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Effective recombination coefficients for N II lines at nebular temperatures and densities[⋆]

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Abstract. We calculate effective recombination coefficients for the formation of selected lines of N II. New photoionization data are computed which accurately map the near threshold resonances and are used to derive recombination coefficients for principal quantum numbers, $n \leq 15$, including radiative and dielectronic recombination. Cascading from higher states is included, allowing for the effects of finite electron density in a hydrogenic approximation. The effects of population in the excited states of the recombining ion are investigated.

Key words. atomic data – line: formation – ISM: H II regions – planetary nebulae: general

1. Introduction

The principal means of determining elemental abundances in nebular plasmas has, until recently, been from the measurement of collisionally excited optical forbidden lines. The emissivities of these lines are very sensitive to the electron temperature at the temperatures typical of photoionized nebulae. An alternative method of determining abundance is to ratio the intensities of recombination lines with those of hydrogen. Such ratios are only weakly dependent on temperature. In planetary nebulae, abundances of C , N and O derived from recombination lines have been shown to be larger than those derived from forbidden lines by factors ranging from 2 to 10 (Liu et al. 1995, 2000, 2001). The origin of these differences is at present unexplained. The prerequisite for determination of recombination line abundances is reliable recombination coefficients for atomic ions. In this paper we present new recombination coefficients for the formation of lines of N II.

Recombination coefficients for N II have been given by Péquignot et al. (1991) considering only radiative recombination, while Nussbaumer & Storey (1984) tabulated dielectronic recombination coefficients for N II obtained from a model in which resonance states are represented by bound-state wave functions. Escalante & Victor (1990) calculated effective recombination coefficients for C I and N II lines using an atomic model potential approximation for transition probabilities and recombination cross-sections and adding dielectronic recombination terms from Nussbaumer & Storey (1984).

We follow the approach of Storey (1994) who, for recombination to O II, used a unified approach to the treatment of radiative and dielectronic recombination by calculating recombination coefficients directly from photoionization cross-sections for each initial state. We also incorporate the further improvements introduced by Kisielius et al. (1998) in their work on the recombination of Ne II. Davey et al. (2000), used the same techniques for recombination of C II but added electron impact ionization and excitation and de-excitation for all atomic levels.

In the present paper, the results of a new calculation of N^+ photoionization cross-sections are presented using the ab initio methods developed for the Opacity Project (Seaton 1987; Berrington et al. 1987) and the Iron Project (Hummer et al. 1993), hereafter referred to only as OP methods. These calculations employ the R-matrix formulation of the close-coupling method, and the resulting cross-sections are expected to be of high quality. The existing photoionization data for N II states deposited in the Opacity Project database (Cunto et al. 1993) is inadequate for our purposes, as explained more fully below. Transition probabilities for all low-lying bound states are also calculated using the same method, so that the bound-bound and bound-free radiative data used here form a consistent set and are expected to be significantly more accurate than those used by previous authors.

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[⋆] All tables are also available in electronic form at the CDS via anonymous ftp to `cdarc.u-strasbg.fr (130.79.128.5)` or via
`http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/387/1135`

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The effects of finite electron density are also incorporated, using the methods described by Hummer & Storey (1987) for hydrogenic ions, but the treatment is not complete and the results are only applicable to plasmas of relatively low electron density. The range of validity is discussed more fully in Sect. 4.1. The process of high temperature dielectronic recombination originally described by Burgess (1964) is not included in the present calculations, so the results are only appropriate for relatively low electron temperatures, $T \leq 27\,000$ K (Nussbaumer & Storey 1983). The temperature and density range are nonetheless sufficient for the analysis of the spectra of nebular objects; planetary nebulae, H II regions and nova shells.

2. Atomic data for N^+

2.1. The N^+ term scheme

The principal series of N II is $2s^22p(^2P^o)nl$, which gives rise to singlet and triplet terms. Also interspersed among the bound states are members of the series $2s2p^2(^4P)nl$ ($n = 3, 4$) giving rise to triplet and quintet terms. Higher members of this series lie above the first ionization limit, appearing as resonances in the photoionization of the true bound states for triplets and hence giving rise to low-temperature dielectronic recombination. There are a few members of the $2s2p^2(^2D)nl$ and $2s2p^2(^2S)nl$ series located above the first ionization threshold which also give rise to a resonance structure in the photoionization cross sections for singlets and triplets. For the photon energies above the second ionization threshold, the main resonance structure is due to the $2s2p^2(^2D)nl$ series with some interlopers from the $2s2p^2(^2S)nl$ and $2s2p^2(^2P)nl$ series.

The tables of Nussbaumer & Storey (1984) show that the process of dielectronic recombination has the largest effect on the three triplet terms $2s2p^3$ ($^3D^o$, $^3P^o$) and $2s^22p3d$ ($^3F^o$). The calculation of recombination coefficients and the role of dielectronic recombination are discussed in Sect. 2.5.

We use the OP methods to calculate the bound-bound and bound-free radiative data for N II assuming LS-coupling. Consequently, there are no radiative transitions between states with different multiplicity. Furthermore, in this coupling scheme quintet states originating from the $2s2p^2(^4P)nl$ series and lying above the first ionization threshold can't decay via autoionization. Our data extend up to principal quantum number $n = 15$ and to total atomic orbital angular momentum quantum number $L = 6$. We therefore partition the calculation of level populations into several distinct regimes, according to quantum numbers and energy. We define E_0 as the ionization energy in the principal series of N^+ corresponding to $n = 15$; ($E_0 = 0.0178$ Ry).

We also define the principal quantum number $n = n_d$, such that for $n < n_d$, the population structure is determined solely by radiative processes. Collisionally induced transitions can be neglected. The approximations that are used for different values of n are described fully in Storey (1994). We give only a brief summary here.

(1) $n > n_d$: the rate of l-changing collisions is comparable to or larger than the rate of radiative decay. Populations in this regime are taken from a purely hydrogenic calculation of departure coefficients, b_{nl}, using the method described by Hummer & Storey (1987), which makes full allowance for all collisional effects. Only states that belong to the principal series of N^+ are included.

(2) $15 < n \leq n_d$: collisional effects are no longer important, so populations are now determined only by radiative processes, but no accurate atomic data are available. Various approximate methods are used to calculate energy levels, radiative transition probabilities and recombination coefficients. Only states that belong to the principal series of N^+ are included.

(3) States with ionization energy less than or equal to E_0: all atomic terms in this energy regime are included in the calculation of populations, irrespective of parentage. An energy ordered list of terms is set up and it is assumed that their populations are determined solely by recombination and radiative cascading from all accessible higher states.

2.2. New R-matrix calculation

We have carried out a new calculation of bound state energies, oscillator strengths and photoionization cross-sections for N II states with $n \leq 15$ using the OP methods (Hummer et al. 1993). The N^{2+} target state wave functions were calculated with the general purpose atomic structure code SUPERSTRUCTURE (Eissner et al. 1974) with the modifications of Nussbaumer & Storey (1978). The wave functions of the nine target terms were expanded in terms of the electron configurations $2s^22p$, $2s2p^2$, $2p^3$, $2s^2\bar{3}l$, $2s2p\bar{3}l$, $2p^2\bar{3}l$, $2s\bar{3}l\bar{3}l'$, $2p\bar{3}l\bar{3}l'$, $2s^2\bar{4}f$, $2s2p\bar{4}f$, $2p^2\bar{4}f$, $2s\bar{3}l\bar{4}f$, $2p\bar{3}l\bar{4}f$ where 1s, 2s and 2p are spectroscopic orbitals and $\bar{3}l$, $\bar{3}l'$ ($l, l' = 0, 1, 2$), $\bar{4}f$ are correlation orbitals. The one-electron radial functions for the 1s, 2s and 2p orbitals were calculated in adjustable Thomas-Fermi potentials, while the radial functions for the remaining orbitals were calculated in Coulomb potentials of variable nuclear charge, $Z_{nl} = 7|\lambda_{nl}|$. The potential scaling parameters λ_{nl} were determined by minimising the sum of the energies of the eight energetically lowest target states in our model. We obtained for the potential scaling parameters: $\lambda_{1s} = 1.41443$, $\lambda_{2s} = 1.25443$, $\lambda_{2p} = 1.20280$, $\lambda_{\bar{3}s} = -0.94850$, $\lambda_{\bar{3}p} = -0.92486$, $\lambda_{\bar{3}d} = -1.09320$, $\lambda_{\bar{4}f} = -1.88658$.

In Table 1, we compare experimental target state energies (Eriksson 1983) with our calculated values. We use the experimental target energies in the calculation of the Hamiltonian matrix of the $(N + 1)$ electron system and in the calculation of energy levels, oscillator strengths and photoionization cross-sections of N II. We use nine target terms in our R-matrix calculation where we add $1s^22s^2\bar{3}d$ ^2D to the terms listed in Table 1 in order to

Table 1. Comparison of calculated and experimental energies (in Ry) for the N^{2+} target states.

Configuration	Term	present	experimental
$1s^2 2s^2 2p$	$^2P^o$	0.00000	0.00000
$1s^2 2s 2p^2$	^4P	0.51771	0.52091
	^2D	0.92246	0.91960
	^2S	1.20597	1.19279
	^2P	1.33866	1.32898
$1s^2 2p^3$	$^4S^o$	1.70403	1.70123
	$^2D^o$	1.85796	1.84962
	$^2P^o$	2.11771	2.09865

increase the dipole polarizability of the ground state of the N^{2+} target. Because such a term represents a pseudostate, its energy does not need to be corrected as is the case for the $n = 2$ states.

2.3. Energy levels

Experimental energy levels for N^+ have been given by Eriksson (1983) for members of the series $2s^2 2p(^2P^o)\, nl$, with $n \leq 16$ and $l \leq 4$, for the series $2s2p^2(^4P)\, nl$, with $n \leq 12$ and $l \leq 4$ and the series $2s2p^2(^2D)\, 3l$, 4p although some levels are missing. For states where no data are given by Eriksson, energies have been estimated in the following ways.

Our new calculation of energy levels includes all terms $2s^p 2p^q (S_c L_c)\, nl\ (SL)$ with ionization energy less than E_0 and $L \leq 6$, where S_c and L_c are the total angular momentum quantum numbers of the core electrons. Energies calculated by ab initio methods have been used in preference to quantum defect extrapolation from experimentally known lower terms because they allow, albeit approximately, for the presence of perturbations of the principal series by members of other series. Such perturbations can significantly alter energy levels and the radiative properties of the states.

Secondly, for states with $15 < n \leq n_d$, and $l \leq 5$, where calculated energies exist for lower members of the series, a quantum defect has been calculated for the highest known member (usually with $n = 15$), and this quantum defect has been used to determine the energies of all higher terms.

Finally, if neither of the above methods can be used, the term is assumed to have a zero quantum defect.

2.4. Bound-bound radiative data

Radiative transition probabilities are taken from three sources:

(1) Ab initio calculation: we have computed values of (gf) for all transitions between bound terms with ionization energy less than or equal to E_0, and with $L \leq 6$. The data are in LS-coupling and in the electric dipole approximation, so there are no transitions between states of different total spin, but two-electron transitions, which involve a change of core state are included.

(2) Coulomb approximation: for pairs of terms where oscillator strengths were not computed by the method described in (1), but where one or both of the states have a non-zero quantum defect, the dipole radial integrals required for the calculation of transition probabilities are calculated using the Coulomb approximation. Details are given by Storey (1994).

(3) Hydrogenic approximation: for pairs of terms with zero quantum defect hydrogenic dipole radial integrals are calculated, either using the expressions of Gordon (1929) in terms of hypergeometric functions, or using direct recursion on the matrix elements themselves as described by Storey & Hummer (1991).

2.5. Photoionization cross-sections and recombination coefficients

The recombination coefficient for each term SL, or orbital nl is calculated directly from the photoionization cross-section for that state. As in the bound-bound case, there are three approximations in which the photoionization data are obtained.

(1) Photoionization cross-sections were computed for all terms with ionization energy less than or equal to E_0 and $L \leq 5$. These cross-sections can in principle be convolved with a thermal distribution of free-electron energies to obtain a recombination coefficient which incorporates both "radiative" and "dielectronic" recombination. There are two potential problems with this approach. The first is a shortcoming of the theory, in that the photoionization cross-sections have been calculated using first-order perturbation theory. This approach does not give the correct behaviour of the cross-section in the vicinity of a resonance whose radiative width is greater than its autoionization width (Seaton & Storey 1976), and overestimates the contribution of such a resonance to the recombination coefficient. We discuss this problem further in Sect. 2.6 below.

The second problem is that in many cases treated in the OP, the free-electron energy mesh on which the cross-section was calculated was too coarse to accurately describe the narrower resonance features. Such resonances may be poorly described or missed altogether by calculation on a coarse energy mesh. We also discuss the treatment of this problem further in Sect. 2.6 below.

(2) Coulomb approximation: as in the bound-bound case, the Coulomb approximation is used for terms where no OP data are available, but which have a non-zero quantum defect. The calculation of photoionization cross-section data using Coulomb functions has been described by Burgess & Seaton (1960) and Peach (1967).

(3) For the remaining states, hydrogenic photoionization cross-sections are used, calculated using the methods and computer codes of Storey & Hummer (1991).

2.6. Energy mesh for N II photoionization cross-sections

The photoionization cross-sections for N II generated by the OP were based on a quantum defect mesh with 100 points per unit increase in the effective quantum number derived from the next threshold. In contrast to the OP calculations, we use a variable step energy mesh for photoionization cross-sections that delineates all resonances to a prescribed accuracy (Kisielius et al. 1998).

Detailed consideration of the energy mesh was undertaken for the regions from the $2s^22p(^2P^o)$ limit up to 0.0178 Ry below the $2s2p^2(^4P)$ limit and from the $2s2p^2(^4P)$ limit up to 0.0178 Ry below the $2s2p^2(^2D)$ limit, since these regions contain the main contribution to the recombination at the temperatures of interest for the triplet and singlet series. The energy 0.0178 Ry corresponds to a principal quantum number of fifteen relative to the next threshold. In the region above the $2s2p^2(^2D)$ threshold and for the all energies in the case of quintet states, a quantum defect mesh was used.

One problem that arose was that of interlopers from higher series. In the region below a particular threshold, the quantum defect method outlined above does not give information about resonances that come from higher thresholds, these having been eliminated by the use of contracted matrices (Seaton 1983). Below the $2s2p^2(^4P)$ threshold and in the range of our variable step energy mesh calculation, there are resonances arising from the $2s2p^2(^2D)3s$, 3d $^{1,3}S$, $^{1,3}P$, $^{1,3}D$, $^{1,3}F$, $^{1,3}G$ and $2s2p^2(^2D)3p$ $^{1,3}P^o$, $^{1,3}D^o$, $^{1,3}F^o$ states. The positions and widths of these resonances were determined from a preliminary calculation of photoionization cross-sections from a suitable bound state. These data were then added to the list of resonance information used to generate the final energy mesh for the detailed photoionization calculations. The same procedure was applied to define positions and widths of resonances in the energy range between the $2s2p^2$ (^4P) and $2s2p^2$ (^2D) ionization thresholds. Here, amongst the series of resonances arising from $2s2p^2$ $(^2D)nl$ $^{1,3}L$ states, the resonances arising from the $2s2p^2$ $(^2S,$ $^2P)3s$, 3d $^{1,3}S$, $^{1,3}P$, $^{1,3}D$, $^{1,3}F$ and $2s2p^2$ $(^2S, {}^2P)3p$ $^{1,3}S^o$, $^{1,3}P^o$, $^{1,3}D^o$ states are present.

The effects of accurate resonance delineation have been described in detail by Kisielius et al. (1998) in the case of Ne^+ and by Davey et al. (2000) in the case of C^+ photoionization.

The unified approach suffers from a shortcoming whereby the cross-section in the vicinity of resonance whose autoionization width is comparable to or smaller than its radiative width overestimates its contribution to the recombination coefficient. To address this problem of radiative damping of resonances, we have compared total radiative decay probabilities (calculated with SUPERSTRUCTURE) with autoionization probabilities calculated with the quantum defect methods described above. As a result, the resonances corresponding to the states $2s2p^2(^4P)5g$ ^3F, ^3G were eliminated from the list of resonances used to generate the energy mesh in the interval below the second ionization threshold. In the second interval, the resonances corresponding to the states $2s2p^2(^4P)nl$ LS with ($l \geq 5$ and usually, $n \geq 10$) have been removed. As a result, a coarse energy mesh was used in the vicinity of these very narrow resonances and they were absent from the calculated photoionization cross-section.

3. Calculation of N^+ populations

The calculation of the population structure is a two-stage process. The first stage involves the calculation of a purely hydrogenic model to determine the departure coefficients b_{nl}, related to the populations N_{nl} by

$$\left(\frac{N_{nl}}{N_e N_+}\right) = \left(\frac{N_{nl}}{N_e N_+}\right)_S b_{nl}, \qquad (1)$$

where the subscript S refers to the value of the ratio given by the Saha equation, and N_e and N_+ are the number densities of electrons and recombining ions respectively. The details of the atomic rate coefficients and the numerical techniques employed in this calculation have been fully described elsewhere (Hummer & Storey 1987; Storey & Hummer 1995).

The second stage starts from the hydrogenic results for $n > n_d$, and then solves for the populations of the states from $n = n_d$ to $n = 16$ in descending order. The populations of states with $n \leq 15$ are determined by matrix inversion. More details are given by Storey (1994).

Baker & Menzel (1938) defined the Cases A and B with reference to the recombination spectrum of hydrogen. In N II, there are three low-lying terms, $2s^22p^2$ ^3P, ^1D ^1S. We define two cases for N II. In Case A, all emission lines are assumed to be optically thin. In Case B, lines terminating on the $2s^22p^2$ ^3P are assumed to be optically thick and no radiative decays to this state are permitted when calculating the population structure. Since the calculations are made entirely in LS-coupling, Cases A and B differ noticeably for the triplet and only slightly for singlet series.

4. Results and discussion

4.1. Total and effective recombination coefficients

The population structure of N^+ has been calculated for the electron temperatures T_e = 1000, 2000, 3000, 5000, 7500, 10 000, 12 500, 15 000, 20 000 K, and for the electron densities $N_e = 10^2, 10^4, 10^5, 10^6$ cm^{-3}. For electron densities greater than 10^6 cm^{-3}, l-changing collisions would have to be included for $n < 15$, which is beyond the scope of the current approximation.

In Table 2, we give the total recombination coefficients for $N^{2+} + e^-$ for the above range of electron temperatures and densities. Total recombination coefficients were

Table 2. Total recombination coefficients for N II ions [10^{-12} cm^3 s^{-1}] at various electron densities compared to data from Nahar (1995).

		log(N_e)				
T[K]	Case	2	4	5	6	Nahar
1000	A	10.67	11.49	12.45	14.13	10.4
	B	8.32	8.96	9.71	11.03	
2000	A	6.98	7.28	7.60	8.12	6.83
	B	5.33	5.56	5.81	6.19	
3000	A	5.76	5.93	6.10	6.36	5.41
	B	4.41	4.53	4.67	4.86	
5000	A	4.87	4.96	5.06	5.17	4.21
	B	3.80	3.87	3.93	4.01	
7500	A	4.26	4.33	4.38	4.43	3.51
	B	3.38	3.42	3.46	3.49	
10 000	A	3.81	3.85	3.89	3.92	3.08
	B	3.03	3.06	3.08	3.10	
12 500	A	3.45	3.49	3.52	3.54	2.78
	B	2.75	2.77	2.79	2.80	
15 000	A	3.18	3.21	3.23	3.25	2.59
	B	2.53	2.55	2.56	2.57	
20 000	A	2.84	2.86	2.87	2.88	2.49
	B	2.26	2.27	2.28	2.29	

Table 3. Effective recombination coefficients [10^{-12} cm^3 s^{-1}] for the metastable states of N II (Case B).

	log(N_e)			
T[K]	2	4	5	6
	$2s^22p^2$ ($^1D^e$)			
1000	2.664	2.942	3.252	3.753
2000	1.726	1.838	1.953	2.111
3000	1.344	1.413	1.479	1.560
5000	0.987	1.024	1.058	1.092
7500	0.781	0.805	0.826	0.843
10 000	0.670	0.688	0.703	0.713
12 500	0.601	0.616	0.627	0.633
15 000	0.556	0.569	0.578	0.582
20 000	0.510	0.519	0.526	0.528
	$2s^22p^2$ ($^1S^e$)			
1000	0.525	0.581	0.642	0.742
2000	0.339	0.361	0.383	0.415
3000	0.263	0.276	0.289	0.305
5000	0.191	0.199	0.205	0.212
7500	0.150	0.154	0.158	0.161
10 000	0.126	0.130	0.133	0.134
12 500	0.111	0.114	0.116	0.117
15 000	0.101	0.103	0.105	0.106
20 000	0.089	0.091	0.092	0.093

obtained by summing recombination coefficients to the metastable and ground states of N^+. Our data are compared to those of Nahar (1995). One can see reasonably good agreement taking into account the fact that the latter data do not include density effects. Some more noticeable disagreement appears in the temperature range $5000 \leq T_e[K] \leq 15\,000$ where the influence of low-energy resonances representing dielectronic recombination are significant. Our results are larger than those of Nahar (1995), being 24% larger at 10 000 K. More detailed discussion of these differences is given in Sect. 4.3.

In Table 3 we give the effective recombination coefficients for the metastable ^{1}D and ^{1}S states of N II in Case B.

In Table 4 are given the effective recombination coefficients $\alpha_{\rm eff}(\lambda)$, for the strongest recombination lines of N II for which the valence electron orbital angular momentum, $l \leq 2$. This restriction is discussed further in Sect. 4.3 below. The effective recombination coefficient is defined such that the emissivity $\epsilon(\lambda)$, in a transition of wavelength λ is

$$\epsilon(\lambda) = N_e N_+ \alpha_{\rm eff}(\lambda) \frac{hc}{\lambda} \quad [{\rm ergs\,cm^{-3}\,s^{-1}}]. \tag{2}$$

Results are tabulated at a single electron density, $N_e = 10^4$ cm^{-3} as the recombination coefficients do not vary greatly with electron density; typically they agree within a few percent. In the table, data are given for Cases A and B, as appropriate, but data for Case B are tabulated only if the recombination coefficients differ by more than 2.5% from the Case A values. Also tabulated is the air wavelength of the multiplet, which is calculated from the centres of gravity of the two terms involved. Most of the multiplets listed have considerable fine-structure and the reader is referred to Eriksson (1983) for a full list of fine-structure transitions and their wavelengths. Transitions are included in the tables according to the following criteria:

(1) Only transitions with effective recombination coefficients greater than 9.5×10^{-14} cm^3 s^{-1} at at least one temperature are tabulated.

(2) The components of the 3d – 3p and 3p – 3s transition arrays are given for all transitions. These transitions fall in the visible part of the spectrum and among them are the strongest recombination lines of N II.

(3) Only transitions giving rise to lines with wavelengths greater than 91.2 nm are tabulated.

In Table 5, fit parameters and maximum deviations δ and Δ (in percent) from the calculated data are given for the effective recombination coefficients at $N_e = 10^4$ cm^{-3}.

Table 4. Effective recombination coefficients [10^{-14} cm^3 s^{-1}] at electron density $N_{\rm e} = 10^4$ [cm^{-3}].

			$T_{\rm e}$ [1000 K]								
Transition	λ[nm]	Case	1.0	2.0	3.0	5.0	7.5	10.0	12.5	15.0	20.0
5d (^{3}F$^{\rm o}$)–3p (^{3}D$^{\rm e}$)	185.9	A	9.42	6.01	4.65	3.37	2.59	2.14	1.84	1.63	1.42
4d (^{3}F$^{\rm o}$)–4p (^{3}D$^{\rm e}$)	1436.5	A	16.35	10.17	7.73	5.46	4.10	3.33	2.83	2.49	2.16
4d (^{3}F$^{\rm o}$)–3p (^{3}D$^{\rm e}$)	231.7	A	17.21	10.71	8.14	5.75	4.32	3.50	2.98	2.62	2.27
4d (^{3}D$^{\rm o}$)–3p (^{3}P$^{\rm e}$)	252.2	A	0.24	0.15	0.11	0.08	0.06	0.05	0.04	0.03	0.03
		B	11.12	6.85	5.18	3.63	2.71	2.19	1.84	1.60	1.35
4p (^{3}D$^{\rm e}$)–3d (^{3}F$^{\rm o}$)	616.8	A	8.52	5.43	4.20	3.06	2.38	1.99	1.73	1.56	1.40
		B	10.20	6.44	4.97	3.59	2.78	2.31	2.01	1.81	1.61
4p (^{3}D$^{\rm e}$)–3s (^{3}P$^{\rm o}$)	185.9	A	7.98	5.08	3.93	2.87	2.23	1.86	1.62	1.46	1.31
		B	9.55	6.03	4.65	3.36	2.60	2.17	1.88	1.69	1.50
3d (^{3}F$^{\rm o}$)–3p (^{3}D$^{\rm e}$)	500.4	A	169.17	96.75	69.55	45.53	32.18	25.04	20.66	17.87	15.36
		B	173.79	99.06	71.13	46.51	32.86	25.57	21.11	18.25	15.68
3d (^{3}D$^{\rm o}$)–3p (^{3}D$^{\rm e}$)	479.4	A	0.80	0.45	0.32	0.21	0.15	0.11	0.09	0.08	0.07
		B	41.21	23.26	16.59	10.76	7.54	5.82	4.78	4.11	3.46
3d (^{3}D$^{\rm o}$)–3p (^{3}P$^{\rm e}$)	593.9	A	1.33	0.75	0.54	0.35	0.24	0.19	0.15	0.13	0.11
		B	68.16	38.47	27.44	17.80	12.47	9.63	7.90	6.79	5.73
3d (^{3}P$^{\rm o}$)–3p (^{3}D$^{\rm e}$)	448.9	A	0.21	0.12	0.08	0.05	0.04	0.03	0.02	0.02	0.02
		B	5.13	2.90	2.07	1.34	0.94	0.73	0.60	0.51	0.43
3d (^{3}P$^{\rm o}$)–3p (^{3}P$^{\rm e}$)	547.9	A	0.69	0.39	0.28	0.18	0.13	0.10	0.08	0.07	0.06
		B	16.94	9.57	6.83	4.43	3.10	2.40	1.97	1.68	1.40
3d (^{3}P$^{\rm o}$)–3p (^{3}S$^{\rm e}$)	500.1	A	1.70	0.96	0.68	0.44	0.31	0.24	0.19	0.17	0.14
		B	41.64	23.52	16.78	10.88	7.63	5.90	4.83	4.14	3.45
3d (^{1}F$^{\rm o}$)–3p (^{1}D$^{\rm e}$)	661.1	A	0.78	0.44	0.31	0.20	0.14	0.11	0.09	0.07	0.06
3d (^{1}D$^{\rm o}$)–3p (^{1}D$^{\rm e}$)	776.2	A	0.10	0.06	0.04	0.03	0.02	0.01	0.01	0.01	0.01
3d (^{1}D$^{\rm o}$)–3p (^{1}P$^{\rm e}$)	444.7	A	1.26	0.71	0.51	0.33	0.23	0.18	0.15	0.13	0.11
3d (^{1}P$^{\rm o}$)–3p (^{1}D$^{\rm e}$)	628.4	A	0.05	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.00
3d (^{1}P$^{\rm o}$)–3p (^{1}P$^{\rm e}$)	391.9	A	0.45	0.26	0.18	0.12	0.08	0.06	0.05	0.04	0.04
3d (^{1}P$^{\rm o}$)–3p (^{1}S$^{\rm e}$)	843.9	A	0.16	0.09	0.06	0.04	0.03	0.02	0.02	0.02	0.01
3p (^{3}D$^{\rm e}$)–3s (^{3}P$^{\rm o}$)	567.9	A	144.81	85.57	63.04	42.90	31.55	25.51	21.86	19.54	17.49
		B	181.59	106.38	78.01	52.70	38.55	31.02	26.43	23.51	20.89
3p (^{3}P$^{\rm e}$)–3s (^{3}P$^{\rm o}$)	462.3	A	9.43	5.95	4.69	3.63	3.04	2.76	2.62	2.54	2.46
		B	81.06	47.75	35.47	24.74	18.66	15.30	13.18	11.76	10.31
3p (^{3}S$^{\rm e}$)–3s (^{3}P$^{\rm o}$)	502.9	A	1.92	1.23	0.96	0.71	0.58	0.52	0.50	0.50	0.52
		B	21.75	12.57	9.13	6.09	4.41	3.52	2.97	2.63	2.31
3p (^{1}D$^{\rm e}$)–3s (^{1}P$^{\rm o}$)	399.5	A	7.46	4.86	3.84	2.91	2.40	2.18	2.10	2.09	2.16
		B	7.74	5.01	3.95	2.97	2.44	2.22	2.13	2.11	2.18
3p (^{1}P$^{\rm e}$)–3s (^{1}P$^{\rm o}$)	648.2	A	4.69	2.99	2.33	1.74	1.44	1.33	1.30	1.32	1.39
		B	4.84	3.07	2.39	1.77	1.46	1.34	1.32	1.33	1.40
3p (^{1}S$^{\rm e}$)–3s (^{1}P$^{\rm o}$)	343.7	A	1.54	1.00	0.79	0.59	0.47	0.41	0.38	0.36	0.36
		B	1.60	1.03	0.81	0.60	0.48	0.42	0.38	0.37	0.37
3p (^{3}D$^{\rm e}$)–2s2p^3 (^{3}D$^{\rm o}$)	134.5	A	21.98	12.99	9.57	6.51	4.79	3.87	3.32	2.97	2.65
		B	27.56	16.15	11.84	8.00	5.85	4.71	4.01	3.57	3.17
3p (^{3}D$^{\rm e}$)–2s2p^3 (^{3}P$^{\rm o}$)	174.2	A	61.43	36.30	26.74	18.20	13.38	10.82	9.27	8.29	7.42
		B	77.02	45.12	33.09	22.35	16.35	13.16	11.21	9.97	8.86
3p (^{3}P$^{\rm e}$)–2s2p^3 (^{3}D$^{\rm o}$)	127.6	A	5.77	3.64	2.87	2.23	1.86	1.69	1.60	1.55	1.51
		B	49.65	29.25	21.73	15.15	11.43	9.37	8.07	7.21	6.31
3p (^{3}S$^{\rm e}$)–2s2p^3 (^{3}P$^{\rm o}$)	167.6	A	2.44	1.56	1.21	0.90	0.74	0.66	0.64	0.63	0.65
		B	27.58	15.94	11.58	7.73	5.59	4.46	3.77	3.33	2.92
3p$'$ (^{3}D$^{\rm o}$)–3s$'$ (^{3}P$^{\rm e}$)	570.0	A	0.05	0.05	0.08	0.13	0.15	0.15	0.14	0.13	0.11
		B	0.27	0.27	0.43	0.70	0.78	0.76	0.71	0.66	0.58
3p$'$ (^{3}P$^{\rm o}$)–3s$'$ (^{3}P$^{\rm e}$)	477.0	A	0.24	0.16	0.15	0.18	0.19	0.19	0.18	0.16	0.15
		B	0.26	0.18	0.17	0.19	0.20	0.20	0.19	0.18	0.16
3p$'$ (^{3}S$^{\rm o}$)–3s$'$ (^{3}P$^{\rm e}$)	887.4	A	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01
		B	0.00	0.01	0.05	0.12	0.16	0.16	0.15	0.14	0.12
2s2p^3 (^{3}D$^{\rm o}$)–2s^{2}2p^2 (^{3}P$^{\rm e}$)	108.5	A	51.53	42.17	57.65	85.74	94.45	90.88	84.59	78.48	68.90
2s2p^3 (^{3}P$^{\rm o}$)–2s^{2}2p^2 (^{3}P$^{\rm e}$)	91.6	A	71.03	44.48	40.63	46.02	48.96	47.60	44.96	42.30	38.16

Table 5. Fit coefficients, maximum fitting errors δ[%] at the electron density $N_\mathrm{e} = 10^4$ [cm^{-3}] and maximum fitting errors Δ[%] in the whole density range investigated, $10^2 \leq N_\mathrm{e}$ [cm^{-3}] $\leq 10^6$. The temperature range of validity for the fits is $1000 \leq T_\mathrm{e}$ [K] $\leq 20\,000$ when $N_\mathrm{e} = 10^4$ [cm^{-3}] and $5000 \leq T_\mathrm{e}$ [K] $\leq 20\,000$ for other densities.

Transition	λ[nm]	Case	a	b	c	d	f	u	v	δ	Δ		
5d (^{3}F$^\mathrm{o}$)–3p (^{3}D$^\mathrm{e}$)	185.9	A	2.136	−0.802	−0.067	−0.103	−1.472	1.090	2.053	0.87	3.01		
4d (^{3}F$^\mathrm{o}$)–4p (^{3}D$^\mathrm{e}$)	1436.5	A	3.330	−0.800	−0.061	−0.116	−1.526	0.895	1.767	0.97	2.61		
4d (^{3}F$^\mathrm{o}$)–3p (^{3}D$^\mathrm{e}$)	231.7	A	3.505	−0.800	−0.061	−0.116	−1.525	0.891	1.675	0.96	2.62		
4d (^{3}D$^\mathrm{o}$)–3p (^{3}P$^\mathrm{e}$)	252.2	A	0.047	−0.787	−0.095	−0.096	−1.543	0.832	1.707	0.77	2.60		
				B	2.185	−0.807	−0.086	−0.088	−1.559	1.009	2.551	0.85	2.82
4p (^{3}D$^\mathrm{e}$)–3d (^{3}F$^\mathrm{o}$)	616.8	A	1.988	−0.877	−0.003	−0.096	−1.491	0.746	1.740	0.78	2.61		
				B	2.313	−0.888	−0.001	−0.089	−1.514	0.948	2.045	0.89	2.71
4p (^{3}D$^\mathrm{e}$)–3s (^{3}P$^\mathrm{o}$)	185.9	A	1.861	−0.877	−0.003	−0.096	−1.491	0.745	1.728	0.78	2.61		
				B	2.166	−0.888	−0.001	−0.089	−1.514	0.943	1.953	0.89	2.72
3d (^{3}F$^\mathrm{o}$)–3p (^{3}D$^\mathrm{e}$)	500.4	A	25.037	−0.826	−0.011	−0.148	−1.686	−0.070	−0.051	1.03	1.16		
				B	25.575	−0.830	−0.010	−0.146	−1.689	0.313	0.782	1.04	1.37
3d (^{3}D$^\mathrm{o}$)–3p (^{3}D$^\mathrm{e}$)	479.4	A	0.113	−0.816	−0.027	−0.144	−1.712	−0.240	−0.545	0.81	0.88		
				B	5.824	−0.821	−0.026	−0.139	−1.709	0.134	0.506	0.84	1.07
3d (^{3}D$^\mathrm{o}$)–3p (^{3}P$^\mathrm{e}$)	593.9	A	0.187	−0.816	−0.027	−0.144	−1.711	−0.210	−0.391	0.81	0.88		
				B	9.632	−0.821	−0.026	−0.139	−1.709	0.134	0.497	0.84	1.07
3d (^{3}P$^\mathrm{o}$)–3p (^{3}D$^\mathrm{e}$)	448.9	A	0.029	−0.826	−0.035	−0.129	−1.729	−0.265	−0.470	0.89	0.96		
				B	0.727	−0.832	−0.034	−0.122	−1.721	0.115	0.632	0.90	1.14
3d (^{3}P$^\mathrm{o}$)–3p (^{3}P$^\mathrm{e}$)	547.9	A	0.096	−0.826	−0.035	−0.129	−1.730	−0.268	−0.507	0.89	0.95		
				B	2.399	−0.832	−0.034	−0.122	−1.721	0.114	0.597	0.91	1.15
3d (^{3}P$^\mathrm{o}$)–3p (^{3}S$^\mathrm{e}$)	500.1	A	0.237	−0.826	−0.035	−0.129	−1.730	−0.262	−0.471	0.89	0.95		
				B	5.897	−0.832	−0.034	−0.122	−1.721	0.119	0.616	0.91	1.14
3d (^{1}F$^\mathrm{o}$)–3p (^{1}D$^\mathrm{e}$)	661.1	A	0.107	−0.811	−0.010	−0.166	−1.716	−0.336	−0.722	1.20	1.28		
3d (^{1}D$^\mathrm{o}$)–3p (^{1}D$^\mathrm{e}$)	776.2	A	0.014	−0.824	−0.009	−0.155	−1.706	−0.193	−0.438	1.10	1.17		
3d (^{1}D$^\mathrm{o}$)–3p (^{1}P$^\mathrm{e}$)	444.7	A	0.178	−0.824	−0.009	−0.155	−1.707	−0.195	−0.417	1.10	1.16		
3d (^{1}P$^\mathrm{o}$)–3p (^{1}D$^\mathrm{e}$)	628.4	A	0.007	−0.811	−0.010	−0.167	−1.715	−0.324	−0.587	1.17	1.27		
3d (^{1}P$^\mathrm{o}$)–3p (^{1}P$^\mathrm{e}$)	391.9	A	0.062	−0.810	−0.010	−0.167	−1.715	−0.328	−0.588	1.17	1.24		
3d (^{1}P$^\mathrm{o}$)–3p (^{1}S$^\mathrm{e}$)	843.9	A	0.022	−0.811	−0.010	−0.167	−1.715	−0.325	−0.582	1.17	1.26		
3p (^{3}D$^\mathrm{e}$)–3s (^{3}P$^\mathrm{o}$)	567.9	A	25.515	−0.934	0.078	−0.131	−1.649	0.200	0.818	0.57	1.48		
				B	31.018	−0.925	0.067	−0.128	−1.660	0.460	1.189	0.66	1.61
3p (^{3}P$^\mathrm{e}$)–3s (^{3}P$^\mathrm{o}$)	462.3	A	2.761	−1.286	0.343	−0.043	−1.581	2.565	−0.854	0.57	5.41		
				B	15.304	−0.935	0.032	−0.073	−1.605	0.711	0.715	0.75	2.17
3p (^{3}S$^\mathrm{e}$)–3s (^{3}P$^\mathrm{o}$)	502.9	A	0.525	−1.329	0.518	−0.185	−1.618	0.497	0.849	0.99	2.00		
				B	3.517	−0.922	0.059	−0.125	−1.688	0.115	1.051	0.59	1.39
3p (^{1}D$^\mathrm{e}$)–3s (^{1}P$^\mathrm{o}$)	399.5	A	2.182	−1.322	0.498	−0.172	−1.588	1.366	1.725	0.80	3.58		
				B	2.216	−1.337	0.511	−0.171	−1.610	1.687	0.720	0.75	3.59
3p (^{1}P$^\mathrm{e}$)–3s (^{1}P$^\mathrm{o}$)	648.2	A	1.327	−0.448	0.227	0.047	−0.636	0.986	0.911	0.82	3.38		
				B	1.344	−0.447	0.229	0.051	−0.642	1.304	0.236	0.74	3.47
3p (^{1}S$^\mathrm{e}$)–3s (^{1}P$^\mathrm{o}$)	343.7	A	0.410	−0.987	0.204	−0.186	−1.426	1.496	2.245	0.15	3.28		
				B	0.417	−1.009	0.216	−0.180	−1.452	1.860	1.232	0.07	3.36
3p (^{3}D$^\mathrm{e}$)–2s2p^3 (^{3}D$^\mathrm{o}$)	134.5	A	3.873	−0.933	0.078	−0.131	−1.648	0.198	0.754	0.57	1.40		
				B	4.708	−0.925	0.067	−0.128	−1.660	0.456	1.233	0.66	1.62
3p (^{3}D$^\mathrm{e}$)–2s2p^3 (^{3}P$^\mathrm{o}$)	174.2	A	10.823	−0.934	0.078	−0.131	−1.649	0.197	0.781	0.58	1.47		
				B	13.157	−0.925	0.067	−0.128	−1.660	0.452	1.130	0.66	1.61
3p (^{3}P$^\mathrm{e}$)–2s2p^3 (^{3}D$^\mathrm{o}$)	127.6	A	1.691	−1.286	0.343	−0.043	−1.581	2.572	−0.815	0.57	5.43		
				B	9.375	−0.934	0.032	−0.073	−1.605	0.708	0.671	0.75	2.11
3p (^{3}S$^\mathrm{e}$)–2s2p^3 (^{3}P$^\mathrm{o}$)	167.6	A	0.665	−1.329	0.518	−0.185	−1.617	0.497	0.820	0.99	2.02		
				B	4.458	−0.922	0.059	−0.125	−1.688	0.122	1.105	0.60	1.40

The coefficients are fitted by a least-squares algorithm to the functional form

$$\begin{aligned}\alpha_\mathrm{eff} \;&=\; 10^{-14} \times a t^f \times \left(1 + 0.01\, u Y + 0.001\, v Y^2\right) \\ &\quad\times \left(1 + b\,(1-t) + c\,(1-t)^2 + d\,(1-t)^3\right), \qquad (3)\end{aligned}$$

where $t = T_\mathrm{e}[\mathrm{K}]/10^4$, $Y = \log_{10}(N_\mathrm{e}) - 4$ and a, b, c, d, u and v are constants. The value of parameter a is constrained to have the value of effective recombination coefficient $\alpha_\mathrm{eff}(\lambda)\times 10^{14}$ at $T_\mathrm{e} = 10^4$ K and $N_\mathrm{e} = 10^4$ cm^{-3}.

The maximum fitting error, δ, refers to the fitting for the whole temperature range studied and the electron

Table 6. Effective recombination coefficients [10^{-15} cm^3 s^{-1}]. Electron densities are $N_\mathrm{e} = 10^2, 10^4, 10^5, 10^6$ [cm^{-3}].

				T_e [1000 K]					
Transition	λ[nm]	Case	N_e	5.0	7.5	10.0	12.5	15.0	20.0
3p′ (^{3}D$^\mathrm{o}$)–3s′ (^{3}P$^\mathrm{e}$)	570.0	A	10^2	1.326	1.490	1.449	1.357	1.261	1.100
			10^4	1.329	1.492	1.450	1.358	1.262	1.100
			10^5	1.332	1.493	1.451	1.358	1.262	1.100
			10^6	1.335	1.494	1.452	1.359	1.262	1.101
		B	10^2	6.954	7.802	7.583	7.099	6.596	5.753
			10^4	6.966	7.807	7.586	7.101	6.598	5.754
			10^5	6.979	7.814	7.590	7.104	6.599	5.755
			10^6	7.000	7.823	7.595	7.107	6.601	5.755
3p′ (^{3}P$^\mathrm{o}$)–3s′ (^{3}P$^\mathrm{e}$)	477.0	A	10^2	1.768	1.895	1.848	1.747	1.644	1.510
			10^4	1.783	1.904	1.855	1.752	1.648	1.513
			10^5	1.796	1.912	1.860	1.756	1.651	1.515
			10^6	1.810	1.918	1.863	1.758	1.652	1.515
		B	10^2	1.909	2.034	1.979	1.868	1.757	1.613
			10^4	1.923	2.042	1.984	1.872	1.760	1.615
			10^5	1.937	2.049	1.989	1.875	1.762	1.617
			10^6	1.953	2.056	1.992	1.877	1.763	1.617
2s2p^3 (^{3}D$^\mathrm{o}$)–2s^{2}2p^2 (^{3}P$^\mathrm{e}$)	108.5	A	10^2	853.02	941.64	906.67	844.13	783.28	687.85
			10^4	857.40	944.49	908.82	845.87	784.77	689.01
			10^5	861.04	946.64	910.33	847.05	785.73	689.73
			10^6	864.13	947.79	910.79	847.18	785.70	689.55
2s2p^3 (^{3}P$^\mathrm{o}$)–2s^{2}2p^2 (^{3}P$^\mathrm{e}$)	91.6	A	10^2	458.80	488.98	475.65	449.42	422.82	381.47
			10^4	460.16	489.59	475.99	449.64	422.98	381.57
			10^5	461.91	490.34	476.39	449.89	423.14	381.66
			10^6	465.07	491.62	477.04	450.24	423.35	381.73

density $N_\mathrm{e} = 10^4$ cm^{-3}. Due to the fact that effective recombination coefficients depend, although weakly, on the electron density, the accuracy of fitting is worse for the other densities studied. The fitting error, Δ, is the maximum deviation from the calculated coefficients for all densities considered. Note that when the fits are applied to the full range of densities, the temperature range over which the fits are valid is restricted at the lower end to $T_\mathrm{e} = 5000$ K. The fits are accurate to within 1.2% for all lines in the main series when $N_\mathrm{e} = 10^4$ cm^{-3} for the whole temperature region.

Nevertheless, there exist some lines originating from the 3p′ ($^3L^\mathrm{o}$) and 2s2p^3 ($^3L^\mathrm{o}$) states where fitting to the form given in Eq. (3) is inaccurate even for a single electron density. For these lines, radiative recombination and dielectronic recombination are at least of equal importance, and the effective recombination coefficients have a more complex dependence on temperature. Therefore, we tabulate the effective recombination coefficients α_eff for these lines in Table 6 at different electron temperatures and densities. The transition 3p′ (^{3}S$^\mathrm{o}$)–3s′ (^{3}P$^\mathrm{e}$) ($\lambda = 887.4$ nm) is not present in Table 6 because it does not depend on electron density in the range studied.

4.2. Population of excited states of N^{2+}

In most calculations of recombination coefficients in nebular plasmas it is assumed that only the ground state of the recombining ion, 2s^{2}2p ^{2}P$^\mathrm{o}$ in the case of N^{2+}, is populated. This is a reliable approximation in the case of astrophysical objects having relatively low electron density. In N^{2+}, the 2s2p^2 ^{4}P lies 57 161.7 cm^{-1} above the ground state (see Eriksson et al. 1983), and the population of this first excited term is negligible (2.35×10^{-6}) even at the highest temperatures and densities considered in this paper ($T_\mathrm{e} = 20\,000$ K, $N_\mathrm{e} = 10^6$ cm^{-3}) for N^{2+}.

We consider direct recombination only to the ground state in our model.

4.3. Discussion

The calculations described here were carried out entirely in LS-coupling. The work of Erikssson (1983) indicates that LS-coupling is no longer a good approximation for $f-$ and $g-$states of N^+, and that the states should be described by an alternative coupling scheme. We therefore do not present any transitions with $l > 2$ even though sometimes such multiplets have relatively strong lines with $\alpha_{\mathrm{eff}} > 10^{-14}$ cm^{3}s^{-1}. These transitions will be the subject of a subsequent paper.

A full treatment of the high-l states also needs to recognise the fact that the ground term of N^{2+} comprises two levels, $^2\mathrm{P}^{\mathrm{o}}_{1/2}$ and $^2\mathrm{P}^{\mathrm{o}}_{3/2}$ and that the populations of the $^2\mathrm{P}^{\mathrm{o}}_J$ levels may well differ from those given by the Boltzmann distribution, so that a correct treatment of the recombination to the high-l states will require intermediate coupling photoionization data and incorporation of the population distribution among the $^2\mathrm{P}^{\mathrm{o}}_J$ levels. The critical electron density, at which the rates of collisional de-excitation and radiative decay from $^2\mathrm{P}^{\mathrm{o}}_{3/2}$ to $^2\mathrm{P}^{\mathrm{o}}_{1/2}$ are equal, is approximately 2000 cm^{-3}. At this density, the populations of the $^2\mathrm{P}^{\mathrm{o}}_{1/2}$ and $^2\mathrm{P}^{\mathrm{o}}_{3/2}$ levels differ from their Boltzmann values by about 30%.

In Table 7 we compare our direct recombination coefficients to individual terms of N II with those calculated by Nahar (1995). In both calculations the R-matrix method was used to compute atomic photoionization cross-sections. For most terms the agreement is good with differences of less than 10%. The exceptions are the recombination coefficients to the three 2s2p^3 states, $^3\mathrm{S}^{\mathrm{o}}$, $^3\mathrm{P}^{\mathrm{o}}$ and $^3\mathrm{D}^{\mathrm{o}}$, which are significantly larger in our calculation. For these states direct photoionization to the 2s^{2}2p $^2\mathrm{P}^{\mathrm{o}}$ ground state of N^{2+} is parentage forbidden and photoionization proceeds mainly through autoionizing resonances in the area below the first threshold 2s2p^2 ^{4}P. The three low-lying resonances belonging to the 2s2p^2(^{4}P)3d configuration are situated between 0.075 and 0.085 Ry above the ionization threshold. These resonances are very narrow, yet are the principal source of recombination to the 2s2p^3 states. The half-widths of the resonances are 5.03×10^{-5} Ry for the 2s2p^2(^{4}P)3d ^{3}F, 1.04×10^{-4} Ry for the ^{3}P and 3.35×10^{-5} Ry for the ^{3}D. In our calculation of the photoionization cross-section data the energy interval was in the range from 3.8×10^{-6} Ry, near the narrowest resonance to 1.2×10^{-5} Ry near the broadest. Thus there were typically about ten points spanning each resonance. By contrast, Nahar (1995) used a fixed interval of 0.0004 Ry in this energy range (Nahar & Pradhan 1994, Nahar personal communication). This interval leads to the area under the resonances and hence their contribution to the recombination coefficients being significantly underestimated.

Table 7. Comparison of our direct recombination coefficients [cm^3 s^{-1}] to states of N^+ with those of Nahar (1995). Electron temperatures are $T_{\mathrm{e}} = 1000$ K and $T_{\mathrm{e}} = 10\,000$ K, the electron density is $N_{\mathrm{e}} = 10^4$ [cm^{-3}].

State	1000 K		10 000 K	
	Nahar	Present	Nahar	Present
2s^{2}2p^2 (^{3}P)	2.44-12	2.26-12	8.31-13	7.69-13
2s^{2}2p^2 (^{1}D)	1.28-12	1.20-12	4.21-13	3.92-13
2s^{2}2p^2 (^{1}S)	2.55-13	2.41-13	8.27-14	7.75-14
2s^{2}2p3d (^{3}F$^{\mathrm{o}}$)	1.88-13	2.00-13	5.26-14	5.59-14
2s^{2}2p3p (^{3}D)	1.29-13	1.41-13	4.84-14	5.42-14
2s^{2}2p4d (^{3}F$^{\mathrm{o}}$)	1.13-13	1.14-13	3.26-14	3.27-14
2s^{2}2p3d (^{3}D$^{\mathrm{o}}$)	1.09-13	1.10-13	2.97-14	3.06-14
2s^{2}2p3p (^{3}P)	7.51-14	7.70-14	2.87-14	3.02-14
2s2p^3 (^{3}D$^{\mathrm{o}}$)	7.25-14	8.10-14	3.28-13	8.16-13
2s^{2}2p3s (^{3}P$^{\mathrm{o}}$)	7.07-14	7.92-14	6.17-14	8.13-14
2s^{2}2p4d (^{3}D$^{\mathrm{o}}$)	7.04-14	7.04-14	1.96-14	1.98-14
2s^{2}2p5d (^{3}F$^{\mathrm{o}}$)	6.32-14	6.33-14	1.86-14	1.84-14
2s^{2}2p3d (^{3}P$^{\mathrm{o}}$)	5.64-14	6.08-14	1.54-14	1.71-14
2s^{2}2p4f (^{3}G)	5.54-14	5.50-14	1.31-14	1.29-14
2s^{2}2p5f (^{3}G)	4.92-14	4.94-14	1.17-14	1.16-14
2s^{2}2p3p (^{1}D)	4.73-14	4.80-14	1.78-14	1.80-14
2s^{2}2p4f (^{3}F)	4.46-14	4.57-14	–	1.08-14
2s^{2}2p5d (^{3}D$^{\mathrm{o}}$)	4.20-14	4.19-14	1.18-14	1.20-14
2s^{2}2p3d (^{1}F$^{\mathrm{o}}$)	4.14-14	4.22-14	–	1.14-14
2s^{2}2p4d (^{3}P$^{\mathrm{o}}$)	3.93-14	4.06-14	–	1.14-14
2s2p^3 (^{3}P$^{\mathrm{o}}$)	–	2.40-14	1.54-13	3.50-13
2s2p^3 (^{3}S$^{\mathrm{o}}$)	–	3.21-17	2.24-14	3.28-14
2s^{2}2p4p (^{3}D)	–	3.71-14	1.31-14	1.37-14
Total	1.04-11	1.07-11	3.10-12	3.81-12

The total recombination coefficients given at the bottom of Table 7 show very good agreement at 1000 K. The difference of 19% at $T_{\mathrm{e}} = 10\,000$ K is caused primarily by the difference in the contributions from the 2s2p^3 states.

Escalante & Victor (1990) have also computed effective recombination coefficients for the N^+ ion but they used an approach where recombination coefficients were obtained by summing radiative recombination coefficients and dielectronic recombination coefficients from Nussbaumer & Storey (1984). Effective radiative recombination coefficients for some of the strongest lines of N II were also obtained by Péquignot et al. (1991). Both Escalante & Victor (1990) and Péquignot et al. (1991) computed their radiative recombination coefficients using simpler and less accurate methods than those described here or in the work of Nahar (1995). In Table 8 we compare our effective recombination coefficient data with the other two calculations. Line wavelengths given in this table are taken from our calculations and may differ from the data of other authors.

In general, there is good agreement between the effective recombination coefficients presented in Table 8. Note that we perform calculations in pure LS-coupling so that we do not present results for transitions between terms of different multiplicity. Péquignot et al. (1991) give effective recombination coefficients for transitions between some states of different multiplicity in the 4f–3d transition array. Thus it is appropriate, for example, to compare the sum of the recombination coefficients given by Péquignot et al. (1991) for the 4f (^{1}G)–3d (^{1}F^o) and 4f (^{1}G)–3d (^{3}F^o) transitions with our result for the 4f (^{1}G)–3d (^{1}F^o) transition alone when assessing the degree of agreement between the two calculations. We present results for the 4f–3d transitions here only for the purpose of comparison with earlier work. They are not included in the main tables for the reason given above, that LS-coupling is not appropriate for these states.

The most striking difference between the present results and those of Péquignot et al. (1991) and Escalante & Victor (1990) occurs for the transitions from the 3p (^{3}D) state to lower states. The total effective recombination coefficient in Case A for the three such transitions given in Table 8 (calculated at $T_e = 10^4$ K in units of 10^{-13} cm^3 s^{-1}), is 4.0 from the present work, 4.4 from Escalante & Victor (1990) and 7.7 from Péquignot et al. (1991). The distribution between the three transitions also differs in the three calculations. Since the distribution depends upon the relative transition probabilities of the three transitions we have more confidence in our own work since it employs the most elaborate treatment for the calculation of the bound-bound radiative data. Péquignot (private communication, 2001) points out that the difference in the total recombination coefficient to the 3p (^{3}D) state is due to an error in Table 2 of Péquignot et al. (1991), where incorrect fit coefficients were given for the λ174.2 and λ134.4 nm transitions. The total recombination coefficient for the 3p (^{3}D) state inferred from the data given by Péquignot et al. (1991) for the λ567.9 nm transition is 4.2×10^{-13} cm^3 s^{-1} at $T_e = 10^4$ K, in good agreement with the present result.

Table 8. Comparison of calculated effective recombination coefficients at T_e = 10 000 K [10^{-13} cm^3 s^{-1}] for N II. Sources are Péquignot et al. (1991, PPB), Escalante & Victor (1990, E&V) and the present work (K&S), calculated at electron density $N_e = 10^4$ cm^{-3}. Column C is for Case A or Case B, and wavelength is λ[nm].

Transition	C	λ	PPB	E&V	K&S
4f (^{1}G)–3d (^{1}F^o)	A	453.4	0.204	0.283	0.304
4f (^{1}G)–3d (^{3}F^o)	A	402.6	0.110		–
4f (^{1}F)–3d (^{1}D^o)	A	416.9	0.134	0.181	0.201
4f (^{1}F)–2s2p^3 (^{1}D^o)	A	149.5	0.097	0.150	0.021
4f (^{1}D)–2s2p^3 (^{1}P^o)	A	223.6	0.112	0.196	0.007
4f (^{1}D)–3d (^{1}P^o)	A	468.2	0.038	0.083	0.125
4f (^{3}G)–3d (^{3}F^o)	A	403.8	0.878	0.924	0.948
4f (^{3}G)–3d (^{1}F^o)	A	455.2	0.071		–
4f (^{3}F)–3d (^{3}D^o)	A	423.4	0.650	0.551	0.629
4f (^{3}D)–3d (^{3}P^o)	A	442.9	0.416	0.269	0.396
3d (^{3}P^o)–3p (^{3}P)	B	547.9	0.238	0.277	0.240
3d (^{3}P^o)–3p (^{3}S)	B	500.1	0.610	0.445	0.590
3d (^{3}D^o)–3p (^{3}P)	B	593.9	0.844	0.819	0.963
3d (^{3}D^o)–3p (^{3}D)	B	479.4	0.520	0.481	0.582
3d (^{3}F^o)–3p (^{3}D)	A	500.4	1.976	2.36	2.504
	B		2.062	2.38	2.558
3p (^{3}D)–3s (^{3}P^o)	A	567.9	1.138	1.58	2.552
	B		1.411	1.84	3.102
3p (^{3}D)–2s2p^3 (^{3}P^o)	A	174.2	5.210	2.20	1.082
	B		6.464	2.56	1.316
3p (^{3}D)–2s2p^3 (^{3}D^o)	A	134.4	1.372	0.575	0.387
	B		1.703	0.669	0.471

5. Conclusion

Total recombination coefficients for N^{2+} +e$^-$ recombination and effective recombination coefficients for lines of N II have been tabulated at temperatures and densities appropriate to nebular plasmas. The use of atomic data of high quality for bound-bound and bound-free radiative processes among all the terms with $n \leq 15$ means that the results given here should be more reliable than those of previous workers. It would be desirable to extend the calculations to higher electron densities to permit reliable interpretation of N II emission from more dense objects such as young novae and stellar winds.

In N II itself, further work is needed on the transition arrays where LS-coupling breaks down. Relatively strong recombination lines exist between 5g, 4f and 3d states which cannot be reliably used at present.

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