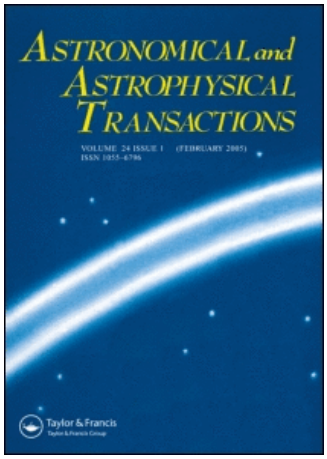

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POPULATIONS OF HIGHLY EXCITED CARBON AND OBSERVATIONS OF DECAMETRE CARBON LINES

N. I. ROVENSKAYA*

Institute of Radio Astronomy, 4 Chervonopraporna Street, 61002 Kharkov, Ukraine

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The populations of highly excited carbon are analytically described as functions of line number, temperature and density of the medium. Allowing for the process of dielectronic recombination, the balance equations for the highly excited carbon populations are solved to obtain the b_n factors. To determine the temperature and the density of the medium from the experimental amplification coefficients, a system of boundary condition equations is formulated as $(\partial^2 b_n/\partial n^2)|_{n=n_1} = 0$. The populations are found analytically in the temperature range $T_e = (25\text{–}100) \times 10^4$ K and compared with the numerical solutions. By using the intensity ratios of the radio lines for the observations at frequencies of 34.5–25 MHz, the magnitudes of the densities for Cassiopeia A are calculated as function of temperature.

Keywords: Radio recombination lines of carbon; Highly excited populations; C II regions

1 INTRODUCTION

The radio recombination lines (RRLs) of carbon are observed with the numbers $C_{202\alpha}$–$C_{680\alpha}$ and $C_{864\beta}$–$C_{868\beta}$. The high-frequency series of RRLs are experimentally found as the emission lines; the low-frequency RRLs are absorption lines. The sign of the RRL amplification coefficient is determined by the highly excited-level populations, and the carbon populations depend upon the dielectronic recombination rate.

The main aim of this paper is to describe the amplification coefficients in an analytical form and by accounting for the autoionization rate and radiative recombination to solve the balance equations in a diffusional approximation. The dielectronic recombination rate has been numerically given by Dupree (1969), Davies and Seaton (1969), Walmsley and Watson (1982) and Ponomarev and Sorochenko (1992). The balance equations for the ion populations in the coronal plasma have been given analytically and independently by Beigman et al. (1968).

Carbon RRL observations were performed as early as 1979. Currently carbon radio lines are observed with the UTR-2 (Ukraine), DKR-1000 (Russia), NRAO and GMRT (India) instruments (Ershov et al., 1984; Konovalenko, 1984, 1990; Konovalenko and Golynkin, 1991; Anantharamajah et al., 1994, 1998a,b; Smirnov et al., 1995; Konovalenko et al., 2001). Such a large number of experiments can be explained by the interest in the populations of highly excited states and, in particular, in accounting for the dielectronic recombination process.

* E-mail: rai@ira.kharkov.ua

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TABLE I RRL Amplification Coefficients.

	$b_n\beta_n$					
	$T_e = 100$ K		$T_e = 50$ K		$T_e = 25$ K	
n	Analytical results	Walmsley and Watson (1982)	Analytical results	Walmsley and Watson (1982)	Analytical results	Ponomarev and Sorochenko (1992)
150	11.9	12.0	6.5	7.0	1.3	1.0
200	3.4	6.4	1.3	4.8	0.3	1.5
250	1.2	2.7	0.5	1.8	0.1	0.5
300	0.0	1.6	0.2	0	−0.9	−0.4
350	−6.7	−5.2	−2.6	−1.5	−1.2	−0.8
400	−8.4	−9.0	−3.3	−2.5	−1.5	−1.0
450	−9.9	−14.5	−3.9	−3.4	−1.7	−1.2
500	−11.2	−15.7	−4.5	−4.2	−2.0	−1.5
550	−12.5	−19.0	−5.0	−5.2	−2.2	−1.8
600	−13.8	−21.0	−5.5	−6.0	−2.4	−1.9
650	−15.0	−24.0	−6.0	−6.7	−2.6	−2.0
700	−16.3	−27.0	−6.5	−7.1	−2.8	−2.1
750	−17.4	−28.3	−7.0	−7.5	−3.0	−2.1
800	−18.6	−29.3	−7.5	−7.6	−3.2	−2.1
850	−20.0	−29.5	−7.7	−7.6	−3.4	−2.1
900	−21.0	−30.0	−8.0	−7.6	−3.6	−2.1

The highly excited hydrogen populations have been calculated by Seaton (1964), Dyson (1967a,b) and Brocklehurst and Salem (1979) as a function of the transition rates for collisions and radiation. The highly excited carbon populations are numerically found as a function of dielectronic recombination rate in the papers by Dupree (1969), Walmsley and Watson (1982) and Ponomarev and Sorochenko (1992). The graphs of the numerical amplification coefficients show that in some highly excited levels the carbon b_n factors differ from the hydrogenic values.

In this paper the carbon populations are found using the same kinetic model as previously, but the carbon b_n factors are written in an analytical form. The solutions analytically found are compared with the numerical solutions obtained by Dupree (1969), Walmsley and Watson (1982) and Ponomarev and Sorochenko (1992).

The equations for $(\partial b_n/\partial n)|_{n=n_2} = 0$ and $(\partial^2 b_n/\partial n^2)|_{n=n_1} = 0$ are found for the b_n factor solutions. These boundary conditions are physically interpreted in the following way. Since at the n_1th level the collisional flow is compensated by the spontaneous transitions and flow is directed downwards, the maximum gradient of the b_n factor appears on the n_1th level. As at the n_2th level the collisional flow is supplemented with the autoionization process, the minimum gradient of the b_n factor is possible for the n_2th state. The numbers n_1 and n_2 depend on the temperature and concentration of the medium.

The results are described in the following sections. Section 2 deals with the balance equation. The solutions are formulated for the negative and positive amplification coefficients. Table I presents the RRL amplification coefficients for temperatures $T_e = 25$–100 K.

TABLE II RRL Observation Results.

ν (MHz)	n	$\tau\, d\nu$	T_e (K)	n_1	n_2	N_e (cm^{-3})
34.5	570	16.1 ± 3.1	25	355	483	0.006
30	600	20 ± 2	50	358	480	0.011
25	640	25 ± 2	75	360	479	0.013
			100	363	477	0.015

Section 3 deals with the density of the medium, described in Table II as a function of temperature. The main conclusions are presented in Section 4.

2 KINETIC EQUATIONS FOR HIGHLY EXCITED CARBON

The RRL intensities can be analysed with the formula for the $b_n\beta_n$ amplification coefficients, where b_n is the population departure coefficient from LTE. The b_n factor follows from the kinetic balance equations (Seaton, 1964; Dyson, 1967a,b; Brocklehurst and Salem, 1979; Beigman, 1987; Rovenskaya, 1999; 2002). To calculate the b_n factors and $(\partial b_n/\partial n)$ functions for the highly excited levels of carbon the balance equations are supplemented with the rate for the dielectronic recombination process (Davies and Seaton, 1969; Dupree, 1969; Walmsley and Watson, 1982; Ponomarev and Sorochenko, 1992).

Let us write the kinetic equations which account for the dominant processes in the highly excited carbon levels as

$$\sum_{n'=n+\Delta n}^{\infty} W^c_{nn'} b_{n'} - \sum_{n'=-\infty}^{n-\Delta n} W^c_{n'n} b_n = \alpha_n + \beta_n,$$

with

$$\alpha_n = \sum_l \frac{D^r_{nl} D^{aut}_{nl}}{D^r_{nl} + D^{aut}_{nl}}, \tag{1}$$

where $W^c_{nn'}$ is the rate of collisional transitions using the Born approximation, α_n is the rate of dielectronic recombination expressed by the rate D^{aut}_{nl} of autoionization, D^r_{nl} is the rate of recombination by radiation and β_n is the rate of collisional recombination.

Equation (1) is solved by the Laplace method (Rovenskaya, 1999), and the solution found is presented as the sum of the general and partial solutions.

With low temperatures ($T_e \ll 10^4$ K), a factor d appears in the formulae. If the principal quantum numbers obey $n < n_1$ the atomic b_n factor is hydrogen like (Rovenskaya, 1999).

For $n_1 < n < n_2$ the atomic gradients are

$$\frac{\partial b_n}{\partial n} = \left(\frac{n}{n_1}\right)^{-5} \left[\left(\frac{n}{n_1}\right)^{-5/3} - \left(\frac{n_2}{n_1}\right)^{-12/3}\right] \left(\frac{n_1}{n_2}\right)^{2/3} d, \tag{2}$$

with

$$d = 1 + \frac{1.58 \times 10^5}{n^2 T_e}. \tag{3}$$

The highly excited atom of carbon absorbs radiation if the radiating flow on some level exceeds the autoionization losses. In the case when $n > n_2$ the atomic population gradients are negative:

$$\frac{\partial b_n}{\partial n} = \left(\frac{n}{n_1}\right)^{-5} \left[\left(\frac{n}{n_1}\right)^{12/3} - \left(\frac{n_2}{n_1}\right)^{7/3}\right] d \left(\frac{n_1}{n_2}\right)^{7/3}, \tag{4}$$

where d is the temperature relation from Eq. (3).

The analytical coefficients $b_n\beta_n$ are compared with the numerical coefficients given in the papers by Walmsley and Watson (1982) and Ponomarev and Sorochenko (1992). In Table I the amplification coefficients $b_n\beta_n$ are calculated for $T_e = 100$, 50 and 25 K and $N_e = 1\,cm^{-3}$ as a function of n.

If we analyse the analytical and numerical results, it is evident that the minimum and maximum magnitudes as functions of the principal quantum numbers n_1 and n_2 are in good agreement for the chosen temperatures and densities.

3 THE CARBON RADIO RECOMBINATION LINE EXPERIMENTS AND THEIR INTERPRETATION

The temperatures and concentrations of the experimentally observed medium have been discussed in the papers by Ershov et al. (1984), Konovalenko (1984, 1990), Konovalenko and Golynkin (1991), Anantharamajah et al. (1994, 1998a,b) and Smirnov et al. (1995). For many possible temperatures these workers calculated the electron density using the RRL width magnitudes. If we use the RRL intensity data for Cassiopeia A the density can be found as a function of the given temperature.

In this section the numbers n_1 and n_2 described in Eqs. (3) and (4) are determined by the RRL intensity ratio method.

Since the continuum radiation is non-thermal in the low-frequency range 770–25 Hz, the temperature cannot be found using the ratio of the line intensity to the continuum intensity (Shaver, 1975; Gordon and Walmsley, 1990; Smirnov et al., 1995; Rovenskaya, 1999).

In Table II we account for the RRL observation results of the experiments towards Cas A for frequencies of 34.5, 30 and 25 MHz (Konovalenko, 1984; Konovalenko and Golynkin, 1991; Anantharamajah et al., 1998b), the temperatures T_e are chosen, and the densities N_e calculated.

4 CONCLUSIONS

The problem of the highly excited carbon b_n factors is analytically solved taking into accounting the dielectronic recombination process. The collision processes with electrons, autoionization and spontaneous recombination are shown to be dominant for highly excited atoms. Since the transition probabilities depend upon Δn as Δn^{-4}, the flows of highly excited electrons in the balance equations are described by the diffusional coefficients in Eqs. (5) and (6).

The carbon b_n factors are found by numerical methods (Davies and Seaton, 1969; Dupree, 1969; Walmsley and Watson, 1982), and in this paper the analytical b_n factors are calculated as functions of temperature, density and principal quantum number using the Laplace method.

With the functions (3) and (4) found analytically it is possible to propose some effective method to calculate the density of the medium. To demonstrate this method, experimental results are chosen for Cas A (Konovalenko, 1984; Konovalenko and Golynkin, 1991; Anantharamajah et al., 1997b). The calculated densities of the medium are given as functions of temperature in Table II.

The analytical coefficients $b_n\beta_n$ are compared with the numerical factors (Dupree, 1969; Walmsley and Watson, 1982; Ponomarev and Sorochenko, 1992). There is good agreement between the analytical calculations and numerical results.

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