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FIRST DETECTIONS OF CARBON RADIO RECOMBINATION LINES WITH THE NENUFAR TELESCOPE

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Abstract. Carbon Radio Recombination Lines (CRRLs) at decameter wavelengths serve as a diagnostic tool to explore the diffuse phase of the interstellar medium (ISM). Observing CRRLs help to characterize the physical properties, particularly the electron density and temperature of line-of-sight clouds. This paper presents the first detections of CRRLs using the recently commissioned NenuFAR telescope, focusing on bright low-frequency sources: Cassiopeia A (Cas A), Cygnus A (Cyg A), and Taurus A (Tau A).

Keywords: Radio lines: ISM, Line: formation, Line: profiles, ISM: clouds, ISM: structure, sources: Cassiopeia A, Cygnus A, Taurus A.

1 Introduction

We present the first detections of Carbon Radio Recombination Lines (CRRLs) by the newly commissioned NenuFAR telescope (New Extension in Nançay Upgrading LOFAR) between 10 to 85 MHz, towards the bright radio sources Cassiopeia A, Cygnus A, and Taurus A (de Gasperin et al. 2020). At decameter wavelengths, CRRLs provide valuable insights into the physical conditions of the diffuse interstellar medium (ISM). Our observations yield improved signal-to-noise ratios (typically of a factor 10) and spectral resolution ($\delta v \sim 0.5$ km/s at 50 MHz) compared with previous studies using LOFAR (Salas et al. 2017; Oonk et al. 2017). We detected 398 Cα lines towards Cas A, for levels with quantum numbers $n = 426$ up to $n = 826$. We also detected hundreds of lines towards Cyg A and, for the first time, Tau A. The derived electron densities and temperatures differ from prior LOFAR measurements, albeit consistently with NenuFAR's larger beam size. These findings demonstrate NenuFAR's capabilities to probe the ionization and thermal states of the diffuse ISM.

2 Theory

CRRLs arise when ionized carbon recombines with electrons to produce highly excited neutral carbon, which radiates as electrons progressively cascade from high energy levels. In the diffuse ISM, we observe the resulting lines in absorption against strong background sources. Their profiles are shaped by Doppler and Lorentzian broadening, whose properties are set by thermal motions, turbulence, collisions and radiation through dependencies on electron temperature (T_{e}) and density (n_{e}), turbulent velocity (v_{t}), and temperature of the local radiation field (T_0). Their intensity is additionnaly driven by the size of the cloud (L), n_{e} and T_{e}. Fitting these profiles hence allows to measure these 5 physical parameters (Gordon & Sorochenko 2002; Salgado et al. 2017).

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3 Methods and results

Observations were conducted with the NenuFAR telescope between 10 and 85 MHz. The beamforming mode was used with integration times of several tens of hours on each target. A custom reduction pipeline was built to handle radio frequency interference (RFI) contamination and to flatten spectral baselines. The data processing then mostly consisted in time averaging and line stacking to enhance the signal-to-noise ratio. At this stage the stacked lines were fitted with Voigt profiles in principle allowing for the measure of n_e, T_e, v_t, L, T_0. For each cloud, we used two successive parameter grids based on χ^2 distance minimization to find the best fits.

Cassiopeia A. The CRRLs were detected in three clouds at velocities: –47 km/s, –38 km/s, and 0 km/s. Component blending compelled us to refine our strategy to evaluate uncertainties. In the –47 and –38 km/s clouds, the derived electron densities range from 0.029 to 0.035 cm^{-3}, and electron temperatures between 33 and 43 K. While T_e is slightly lower than the one derived by (Salas et al. 2017) with LOFAR, our values of n_e are comprised within LOFAR uncertainty ranges. The difference in T_e is likely due to the larger beamsize of NenuFAR. These values are characteristic of Cold Neutral Medium (CNM). This effect suggested that NenuFAR was sensitive to absorption against the Galactic plane background. The 0 km/s cloud presents $T_\mathrm{e} = 54 - 100$ K and $n_\mathrm{e} = 0.010 - 0.011$ cm^{-3}.

Cygnus A. As the source is weaker compared to Cas A, stacking of groups of 30 to 50 lines allowed us to detect CRRLs at a velocity of +3.5 km/s, consistent with observations of foreground clouds in the Orion Spur. The electron density and temperature derived from these detections are comparable to those obtained from LOFAR, with $n_\mathrm{e} \sim 0.015$ cm^{-3} and $T_\mathrm{e} \sim 60$ K. The beam size effect was mitigated by the fact that Cyg A is farther from the Galactic plane.

Taurus A. For the first time ever, RRLs are detected towards this souce, in one line-of-sight cloud at a velocity of +14 km/s, associated with a molecular cloud. We were able to constrain n_e between 0.015 and 0.023 cm^{-3} and T_e between 39 and 76 K. Towards this source, variation of the line center with frequency might be indicative of shocks in the line-of-sight.

4 Conclusion

The sensitivity of NenuFAR opens a new era in the study of the ISM at low frequency. In this first study, we have focused on the interpretation of Cα radio recombination lines only. In the future, we will focus on other series of transitions (β and others), and on other species (H, He...). We have already started to probe various environments: more evolved supernova remnants, and the diffuse medium of our Galaxy, seen in absorption against the Galactic plane. The confirmed detections we obtained and the possibility to use NenuFAR as a distant station of LOFAR, recently made available to the scientific community, contribute to make NenuFAR a unique pathfinder towards the use of the SKA to study the ISM.

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