DISCOVERY OF CARBON RADIO RECOMBINATION LINES IN M82

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ABSTRACT

Carbon radio recombination lines (RRLs) at low frequencies (≤ 500 MHz) trace the cold, diffuse phase of the interstellar medium, which is otherwise difficult to observe. We present the detection of carbon RRLs in absorption in M82 with LOFAR in the frequency range of 48 – 64 MHz. This is the first extragalactic detection of RRLs from a species other than hydrogen, and below 1 GHz. Since the carbon RRLs are not detected individually, we cross-correlated the observed spectrum with a template spectrum of carbon RRLs to determine a radial velocity of $219 \pm 9 \, \text{km s}^{-1}$. Using this radial velocity, we stack 22 carbon-alpha transitions from quantum levels $n = 468 - 508$ to achieve an 8.5σ detection. The absorption line profile exhibits a narrow feature with peak optical depth of $3 \times 10^{-3}$. Closer inspection suggests that the narrow feature is superimposed on a broad, shallow component. The total line profile appears to be correlated with the 21 cm H I absorption in the direction of supernova remnants in the nucleus. The narrow width and centroid velocity of the feature suggests that it is associated with the nuclear starburst region. It is therefore likely that the carbon RRLs are associated with cold atomic gas in the direction of the nucleus of M82.

Subject headings: galaxies: ISM — galaxies: individual(M 82) — ISM: general — radio lines: ISM — radio lines: galaxies

1. INTRODUCTION

The nearby (3.52 ± 0.02 Mpc; Jacobs et al. 2009) nuclear starburst galaxy M82 has been observed to host a wide range of phases of the interstellar medium (ISM). Observations of disrupted H I within the disk show that the neutral gas is more concentrated in the nuclear region (Yun et al. 1993). There is a rotating ring of molecular gas in the nucleus, as seen from observations of HCN, HCO+, CO(2–1) (Kenley et al. 2014), OH (e.g., Argo et al. 2010), and CO images (e.g., Westmoquette et al. 2013). Numerous H II regions are seen (e.g., McDonald et al. 2002; Gandhi et al. 2011) in this area. The nuclear region is also studied with compact, bright supernova remnants (SNRs; e.g., Muxlow et al. 1994; Fenech et al. 2010). The spectral turnovers of the SNRs (Varenius et al., in prep., Wills et al. 1997) as well as the overall spectrum (Varenius et al., in prep., Adebahr et al. 2013) indicate the presence of free-free absorption by ionized gas. The complex interplay of all these components of the ISM is not fully understood.

Carbon radio recombination lines can help characterize the cold, diffuse phase of the interstellar medium (ISM). When free electrons recombine with atoms at quantum numbers $n \geq 50$, the decreased energy spacing of subsequent levels produces radio recombination lines (RRLs). By comparing observations of RRLs with detailed physical models, we can determine information on the physical properties, such as electron temperature and density, of the gas in which the RRLs originate (e.g., Salgado et al., in preparation: Walmsley & Watson 1982).
At frequencies $\lesssim 500$ MHz, RRLs are spaced closely enough that wide-bandwidth instruments like the Low Frequency Array (LOFAR; van Haarlem et al. 2013) are able to track the dependence of line properties on quantum number within a single observation. These properties make RRLs a powerful tool for determining the temperature and density of their host phases of the ISM.

Diffuse RRLs fall into two categories: discrete and diffuse. Discrete RRLs trace warm ($T_e \sim 10^4$ K), high-density ($n_e > 100$ cm$^{-3}$) gas associated with H II regions (Palmer 1967). They are predominantly seen at frequencies above $\sim 1$ GHz and originate from hydrogen, helium, and carbon (e.g., Pompi et al. 2007; Konовалenko & Stepkin 2002; Roelfsema & Goss 1991). These types of RRLs have been detected in a handful of nearby bright star-forming galaxies (e.g., Shaver et al. 1977; Anantharamaiah et al. 1993; Rodriguez-Rico et al. 2003; Rov et al. 2008).

In this paper, we present the first detection of extragalactic CRRLs. Diffuse carbon RRLs (CRRLs) trace the cold neutral medium (CNM), which is cold ($T_e \sim 100$ K), and diffuse ($n_e \lesssim 0.1$ cm$^{-3}$). Diffuse RRLs are observed at frequencies below 1 GHz. Typically the CNM has ionization levels that are too low to produce hydrogen and helium lines, and only CRRLs are observed. The ionization energy for atomic carbon is only 11.3 eV, lower than that of hydrogen, 13.6 eV. Some photons that can escape H II regions can therefore ionize carbon, and thus C II is expected to be the dominant state of carbon in the ISM. While discrete RRLs are used extensively to study star forming regions (e.g., Anderson et al. 2011; Roelfsema et al. 1992), not much is yet known about the CNM associated with diffuse RRLs, even in our Galaxy. Low frequency observations have shown that the CRRL emitting and absorbing gas is prevalent on scales of degrees along the Galactic plane (Erickson et al. 1993; Kauhanja & Anantharamaiah 2001). Pinhole studies in the direction of H II regions (e.g., Golynkin & Konovalenko 1991), supernova remnants (Cassiopeia A; e.g., Asgekar et al. 2013; Payne et al. 1983; Konovalenko & Sodin 1983) or bright background extragalactic sources (Don et al. 2014) have detected CRRLs on smaller scales. The new Low Frequency Array (LOFAR; van Haarlem et al. 2013) has observed CRRLs in our Galaxy. Over the next several years, LOFAR will perform a CRRL survey of the Galactic plane, on scales from degrees down to several arcseconds, producing maps that will provide a comprehensive picture of the Galactic CNM by quantifying the average gas temperatures and densities, as well as abundances.

In this paper, we present the first detection of extragalactic CRRLs, observed in M82 at frequencies near 60 MHz with LOFAR. This is the first extragalactic detection of diffuse RRLs, and the first extragalactic detection of RRLs from a species other than hydrogen. This detection opens up the possibility of tracing the evolution of the CNM through all stages of galaxy formation.

Section 2 outlines observations, data reduction, and imaging. Section 3 describes the extraction and processing of the spectra, cross-correlation of the overall spectrum to determine a velocity, and subband stacking to achieve a detection. Results are presented in § 4. Discussion and conclusions follow in § 5 and § 6, respectively.
nuclear region there is a spread of $\alpha$-transition detections of lines, which were not seen. In order to by visual inspection. Five subbands were removed from

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The template line peaks were normalised to a value of Gaussian line profiles at known CRRL frequencies) with cross-correlating a spectral template of CRRLs (using

constrained the velocity for the CRRL absorbing gas by
cross-correlation. We also tried blanking different ranges of $\tau$ = 0

$\pm$ 20 km s$^{-1}$ relative to the LSR (optical velocity), and we iterated with a template that only contains sub-bands for which rest-frame CRRLs would appear at this redshift. This reduces the amount of noise which is cross-correlated, very slightly improving the definition of the peak of the cross-correlation.

Figure 2 shows a clear peak in the cross-correlation at $v = 219$ km s$^{-1}$ ($z = 0.00073 \pm 0.00003$), consistent with the systemic velocity of M82, and we used this to stack our lines. We did not find evidence for CRRL features at either of the velocities of the two secondary peaks, $v = 168$ km s$^{-1}$ and $v = 255$ km s$^{-1}$.

3.3. Reconstructing the Line Profile

Requiring that rest-frame CRRL frequencies be at least six channels away from the edge of a subband to avoid problems with noisy edge channels, we find that twenty-three subbands have $\alpha$-transitions. We clipped the first and last three edge channels and converted to optical velocity using the rest frequency of the CRRL within the subband. After blanking $\pm 50$ km s$^{-1}$ around the expected velocity of the CRRL, we fitted the continuum in each subband individually with a low (first or second) order polynomial. We also tried blanking different ranges around the line, from $\pm 50$ to $\pm 250$ km s$^{-1}$, without seeing substantial differences in the final spectrum. For one subband, any blanking left continuum only on one side of the line, so we did not include this subband in the final stack. Each subband was continuum subtracted. The final spectrum was constructed from the individual points of 22 subbands, see Fig. 5.

The final stacked spectrum has a velocity sampling of $\sim 1.5$ km s$^{-1}$ within approximately $\pm 150$ km s$^{-1}$ of the measured velocity (219 km s$^{-1}$, LSR). The measurement error of each point is equal to the standard deviation of the continuum in the subband from which the point originates. The weighted standard deviation of the continuum in the final spectrum within approximately $\pm 150$ km s$^{-1}$ of the expected CRRL line centre is $\sigma_w = 0.005$, which is approximately $\sqrt{22}$ smaller than the average noise in a subband.

Galactic CRRLs show peak optical depths of $10^{-3} - 10^{-4}$ (e.g., Kantharia & Anantharamai 2001).
Radial velocities within the nuclear region range from $\sim 120 - 300$ km s$^{-1}$. The centroid of the CRRL feature is therefore consistent with an absorption feature associated with the centre of the nuclear region. The cross-correlation is already strong evidence that the feature does not arise merely from a chance alignment of noise, since the feature only arises from a location where we know there to be gas, which is necessary but not sufficient for CRRLs. To rule out other possibilities, we conducted a series of tests. We used a ‘jack-knife’ procedure where we re-stacked the subbands, each time leaving out an individual subband. None of the stacks produced a significant change to the absorption feature, confirming that the stacked spectrum is not dominated by one subband. Additionally, we stacked the subbands after introducing random velocity shifts to each subband before stacking, and were unable to produce any credible features. Spectra extracted from the background sky also do not show an absorption feature when stacked. From these tests, we conclude that our feature is real and associated with the M82 starburst galaxy.

We tried to detect CRRL $\beta$-transitions ($\Delta n = 2$), without success. This is not unexpected, as the CRRL $\beta$-transitions are expected to have integrated optical depths that are only $15 - 30\%$ that of the $\alpha$-transitions (e.g., Stepkin et al. 2007; Payne et al. 1989). We did not find evidence for local CRRLs at $z = 0$. A search for hydrogen RRLs, both locally and at the redshift of M82, was also unproductive. This is unsurprising as these are believed to be very weak at these frequencies (e.g., Salgado et al. in preparation; Shaver 1975).

4. RESULTS

We stacked the spectra to search for CRRLs in M82 using our measured velocity, $v = 219$ km s$^{-1}$, and detect carbon $\alpha$-transition RRLs with a combined signal-to-noise ratio of $8.5\sigma$ in the filtered spectrum. The central absorption feature can be fitted by a four parameter Gaussian profile with a depth of $2.8_{-0.16}^{+0.12} \times 10^{-5}$, a FWHM of $30.6_{-1.0}^{+2.3}$ km s$^{-1}$, a centre of $211.3_{-0.7}^{+0.5}$ km s$^{-1}$, and an additive offset of $-2.0_{-0.072}^{+0.12} \times 10^{-4}$ (see Fig. 4).

5. DISCUSSION

Other absorption features have been observed in M82 with similarly narrow widths. Weiß et al. (2010) observed p-H$_2$O absorption (in the far infrared) with a FWHM of $60$ km s$^{-1}$, although this is offset from the CRRL absorption by $\sim 50$ km s$^{-1}$. Additionally, a narrow component results if we limit the reconstruction of the H I absorption profile in the direction of SNRs in the nucleus of M82 to only the handful of bright SNRs which are relatively unaffected by free-free absorption at low frequencies. We constructed the H I absorption line profiles from measurements in Wills et al. (1998). We interpolated the spectra (mJy/bm) in the direction of each of the 26 SNRs which show H I absorption onto a velocity grid with $1$ km s$^{-1}$ resolution using a cubic spline function. Addition of the individual spectra produces a combined spectrum with information in the direction of SNRs. For the low frequency spectrum, we cross matched the SNRs in Table 1 of Wills et al. (1998) with those still seen by LOFAR at 154MHz.

Konovalenko & Sodin (1981). If the CRRLs in M82 have similar peak optical depths then these would be within the noise of this spectrum. We therefore used a low-pass Savitzky-Golay filter (SGF, Savitzky & Golay 1964) which is a special case of a least-squares (LS) smoothing function that convolves the data with a filter whose shape is dependent on the polynomial order used for fitting. Other filtering methods (see Fig. 4) produced similar line profiles. After testing SGF filter widths from 15 to 60 data points for both first and second order polynomials, we selected an SGF with a width of 31 data points, which provided the flattest continuum. Within approximately $\pm 200$ km s$^{-1}$ of the feature in the final, smoothed spectrum, the standard deviation of the continuum is $\sigma_T = 3.3 \times 10^{-4}$, in good agreement with our expectations from the raw spectrum noise and filter window size. We assessed this filtering method with modelled spectra and found that the integrated line profile is preserved within the errors even after introducing Gaussian noise.
Figure 5. Comparison with other tracers. The CRRL profile is shown by the dashed lines and are inverted for easier comparison, and H I absorption in the direction of SNRs in M82 (Wills et al. 1998) plotted with solid colored lines. The gold solid line is the overall CRRL profile follows the low-frequency H I profile (Fig. 5). This shows that the CRRL absorbing gas, indicating that possibly we are observing a widespread CRRL component associated with cold diffuse H I throughout M82.

Integrating the line profile gives $\int f_{CI\nu} d\nu = 21.3 \text{ s}^{-1}$. To constrain physical parameters of the gas, i.e. temperature and density, a single measurement is not enough. Additional measurements at higher frequencies (100-400 MHz) are necessary.

6. CONCLUSIONS

We have presented the first detection of extragalactic carbon radio recombination lines, in M82, using early science (Cycle 0) observations with LOFAR. While we already know that cold, neutral gas exists in M82 from H I measurements, this is the first independent measurement of the atomic CNM. The narrow CRRL line is at a velocity corresponding to the centre of M82 and the profile corresponds to the absorption feature seen in the H I spectrum. Higher resolution, higher sensitivity studies of M82 at the same frequencies would help to confirm that this feature is indeed associated with the nuclear region, and potentially shed more light on the origin of the optical depth. To constrain the gas properties we need studies at higher frequencies, and we are working towards detecting CRRLs in the range of 120 – 240 MHz with LOFAR’s high band antenna array.

This discovery paves the way for future extragalactic CRRL studies to trace the CNM throughout the formation and evolution of galaxies, and is the basis of a pilot survey for CRRLs in other extragalactic sources.

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