced for the whole array, instead of one complex-valued quantity for each baseline ($N(N-1)/2$ values for an array with N stations). Additionally, since there is no need to invert visibilities (the products of the cross-correlation between station voltages), the resulting maps do not have a mean flux of zero (as opposed to the imaging case when a baseline of zero length is not measured). This avoids the appearance of large negative bowls around the bright radio continuum of the Galactic plane. Despite these benefits, the use of tied-array observations removes the ability to calibrate the observations, as well as fixing the observed position on the sky (imaging observations are sensitive to the whole FoV of the stations, and more, while in tied-array mode the effective FoV is limited to the beam of the tied-array, $10'$ at 30 MHz for the core stations of LOFAR). Basically, tied-array observations trade flexibility for data volume.

As in synthesis imaging, tied-array observations also have the array beam imprinted on the resulting maps. That is, a map produced from tied-array observations is a dirty map (the convolution of the tied-array beam, dirty beam, with the sky distribution, e.g., Thompson et al., 2017), unless cleaned. Since in tied-array mode the time delays between stations cannot be calibrated, the dirty beam will not only be the Fourier transform of the station positions, but it will also contain any errors on the time delays present during the observations (e.g., the time delays introduced by the ionosphere, Crane, 1977). Thus, if we want to clean tied-array maps, we need a model of the dirty beam which also contains information about the time delays. For this reason we characterized the tied-array beam of the stations using radio holography (e.g., Scott & Ryle, 1977).

1.3. THIS THESIS

To understand the ISM we need to study different gas phases across different scales and that we piece it all together. What we know about these different phases is expanded by the use of different tracers, as they often provide complementary information. Here we focus on diffuse atomic clouds and the surface of molecular clouds as these are main reservoirs of interstellar gas, they feed molecular clouds, the star formation engines of the Galaxy, and they couple radiative and mechanical energy to the ISM. We do this by observing low-frequency CRRLs in our Galaxy using LOFAR. Previous studies of low-frequency CRRLs in our Galaxy have been hampered in their interpretation due to the lack of spatial information (e.g., Kantharia & Anantharamaiah, 2001). The unprecedented frequency coverage, and spatial and spectral resolution afforded by LOFAR, studies of CRRLs are now possible from degree to arcsecond scales. This opens up the low-frequency sky to systematic studies of the cold atomic and diffuse molecular gas. The spatial and velocity resolutions achieved by LOFAR are comparable to those of surveys of the ISM through other tracers, such as 21 cm HI and rotational transitions of CO in the millimeter (e.g., HI4PI Collaboration et al., 2016; Dame et al., 2001), a fundamental requirement for understanding the structure of the ISM.

In **Chapter II** we explore what can be learned from the lowest frequencies observable from Earth. Using LOFAR we observe CRRLs in the frequency range 10–30 MHz towards Cas A. These observations show that the integrated optical depth of the lines is roughly constant, indicating that the population of ionized carbon atoms is close to that in LTE. This result is qualitatively different from previous observations and theory, in which the integrated optical depth seemed to keep increasing towards low frequencies (Konvalenko, 1984; Ponomarev & Sorochenko, 1992). From the observed line widths, and their relative strengths, we were able to constrain the gas physical properties. Moreover, by adding the information provided by the far-infrared line of ionized carbon at 158 μm , we could determine the gas physical properties with an accuracy similar to that obtained by using observations of CRRLs over a larger frequency range (Oonk et al., 2017). In summary, the lowest frequency CRRLs provide a good barometer, while the ratio between radio and FIR carbon lines is a good thermometer.

In **Chapter III** we perform an analysis of the spatial distribution of low-frequency CRRLs towards Cas A. Using observations with a spatial resolution of $\approx 1'$ we explore the relation between CRRLs, the 21 cm line of HI and CO. We find that these tracers are arranged in a layered structure, reminiscent of the structure found in a PDR. Based on the spatial location of the CRRLs, sandwiched between the diffuse atomic gas and the dense molecular gas, we are able to establish that low-frequency CRRLs trace the interface between atomic and molecular gas. Using a set of four CRRLs (C268 α , C357 α , C494 α and C539 α) we determine the gas temperature and density over the face of Cas A. We find that the gas properties are comparable to those found from spatially unresolved studies (Oonk et al., 2017). Moreover, using the derived physical conditions, as well as other properties of the region derived independently, as input to a PDR model we predict the strength of the rotational lines of CO available and of the 158 μm -[CII] line. The PDR model predictions match the observed line strengths remarkably well, highlighting that low-frequency CRRLs provide accurate physical conditions.

In **Chapter IV** we use new and archival observations of CRRLs over a wide frequency range (230 GHz to 150 MHz) to study the star forming region Orion A. This is the largest frequency coverage of CRRLs of a single region, including the first two detections of CRRLs in absorption towards this source. We complement the CRRL data with SOFIA observations of the $158\ \mu\text{m}$ -[CII] line. The use of CRRLs over a wide frequency range enables us to study two PDRs found in this region: the foreground Veil and the dense PDR between the HII region and the background molecular cloud. In the Veil we are able to determine the gas temperature and electron density, which we use to measure the ionization parameter and the photoelectric heating efficiency. In the dense PDR, we are able to identify a layered PDR structure at the surface of the molecular cloud to the South of the Trapezium. There we find that the radio lines trace the colder portion of the ionized carbon layer, the $\text{C}^+/\text{C}/\text{CO}$ interface. We explore the ratios of three CRRLs, $\text{C}30\alpha$, $\text{C}65\alpha$ and $\text{C}91\alpha$, and find that they alone can be used to constrain the gas temperature and electron density. Our work also highlights the potential of CRRLs as probes of molecular gas formation. By modeling the emission of the $158\ \mu\text{m}$ -[CII] line and CRRLs as arising from a PDR we derive a thermal pressure $\approx 8 \times 10^7\ \text{K cm}^{-3}$ and a radiation field $G_0 \approx 10^4$ close to the Trapezium, and lower values as we move away from it. This work provides additional observational support for the use of CRRLs and the $158\ \mu\text{m}$ -[CII] line as complementary tools to study dense and diffuse PDRs.

Chapter V presents the characterization of the core stations of LOFAR using radio holography. Radio holography is a technique by which the complex-valued beam of a telescope can be measured. Along radio holography, we apply a new calibration method which enables us to obtain a higher signal-to-noise ratio in the observed complex-valued beam maps. From the complex-valued beam of the telescope we infer the time delays of its stations. For short (60 s and 600 s) radio holographic observations of 3C196, 3C147 and 3C48 we are able to derive time delays with errors smaller than one ns, under good ionospheric conditions. We use the derived time delays to update the instrumental time delays in the digital beamformer. For the HBA this leads an improvement of 28% in its sensitivity at 115 MHz, and up to 75% at 165 MHz. For observations with the LBA the sensitivity improves by a factor of six at the center of the frequency band, close to 55 MHz, and larger at higher frequencies. The results from this chapter show that radio holography is a powerful method to calibrate the instrumental time delays applied by the digital beamformer. In the future it should be possible to perform this calibration in real time, providing, for the first time, tied-array observations in which the effects of the ionosphere are accounted for.

1.4. MOVING FORWARD

As this thesis shows, observations of low-frequency CRRLs offer a unique perspective to explore the ISM. They trace cold gas, atomic and diffuse molecular, are excellent probes of the gas physical conditions (e.g., temperature and electron density) and kinematics, and they can be mapped over large areas. In the future it should be possible to construct a temperature and density map of the gas in our Galaxy using CRRLs. For this, the next step is a survey of low-frequency CRRLs on the northern hemisphere

using LOFAR.

A survey of low-frequency CRRLs with LOFAR would be a big leap in our understanding of the ISM. This survey would provide cubes of $Cn\alpha$ CRRLs with principal quantum numbers between 297 and 869. These observations would map the gas traced by CRRLs over the disk of the Milky Way with a spatial resolution of $10'$ and a spectral resolution of $\approx 1 \text{ km s}^{-1}$, enabling us to determine the temperature and density of the gas and how stellar feedback couples to the ISM. These would be the first spatially and velocity resolved maps of cold atomic and *CO-dark* molecular gas of the galactic disk.

Moreover, CRRL observations would also enable us to measure the strength of the magnetic field. Using Zeeman splitting measurements of CRRLs it would be possible to probe the magnetic field over large regions of the galactic disk. Low-frequency observations of Zeeman splitting are particularly interesting, since the frequency width of the lines, $\Delta\nu$, narrows towards lower frequencies while the Zeeman splitting, $\Delta\nu_Z$, remains constant. In the regime where $\Delta\nu_Z > \Delta\nu$ it is possible to directly measure the strength of the magnetic field (e.g., Heiles et al., 1993).

Another advantage of low-frequency CRRL observations with LOFAR is that with the same observational setup it is also possible to observe HRRLs. With a mass difference of ≈ 12 , HRRLs are shifted from CRRLs by a velocity of 149.4 km s^{-1} . The study of low-frequency HRRLs has suffered from the same limitations as that of CRRLs. With LOFAR it is now possible to observe HRRLs with a spatial resolution of $10'$. These observations would shed light on the presence of dense ionized gas in our Galaxy (e.g., Goldsmith et al., 2015).

In the future, the Square Kilometer Array (SKA) will be the world largest radio interferometer, operating between 50 MHz and 14 GHz. It will cover this frequency range with two different arrays, the SKA-low (between 50 MHz and 350 MHz) and the SKA-mid (between 350 MHz and 14 GHz). SKA-low promises to deliver a sensitivity eight times better than that of LOFAR. Both SKA-low and SKA-mid will be commissioned in two phases, the first phase will deliver a fraction of the total collecting area. For SKA-low, during the first phase 476 of the 512 stations will be constructed, with a maximum baseline of 40 km. As of 2017, the brightness sensitivity of SKA-low during phase 1 (SKA-low1) is expected to be roughly 23 mK at 160 MHz, for an integration time of 8 hours, an angular resolution of $4''.2$, and a channel width of 4.2 kHz. And 260 mK at 50 MHz, with an angular resolution of $13''.4$. This implies that on arcminute scales, it will be possible to detect CRRLs ($\tau \sim 1 \times 10^{-3}$) all over the Galactic plane at longitudes $|b| < 5^\circ$, using the Galactic synchrotron emission as background. This is not considering that we can stack several CRRLs to detect weaker lines (there are 243 $Cn\alpha$ lines between 50 MHz and 350 MHz).

At lower frequencies, between 85 MHz and 10 MHz, the new extension in Nançay upgrading LOFAR (NenuFAR) will have a collecting area equivalent to that of 38 LOFAR stations, and it will be able to reach an angular resolution of $23'$ at 15 MHz. This increase in collecting area will enable the detection of low-frequency RRLs from regions where the gas column densities are lower. Moreover, NenuFAR will be sensitive to larger angular scales than LOFAR. This makes NenuFAR a great instrument to study neutral and partially ionized gas outside the disk of the Milky Way, and its properties on large scales.

On the higher frequency end (> 1 GHz) the next generation Very Large Array (ngVLA, 1–116 GHz) and SKA-mid (0.35–14 GHz) will improve over the sensitivity of existing telescopes. Higher frequency RRLs trace denser gas than their low-frequency counterparts. Thus, the combined use of RRLs over the whole radio regime will enable us to study the properties of HII regions, and how the radiation emitted by the massive stars that power them interact with the dense molecular clouds that surround them, how it escapes these regions, and how then it couples to the diffuse ISM. Providing the observational information required to understand stellar feedback.

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