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# OBSERVATIONS OF LOW FREQUENCY RECOMBINATION LINES

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Recombination lines have been detected in the radio part of the electromagnetic spectrum over a frequency range from about 200 MHz to 30 GHz. This corresponds to a range in principal quantum number, n, of n ∿ 300 to n ∿ 60. As well as emission from ionized hydrogen recombination lines have also been detected from heavier elements such as helium, carbon and silicon. Most of the recombination lines detected originate in hot gas, with an electron temperature Te ∿ $10^3$ -$10^4$ K, which is associated with HII regions. At high frequencies the combination of the physics of recombination line emission and the fact that radio telescopes have smaller half-power beamwidths result in the observations being more sensitive to high density, high emission measure, small diameter sources such as compact HII regions. Conversely, at low density, low emission measure, large diameter sources such as extended HII regions. For the purpose of this article I shall consider only a transitions (Δn=1) from hydrogen and further that low frequency recombination lines are those which is close in frequency to the 21 cm line of neutral hydrogen. For reasons that will be given below this frequency at which the division is made is not as arbitrary as it may first seem.

The physical processes which govern radio recombination line emission are one of the best, if not the best, understood mechanisms in astrophysics. This is certainly the case where non-thermodynamic equilibrium (TE) emission is concerned. Many of the well studied larger HII regions in the Galaxy may be described very simply as a region of ionized hydrogen of moderate density which forms an envelope inside which a small diameter, high emission measure source is often found. If we consider such a homogeneous, two density regime model we can ask what will the character of the recombination line emission be as a function of frequency.

Under conditions of local thermodynamic equilibrium (LTE) the optical depth of an Hα line is given by (Shaver, 1976).

$$t_L^* = \frac{4.61\times10^{-4}\; n_e\, n_i\, n^3}{T_e^{2.5}\;\Delta V\;(1+1.48\;\gamma)} \cdot \left(\frac{fn,\ n+1}{n}\right) \cdot \exp\left(\frac{1.58\times10^5}{n^2\; T_e}\right), \tag{1}$$

where $n_e$, $n_i$ are the electron and ion densities, usually assumed equal: $T_e$ is the electron temperature, ΔV is the full Doppler width in Km/s, and (fn, n+1/n) is the oscillator strength which for α transitions is $\simeq$ 0.2 γ is the pressure broadening (stark) factor and depends strongly on n as follows,

$$\gamma \propto n_e \, n^{7.4} \, . \, T_e^{-0.1} \, . \, T_D^{-0.5} \quad , \qquad (2)$$

where the Doppler temperature is related to the width via $\Delta V = 0.215\ T_D^{0.5}$. Thus the factor $\gamma$ becomes important for high n transitions or very high densities. For our simple HII region model, assuming small optical depths, the antenna temperature of the recombination line emission is $T_L = \eta\ T_e\ \tau_L^* \ \alpha\ \tau^{-1}$ for $\Omega$ source $\geq \Omega$ beam and where $\eta$ is the beam efficiency, and is $T_L = \Omega s\ T_e\ \tau_L^* \ / \ \Omega_B\ \alpha \nu$, when $\Omega$ source $< \Omega$ beam. Hence high density, small diameter sources are best observed at high frequency where the region is optically thin. At low frequencies the denser regions become optically thick and the line intensity increases with wavelength for extended low density regions.

At wavelengths of about 21 cm the LTE assumption for hot gas turns out to be valid for densities greater than $\sim 1$ cm$^{-3}$. At higher and lower frequencies non-LTE effects nead to be taken into account more seriously. The departure from TE is usually decribed by the factor $b_n = b(n,\ n_e,\ T_e,\ E)$ relating the population of level n to its value in TE. From observations of recombination lines an electron temperature is usually derived under the assumption of LTE from the observed ratio $\Delta V\ T_L/T_C$, where $T_C$ is the continuum antenna temperature of the source emitting the lines. This derived temperature will be incorrect if non-LTE effects are important. For a homogeneous uniform density HI region the actual electron temperature, $T_e$, may be related to the temperature derived assuming LTE, $T_e{}^*$, by the expression (Dyson 1967).

$$T_e^* = T_e \left[ b_n \frac{(1-\beta \ \tau c)}{2} \right]^{-0.87} \quad , \qquad (3)$$

where

$$\beta = (1 - 20.84 \ \frac{T_e}{\nu} \frac{\Delta b}{b_n} ) \quad , \qquad (4)$$

with $\upsilon$ in GHz and the optical depth of the free-free continuum emission from the HII region, $\tau_C$, is given by

$$\tau_C = \frac{0.0314 \ E}{\nu^2 \ T_e^{1.5}} \ . \ f \ . \left[ 1.5 \ln Te - \ln(20.2\nu) \right] \qquad (5)$$

Here E is the emission measure in pc cm$^{-6}$ and f $\sim$ 1. A "typical" extended HII region has the following properties: $T_e \sim 5000$ K and E $\sim$ $5 \mathrm{x} 10^3$ pc cm$^{-6}$. For a series of densities the variation of $T_e{}^*$ with n can be plotted. In the vicinity of n $\sim$ 170 the derived electron temperatures are found to be correct to within $\pm$ 10-20 % for densities $n_e \geq 1$ cm$^{-3}$. Here then is the reason for the choise of frequency to divide low and high frequency recombination lines. For the densities considered here pressure broadening only becomes important for n > 300, low frequency lines can thus be used to determine the effects of stimulated emission in the derived electron temperatures.

In non-LTE effects are unimportant in the H166α emission from low density extended HII regions there should then be a correlation between emitted power in the recombination lines, $T_L\ \Delta V$, and the continuum temperature, Tc. This is seen to be the case for example for the HII regions w4, w5, w16 and w80 (Hart and Pedlar 1976b). The slope of the correlation represents a constant electron temperature $T_e$ = 7000 K.

The theory of radio recombination line emission also predicts that line emission from cold regions, $T_e \sim 20$ K, should be strong with large enhancements at low frequencies. The presence of such partially ionized cool gas is inferred from observations of carbon and heavy element recombinations lines. It seems that this gas may only be present in small regions at the interfase between ionized and neutral gas. I will not consider this component further in this article.

The presence of low density ionized hydrogen with $T_e \sim 5 \times 10^3$ K has been shown, through H166 $\alpha$ observations, to exist not only immediately around HII regions but over a larger volume in the Galaxy. This low density distributed gas has been detected along the northern galactic plane for $\ell \leq 60°$ (Hart and Pedlar 1976a, Lockmann 1976). The emission is typically weak $T_L \sim 0.03 - 0.05$ K with $\Delta V \sim 50-100$ km/s and has a density $n_e \sim 10$ cm$^{-3}$. The spatial distribution of the ionized gas is similar to that of neutral hydrogen except that it is much more concentrated between galactocentric radii R = 4-6 kpc. Molecular hydrogen and formaldeyde also exhibit a similar radial distribution to ionized hydrogen.

At present I am working at the Instituto Argentino de Radioastronomía (IAR) in collaboration with Dr. R. Colomb, Lics. I. Azcárate and J.C. Cersósimo on a project to survey the H166 $\alpha$ emission along the southern part of the galactic plane using the 30m telescope.

At low frequencies it is possible that for a sufficiently intense background source stimulated emission may dominate over spontaneous emission. In the most general case where an extended ionized region is observed against the galactic background radiation, $T_G$, and a background source, $T_S$, the equation for the line antenna temperature in conditions of non-LTE becomes (Shaver 1976).

$$T_L = \eta b_n \tau^*_L T_e \left(1 - \frac{\beta \tau_c}{2}\right) - b_n \beta \tau^*_L \cdot (T_G + T_S). \tag{6}$$

The first term represents the spontaneous and stimulated emission from the ionized gas and the second term represents stimulated emission caused by the background radiation field. At low frequencies, $\nu \leq 500$ MHz, in the direction of a strong source this equation reduces to

$$T_L \simeq - b_n \beta \tau^*_L \cdot T_s \quad . \tag{7}$$

Such a situation arises when observations are made towards the galactic centre source Sgr A. Here the most intense low frequency lines yet seen are found (Pedlar et al. 1978). H166 $\alpha$ observations show the emission to consist of two components. A broad component ($\Delta V \sim 100$ km/s) which arises from HII regions close to the galactic centre, and which are best observed at high frequency, and a narrow component ($\Delta V \sim 30$ km/s) which arises in gas along the line of sight. At low resolution, $\theta \sim 30$ arcmin, H166 $\alpha$ observations show only the foreground extended component. Observations of recombination line emission from n = 300 to n = 91 towards Sgr A show that the velocity extend of the emission increases with frequency of observation. Ne II observations at 12.8 μ, which have a spatial resolution corresponding to about 0.3 pc at the galactic centre, show that the ionized gas close to the centre may be rotating about Sgr A-W with a velocity of ∿ 150 km/s (Wollman et al. 1876).

For the narrow velocity component seen towards the galactic centre the line intensity increases more quickly than the wavelength and at low frequencies the recombination line emission is enhanced by a factor of 3-4. In comparison, the extended HII region W35 shows no anomalous behaviour at low frequencies with $T_L \propto \lambda$ and $T_L/T_C \propto \nu$. For both these regions there is no significant change in velocity width of the profiles with decreasing frquency down to n ∿ 300. However, no line was detected at n = 352 (151.4 MHz) towards the galactic centre presumably because of pressure broadening. This observation alone requires that the density of the ionized gas be greater than 5 $cm^{-3}$. The behaviour of the line of sight gas can be modeled quite well for n = 100 to n = 350 by using a single component with $T_e$ = 5000 K, $N_e$ = 10 $cm^{-3}$ and E = 1500 pc $cm^{-6}$. Some variation of central velocity with galactic latitude may indicate the presence of more than one HII region.

One further effect of the presence of low density ionized gas between us and the galactic centre is that at frequencies less that 50 MHz this region becomes optically thick and the intervening gas is seen in absorption on low frequency continuum maps eg. on the 29.9 MHz map of Jones and Finday (1974).

Similar effects as I have described for the recombination line observations towards the centre of our galaxy are enabling extragalactic recombination lines to be detected. Here the observations are at high frequencies and ionized gas in an external galaxy is seen by recombination line emission which is stimulated from the background continuum radiation of the galactic nucleus. So for only 3 extragalactic sources are known, two of them nearby galaxies and one a nearby, Z ∿ .07, quasar. The hope is that one day it would be possible to detect such emission from the ionized gas associated with more distant quasars. For a review of these and other topics in radio recombinations lines see Shaver (1980).

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