HIGH RYDBERG STATE RECOMBINATION LINES FROM INTERSTELLAR CARBON : AN OBSERVATIONAL STUDY

A Thesis

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By

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Declaration

I hereby declare that the work presented in this thesis is entirely original, and has been carried out by me at the Raman Research Institute under the auspices of the Joint Astronomy Programme of the Department of Physics, Indian Institute of Science. I further declare that this has not formed the basis for the award of any degree, diploma, membership, associateship or similar title of any University or Institution.

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Synopsis

This thesis describes the results of an observational study of the **partially** ionized gas in the Galaxy using low-frequency radio recombination lines of carbon arising due to electronic transitions at large quantum numbers ($150 < n < 600$).

Radio recombination lines are useful for studying the ionized component of the interstellar medium. **Different** types of ionized regions in the Galaxy give rise to detectable recombination lines of various atomic species such **as** hydrogen, helium and carbon. In general, recombination lines of hydrogen and helium ***are*** detected from hot ($T_e \sim 10^4$ K) fully ionized clouds known **as** H II regions. On the other hand, recombination lines of **carbon arise** in cooler (50 – 500 K) partially ionized regions. Although extensive studies of hot, ionized regions using recombination lines of hydrogen and helium have been **carried** out, there are only a few observations of recombination lines of carbon from partially ionized gas. Carbon lines at relatively high frequencies ($\nu > 1$ **GHz)** are detected **from** the partially ionized gas surrounding some strong H II regions and these have been reasonably **well** studied. In 1980, Konovalenko & **Sodin** discovered a new **type** of carbon recombination line at a very low frequency ($\sim$ 26 MHz) in the direction of the strong radio source, **Cas** A. **This** line was in absorption and corresponded to the transition between $n = 631$ & $n = 632$ in carbon. Subsequently **many** other transitions at higher ($n \sim 800$) and at lower quantum numbers ($n \sim 160$) have been observed in this **direction.** These low-frequency carbon recombination lines **exhibit** interesting **observable** properties. The line width increases sharply **towards** lower frequencies (*i.e.* higher quantum numbers) due to pressure and radiation broadening and the lines turnover into emission at frequencies above 150 MHz ($n < 350$) due to inversion of level population and consequent stimulated emission. Interpretation of these lines has led to the conclusion that the lines arise in one of the major constituents of the ISM *i.e.* either atomic clouds or molecular clouds or possibly both. In these largely neutral component of the ISM, carbon, due to its lower ionization potential (11.4 eV) can be ionized by the background ultraviolet radiation.

Since these low-frequency carbon recombination lines arise in a major component of the ISM, these lines **are** potentially widely detectable and could be a useful diagnostic of physical conditions in the ISM. Searches for these lines in other directions in the Galactic plane have met with some success. Near 25 MHz, carbon lines have been detected in absorption from the directions of **G75+00, NGC2024, S140, L1407** & **DR21.** Towards the Galactic centre, lines have been detected in absorption at 75 MHz and in emission near 328 MHz. Similarly towards M16, absorption lines at 69 & 80 MHz and emission line near 325 MHz have been detected. In a recent survey at 76 MHz using the Parkes radio telescope, recombination lines of carbon were detected in absorption from all the observed directions with longitude $\leq 20^\circ$. In all, there were more than 20 new detections which showed that ionized carbon is fairly widespread in the inner galaxy and that the recombination lines of carbon are detectable at low frequencies with existing instruments.

In this thesis, we undertook extensive observations of carbon recombination lines near 34.5 MHz using the low frequency 'T'-shaped dipole array located at Gauribidanur which is 80 km north of Bangalore. Since these were the first major spectral line observations using this radio telescope, a new spectrometer with associated hardware and software was developed for this purpose. Using this instrument, we searched for recombination lines of carbon at 34.5 MHz ($n \sim 575$) from about 35 positions, most of them in the Galactic plane and a few against specific sources from which low frequency lines had been previously detected. We detected carbon lines in absorption, from ten of these positions, eight of them in the first quadrant and one in the fourth quadrant of the Galaxy. The positive results include the first detection of a broad Voigt-shaped line profile from the direction of Cas A. The Voigt-shaped profile results from pressure and/or radiation broadening and in this thesis we derive constraints on the line-forming region from the observed line parameters.

To complement the absorption line detections made with the Gauribidanur telescope, we observed a subset of these directions at 328 MHz ($n \sim 270$) using the Ooty Radio Telescope and detected recombination lines of carbon, in emission, from all the positions with Galactic longitude $< 20^\circ$. An emission line at 328 MHz was also detected from the direction of Cas A. At low frequencies, Cas A is an extremely strong continuum source because of which the effective angular resolution is determined by the angular size of Cas A *i.e.* $\sim 5'$. However, towards other directions in the Galactic plane, the angular resolution is determined by the telescope beam. At low frequencies, angular resolutions are generally poor (beam size $\sim$ several degrees) and cloud sizes are likely to be smaller than the beam size and therefore beam-dilution effects are likely to be significant. Since this modifies the line strengths, the models that fit the observed data also change. Thus, the size of the line-forming clouds plays a significant role in the interpretation of the observed line strengths. In order to obtain some constraints on the sizes of the line-forming regions, the observations with the Ooty Radio Telescope were made with two different angular resolutions *i.e.* $2^\circ \times 6'$ and $2^\circ \times 2''$. Furthermore, we attempted to image one of the Galactic-plane positions in recombination lines of carbon with high angular resolution (~ 5') near 330 MHz using the Very Large Array (VLA) which is an aperture synthesis instrument located in the USA. The methods, the data analysis and results of all these observations are described in this thesis.

We have combined our observed recombination-line data towards various directions in the Galactic plane with previous results at other frequencies to model the carbon line-forming regions. Two types of models are considered. The first one is the cold gas ($T_e \leq 20$) model in which the carbon line regions are considered to be associated with molecular clouds which may not be in pressure equilibrium with the interstellar medium. In the second type, which we refer to as the warm gas ($50 < T_e < 300$ K) model, the observed carbon lines are considered to originate in the neutral H I component which is in rough pressure equilibrium with other atomic components of the interstellar medium. In both these models, the effect of a dielectronic-like recombination pro—— on the level populations of high quantum number states of carbon have been included. In this process, an energetic (~ 100 K) free electron recombines to a high quantum number level in carbon with simultaneous excitation of a core electron from the fine-structure state $^2P_{1/2}$ to $^2P_{3/2}$. Since these fine-structure levels are separated by ~ 92 K, this process is more effective in the neutral H I component with temperaturea ~ 100 K. The physical parameters that we obtain from modelling favours the association of the carbon.line region with neutral H I gas in the Galaxy. However, the origin of these lines in molecular gas cannot be entirely ruled out. We find that a range of physical conditions are probable depending on the cloud size.

The only direction that has been extensively investigated in low frequency recombination lines of carbon is that towards Cas A. The observed dependence of optical depth on quantum number seems to rule out the origin of these lines in cold (~ 20 K) molecular clouds and favour the association with warmer (~ 100 K) H I gas. If the spatial distribution of the carbon recombination lines over the face of Cas A can be compared with that of the H I 21-cm line which traces the atomic gas and ^{12}CO line which traces the molecular gas, then further knowledge on the possible association of the carbon line region with the neutral gas components can be obtained, For this purpose, we have imaged Cas A in the C270α line emission near 332 MHz using the VLA with an angular resolution of ~ 25". The ^{12}CO line emission with a resolution of ~ 1' was obtained using the 10.4-m mm-wave telescope at Raman Research Institute, Bangalore. The distribution of H I emission was obtained from published data. A comparision of recombination line distribution with ^{12}CO & H I distributions showed that there is good correspondence between C270α & H I distributions and rather poor correlation between ^{12}CO & C270α distributions. These observations lend support to the models in which the line-forming regions are associated with the H I gas.

Lastly, we have investigated in this thesis, the partially ionized gas adjacent to the well known Galactic H II region **W3A**, using radio recombination lines of carbon and hydrogen near 1420 MHz. High angular resolution, high-sensitivity images of W3A were obtained in **C168α** and **H168α** lines using the VLA. The **H168α line** is found to be a combination of a broad ($> 20\ kms^{-1}$) and a narrow ($< 10\ kms^{-1}$) component. While the broad line emission is attributable to the fully ionized hot **H II** region, the narrow line arises in the partially ionized gas surrounding the **H II** region. The intense carbon and hydrogen line emission is a result of stimulated emission by the background thermal region. We find from a comparison of the narrow **H168α** and **C168α** distributions across the continuum source that the two line-forming regions, although sharing some overlap, are not entirely coextensive. We have constrained the physical properties of these regions from the observed line parameters. The parameters of broad hydrogen line and the continuum emission detected towards W3A are combined with other data to obtain **constraints** on the temperature, density and **clumpiness** in the **H II** region.

In summary, we present in this thesis an extensive observational study of **low-**frequency carbon recombination lines from partially ionized gas associated with a widely distributed component of the interstellar medium. In addition, we also present a limited study of carbon and hydrogen recombination lines at a higher frequency from the partially ionized medium adjacent to a well known **H II** region.

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