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Production of vibrationally excited N_2 by electron impact

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Abstract

Energy transfer from electrons to neutral gases and ions is one of the dominant electron cooling processes in the ionosphere, and the role of vibrationally excited N_2 in this is particularly significant. We report here the results from a new calculation of electron energy transfer rates (Q) for vibrational excitation of N_2, as a function of the electron temperature T_e. The present study was motivated by the development of a new cross-section compilation for vibrational excitation processes in N_2 which supercedes those used in the earlier calculations of the electron energy transfer rates. We show that the energy dependence and magnitude of these cross sections, particularly in the region of the well-known $^2\Pi_g$ resonance in N_2, significantly affect the calculated values of Q. A detailed comparison between the current and previous calculated electron energy transfer rates is made and coefficients are provided so that these rates for transitions from level 0 to levels 1–10 can be calculated for electron temperatures less than 6000 K.

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Keywords: Electron; Energy; Transfer; Rates

1. Introduction

The rate of energy transfer from electrons to neutral gases in the upper atmosphere has been recognised as being important for many years (Dalgarno, 1969). This is important both for theoretical calculations of the electron temperature distribution in the ionosphere, and in predicting the production rate of NO^+ by the reaction of O^+ with vibrationally excited nitrogen (Richards and Torr, 1986). While NO is but a minor constituent, it plays a critical role in both the chemistry and heat budget of the thermosphere (Wise et al., 1995).

In the ionosphere photoelectrons are generated by solar ultraviolet radiation (Stubbe and Varnum, 1972), with energy transfer from the electrons to neutral gases being one of the dominant electron cooling processes (Pavlov, 1998). Energy transfer due to collisions with molecular nitrogen is of most interest and the rates for this process have been calculated (Stubbe and Varnum, 1972; Newton et al., 1974; Pavlov, 1998) previously.

The formulae for these rates were extended to include their dependence on the neutral temperature and complemented with analytic approximations (Stubbe and Varnum, 1972). Reliable transfer rates require inclusion of accurate electron-impact excitation cross-sections. For molecular nitrogen Stubbe and Varnum used cross sections from Schulz (1964); Engelhardt et al. (1964); Chen (1964b). Soon afterwards similar expressions were presented (Newton et al., 1974) based on only the cross sections of Chen (1964a, b, c). Recently, results for the energy transfer rates for N_2 have been updated (Pavlov, 1998) to take into account more recent data of the electron-impact cross sections (Schulz, 1976; Haddad, 1984; Robertson et al., 1997; Dubé and Herzenberg, 1979). However new cross-section data are now available and differences from previous cross section data suggests that previously reported energy transfer rates be re-examined.

In this study we report on a revised array of cross sections for vibrational excitation in N_2. This cross-section array is largely based on the compilation of Brunger and Buckman (2002), extended for the first vibrational excitation process ($0 \rightarrow 1$) to lower energies using the accurate calculation in Robertson et al. (1997) and the data set of Ohmori et al.

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(1988). Using this new set of cross sections the present electron energy transfer rates, as a function of the electron temperature T_e, for vibrational excitation of N_2 are calculated and the results compared against those from the earlier studies.

In the next section of this paper we discuss the direct mechanisms for producing vibrationally excited N_2, with particular attention being paid to our recommended cross section data set. In Section 3 details of our calculations are provided, and in Section 4 our results and a discussion of these results is presented. Finally, some conclusions from the present work are drawn.

2. Direct mechanisms for producing vibrationally excited N_2

Due to its lack of a permanent dipole moment and due to the large disparity between electron and nuclear masses, one-step "direct" excitation of vibrational motion in N_2 by electrons does not occur with appreciable probability. In the latter case this is because of poor momentum transfer from the electrons to nuclear motion. Instead, "direct" vibrational excitation of N_2 occurs by a two-step process in which electrons with energy in the ~1.5–4.5 eV range are first captured by the N_2 molecule to form a temporary negative ion. The N_2^- molecule is energetically unstable (i.e. the 15-electron system has an energy above the ground state of neutral N_2) so it autodetaches into a zero-energy electron and molecular N_2 with the maximum vibrational energy determined by energy conservation. The resonance nature of this process results in an excitation cross section which is anomalously large over a relatively narrow energy range, but essentially zero at all other energies, compared to that for other inelastic electron scattering processes.

The available data for electron impact excitation of vibrational quanta in the ground electronic state of N_2 ($^1\Sigma_g^+$) were recently reviewed by Brunger and Buckman (2002). This review took account of all new crossed-beam and electron-swarm experiments and ab initio theoretical calculations since the earlier work of Trajmar and colleagues (1983). All the experimental data in the review by Brunger and Buckman (2002) dealt with excitation from the ground-vibrational quantum ($v'' = 0$) of the ground-electronic state. On the basis of this review, Brunger et al. (2003) constructed a set of recommended integral cross sections (ICSs) for the $0 \to 1$, $0 \to 2$ and $0 \to 3$ excitation processes in N_2. These data are shown as dots in Fig. 1a. Also shown in Fig. 1a (solid line) are the swarm-derived data of Ohmori et al. (1988) for the excitations $0 \to 1, 2, 3 \ldots 10$. These data were determined from an iterative solution of the Boltzmann equation, optimised to give the best agreement between their calculated and measured macroscopic transport parameters (Brunger and Buckman, 2002). Note that the original $0 \to 2$, $0 \to 3$ ICS data of Ohmori et al. (1988) have been shifted slightly in energy to account for a mismatch in their respective excitation thresholds (to the known physical values), for these processes, while the $0 \to 1$ ICS has been scaled upwards by 17%. All these changes to the original compilation of Ohmori et al. follow the prescription of Kelly (1990). There is good agreement in Fig. 1a between the data of Ohmori et al. (1988) and the results reported by Brunger et al. (2003) for each of the $0 \to 1$, $0 \to 2$ and $0 \to 3$ integral cross sections. While there are always questions relating to the uniqueness of swarm-derived ICSs (Brunger and Buckman, 1997), the good agreement shown in Fig. 1a provides compelling evidence that the cross sections to the higher vibrational levels reported by Ohmori et al. [i.e. $v = 0 \to 4, 5, \ldots 10$] should also be reliable. As a consequence, the data embodied by the solid lines in Fig. 1a for $0 \to 1, 2, 3, \ldots 10$ constitute our recommended ICS set for these vibrational excitation processes. The corresponding ICSs for the de-excitation processes $10, 9, 8, \ldots 1 \to 0$ can be obtained from our recommended data set by using the principle of detailed balance (Fowler, 1936). The cross sections derived in this manner should also be reliable and selected cross sections connecting various pairs of vibrational levels are shown in the upper section of Fig. 1b.

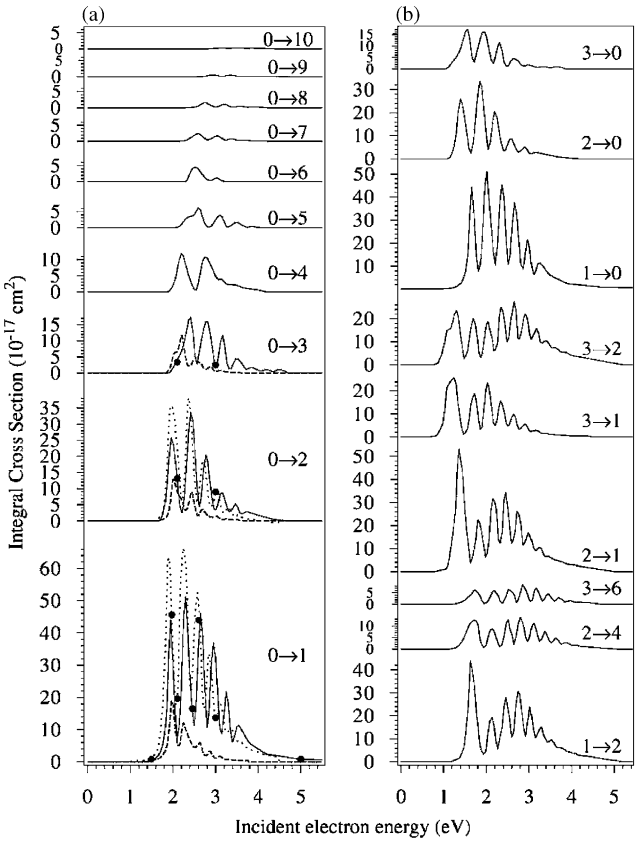

Fig. 1. Recommended (—) vibrational excitation and de-excitation integral cross sections for $e^- + N_2(^1\Sigma_g^+)$ scattering, as used in the present study. Also shown in this figure are the data from Brunger et al. (2003), (●), and the results from calculations due to Dubé and Herzenberg (1979), (· · · · ·) and Chen (1964b, c), (- - - -).

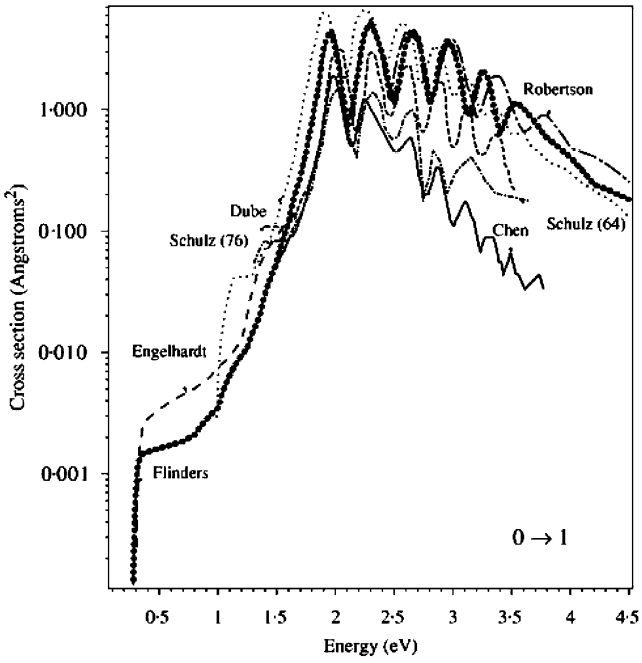

Fig. 2. Integral cross sections for the $0 \rightarrow 1$ excitation process in N_2, at energies from threshold to 4.5 eV. The present recommended cross section (• • • •) is compared against those used in previous modelling studies (Stubbe and Varnum, 1972; Newton et al., 1974; Pavlov, 1998). Those earlier cross sections are due to: Schulz (1964), (– · –·), Chen (1964b, c), (—), Engelhardt et al. (1964), (– – –), Schulz (1976), (- - -), Dubé and Herzenberg (1979), (• • • •) and Robertson et al. (1997), (— -).

The state-of-the-art calculation for vibrational excitation in N_2 is by Morrison and colleagues (Sun et al., 1995; Robertson et al., 1997). These calculations are fully ab initio and the relatively good agreement between their theoretical predictions and the available experimental data for the differential cross sections, excitation functions, and ICSs indicates that it is adequately addressing all the important dynamics of the scattering process. Indeed it is on the basis of this relatively good agreement that we have used the cross section in Robertson et al. (1997) to extend our recommended $0 \rightarrow 1$ ICS from an energy of ~1.5 eV down to threshold. This extension in our recommended ICS to lower energies for the $0 \rightarrow 1$ process is illustrated in Fig. 2, as is the calculated ICS from Robertson et al. (1997). Note that as Robertson et al. (1997) provided only tabulated values of their ICS for the $0 \rightarrow 1$ excitation, we do not also plot their data in Fig. 1a. What we have plotted in Fig. 1a are the theoretical results from two earlier calculations: Dubé and Herzenberg (1979)—small dots and Chen (1964a, b, c)—small dashes. While neither of these two calculations are as accurate as those of Sun et al. (1995) and Robertson et al. (1997), we have plotted their results in Fig. 1a because their cross sections have been widely used in modelling studies by the geophysical communities (Stubbe and Varnum, 1972; Newton et al., 1974; Aladjev and Kirillov, 1995; references therein). The ICSs reported by both Dubé and Herzenberg (1979) and Chen (1964b, c) are not in particularly good agreement with our more recent and experimentally based recommended set (see Fig. 1a).

Our improved array of cross sections means that the excitation rates for N_2 vibrational excitation reported by Newton et al. (1974) [who used the ICS of Chen (1964b, c)] and those from Stubbe and Varnum (1972) [who also used Chen (1964b, c), older swarm data from Engelhardt et al. (1964), and the superceded data from Schulz (1964)] may not be sufficiently accurate for some studies. The implicit relationships between the ICSs and the electron energy transfer rates in N_2 are given in the next section of this paper. A more recent study of the energy loss rate of electrons in N_2 has been reported by Pavlov (1998). This work used the $0 \rightarrow 1$ vibrational excitation cross section from Robertson et al. (1997) which, as discussed above, should be accurate, the $0 \rightarrow 1$ cross section of Engelhardt et al. (1964) for impact energy below 1.7 eV, momentum transfer values for $0 \rightarrow 2$ from Robertson et al. (1997), selected (but scaled—as recommended by Haddad, 1984) ICS values from Schulz (1976) for the $0 \rightarrow 3, 4, \ldots$ excitation processes and the remaining cross sections from Chen (1964b) and Dubé and Herzenberg (1979). The cross sections from Schulz (1976) and Haddad (1984) have also been superceded (Brunger and Buckman, 2002) so that the rates reported by Pavlov (1998) may similarly not be sufficiently accurate for future studies. Perhaps the best way to illustrate the differences between the present $0 \rightarrow v'$ recommended cross sections and those used in the earlier modelling studies (Stubbe and Varnum, 1972; Newton et al., 1974; Pavlov, 1998), is to consider Fig. 2 in more detail. While Fig. 2 specifically deals with the $0 \rightarrow 1$ excitation quantum, the observations we make in relation to it are equally applicable to excitation to the higher vibrational quanta ($0 \rightarrow 2, 3 \ldots$). It is clear from Fig. 2 that, with the exception of the calculation of Robertson et al. (1997), the present recommended $0 \rightarrow 1$ cross section differs significantly (note the vertical-axis log-scale) from those used in the previous modelling studies. This is apparent in terms of both the magnitude and energy dependence of the ICS. In particular we highlight the major differences between the present ICS and that from Schulz (1976), discrepancies which are usually exacerbated when the data of Schulz (1976) is scaled to a $0 \rightarrow 1$ cross section of 4.45×10^{-16} cm^2 at 2 eV, as was done by Pavlov (1998) for $0 \rightarrow 3, 4, \ldots$.

If the cross sections we use in this study are thought of as constituting a matrix array, then an issue arises as to how to determine the diagonal ($Q_{00}, Q_{11}, Q_{22}, Q_{33}, \ldots$) and remaining off-diagonal ($Q_{12}, Q_{13}, Q_{23}, Q_{24}, \ldots$) excitation cross sections needed to obtain values for electron-impact processes between all pairs of ground state vibrational levels in N_2. Note that the corresponding de-excitation cross sections ($Q_{21}, Q_{31}, Q_{32}, Q_{42}, \ldots$) can always be obtained by detailed balance. For the 0–0 transition, the recommended values are those from Buckman et al. (2003). However, there exists no experimental data for any of the other excitation or de-

Q_{00}	Q_{01}	Q_{02}	Q_{03}	Q_{04}	Q_{05}	Q_{06}	Q_{07}	Q_{08}	Q_{09}	Q_{010}
Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	—	—	—	—	—	—
Q_{20}	Q_{21}	Q_{22}	Q_{23}	Q_{24}	Q_{25}	—	—	—	—	—
Q_{30}	Q_{31}	Q_{32}	Q_{33}	Q_{34}	Q_{35}	Q_{36}	—	—	—	—
Q_{40}	Q_{41}	Q_{42}	Q_{43}	—	—	—	—	—	—	—
Q_{50}	—	Q_{52}	Q_{53}	—	—	—	—	—	—	—
Q_{60}	—	—	Q_{63}	—	—	—	—	—	—	—
Q_{70}	—	—	—	—	—	—	—	—	—	—
Q_{80}	—	—	—	—	—	—	—	—	—	—
Q_{90}	—	—	—	—	—	—	—	—	—	—
Q_{100}	—	—	—	—	—	—	—	—	—	—

Fig. 3. Data array of all the recommended ICSs used in the present study.

excitation processes and nor are any likely to become available in the near future. A theory of the calibre of Sun et al. (1995) and Robertson et al. (1997) offers real promise but, as yet, has not been applied to the transitions between higher vibrational levels. As a consequence we have little choice but to obtain estimates for these transitions between higher vibrational levels from whatever data are available. In this context, it is clear from Fig. 1a that the ICS results of Dubé and Herzenberg (1979) are in better agreement with our experimentally validated recommended data set than are those of Chen (1964b, c). By inspection of the data, one notes that if the $0 \rightarrow 1$ and $0 \rightarrow 2$ ICSs of Dubé and Herzenberg (1979) are reduced by a factor $\sim$1.2, reasonable overall agreement between their predicted values and our recommended data is achieved. Hence in order to obtain estimates for cross sections for transitions between higher vibrational levels, we expanded our recommended array of vibrational excitation cross sections by taking the data in Figs. 6–8 of Dubé and Herzenberg (1979) and reducing all of them by a factor of 1.2. While this is hardly an ideal solution it is certainly the best available option at this time.

A summary of our vibrational cross section data array, which contains our recommended ICS values for vibrational excitation and de-excitation in the ground electronic-state of N_2 (see Fig. 1), is given in Fig. 3. Although the array is incomplete it represents the most accurate cross section values available at this time and it is certainly more extensive and appears to be more complete than those used previously in the type of modelling studies we are considering here. The tables of our vibrational cross section data array are available electronically from the authors on request.

3. Details of the calculations

The cross sections used in previous work have been obtained from the publications and digitised from figures where tables were not given. Energy transfer calculations were performed with both the previous and present cross sections. The accuracy of this procedure is demonstrated in Fig. 4.

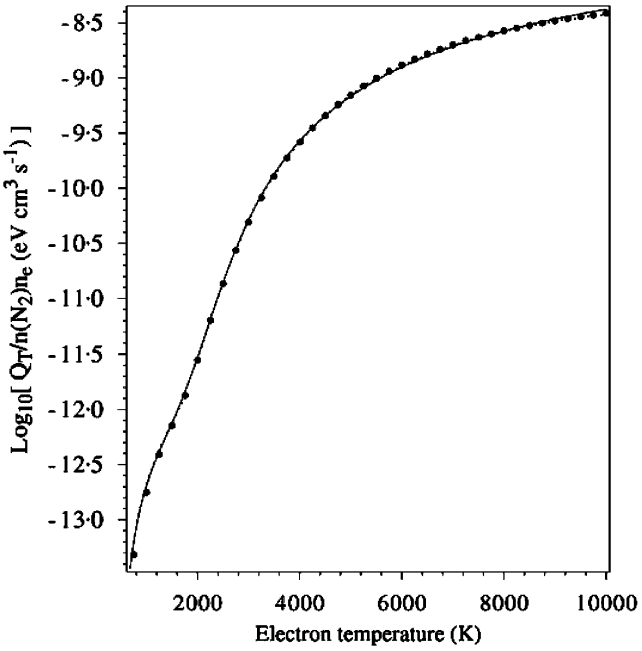

Fig. 4. $\mathrm{Log}_{10} Q_T/n_e n_k$ versus electron temperature from the Stubbe and Varnum (1972) formulation. (———) Present calculation using Stubbe and Varnum's analytic approximation, (- - -) digitised from Stubbe and Varnum's Fig. 2, and (●) present calculation using Stubbe and Varnum's cross section data base and Eq. (1) of their paper.

The dots in Fig. 4 show the values of the total energy transfer rate Q_T evaluated as a function of electron temperature T_e using Eq. (1) of Stubbe and Varnum (1972) and the electron impact cross sections that they specify (Schulz, 1964; Engelhardt et al., 1964; Chen, 1964a, b, c). This equation is given (Stubbe and Varnum, 1972) as

$$Q_T = \frac{n_e n_k}{\sqrt{\pi m_e}} \frac{1}{Z} \left(\frac{2}{kT_e}\right)^{3/2} \sum_{i=0}^{m-1} \sum_{j=i+1}^{m} g_i E_{ji} \times \exp\left(-\frac{E_i}{kT_n}\right) \left\{\exp\left[-\frac{E_{ji}}{kT_e T_n}(T_e - T_n)\right] - 1\right\} \times \int_{E_{ji}}^{\infty} E' \sigma_k(i \rightarrow j, E') \exp\left(-\frac{E'}{kT_e}\right) \mathrm{d}E', \quad (1)$$

where

$$Z = \sum_{j=0}^{\infty} g_j \exp(-E_j/kT_n),$$

n_e is the electron number density, n_k is the number density of neutral species k, m_e is the electron mass, T_e is the electron temperature, T_n is the neutral temperature, E_i is the energy of state i of the neutral particle, $E_{ji} = E_j - E_i, m$ is the number of energy states of the neutral particle, k is Boltzmann's constant, g_j is the statistical weight of state j, and $\sigma_k(i \rightarrow j, E)$ is the cross section for excitation by electrons of neutral species k from state i to j as a function of electron energy E. This equation includes both excitation and deexcitation.

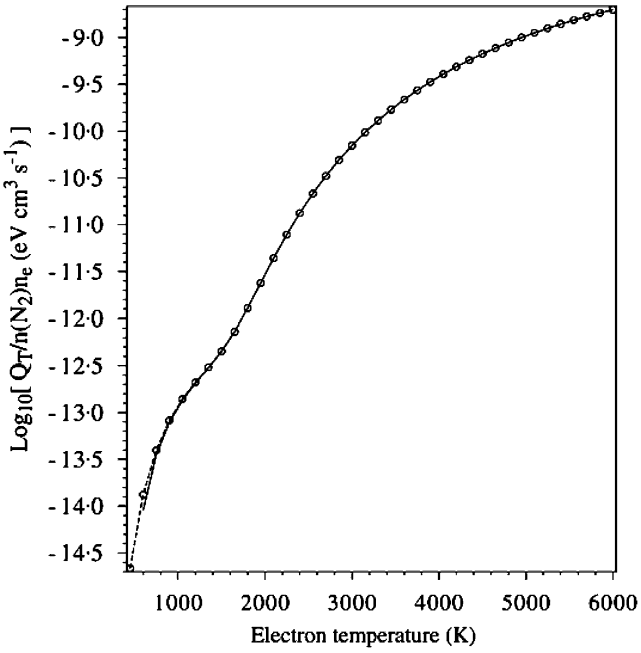

Fig. 5. $\mathrm{Log}_{10}Q_T/n_e n_k$ versus electron temperature. (——) Present calculation using the Stubbe and Varnum formulation with our recommended cross section array; (○○○○) present calculation using the Newton et al. formulation with our recommended cross section array; (- - - - - -) present calculation using the Pavlov formulation with our recommended cross section array.

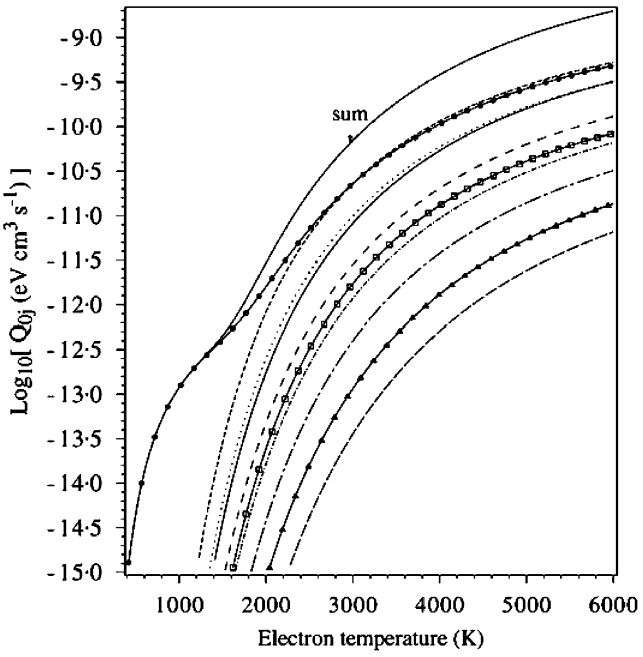

Fig. 6. Subset of the present electron energy transfer rates versus electron temperature, as calculated using the formulation of Pavlov: (• • •) $0\rightarrow1$; (- - - - -) $0\rightarrow2$; (——) $0\rightarrow3$; (- - -) $0\rightarrow4$; (— —) $0\rightarrow5$; (□—□) $0\rightarrow6$; (– – –) $0\rightarrow7$; (——-) $0\rightarrow8$; (— • — • —•) $0\rightarrow9$; (——) $0\rightarrow10$. In all these cases our recommended cross section array was employed.

The solid line in Fig. 4 denotes a present calculation using an analytic approximation, given by Eq. (9) of Stubbe and Varnum, to Q_T. The dashed line shows the result of the calculation by Stubbe and Varnum, digitised from Fig. 2 of their paper. The agreement between these three cases gives confidence in the current calculations and particularly in the adequacy of the digitisation of cross sections from published graphs.

The calculation of Eq. (1) of Stubbe and Varnum is repeated with their specified cross sections replaced with the present recommended set, giving the result shown by the solid line in Fig. 5. The calculation is also made using two other formulations (Pavlov, 1998; Newton et al., 1974) but inserting the recommended cross-section set. Pavlov gives a formula (his Eq. (4)) for an electron cooling rate Q_{0v} (per molecule) for the transition $0\rightarrow v$. This formula is

$$Q_{0v} = E_v\{8kT_e(\pi m_e)^{-1}\}^{0.5}\int_0^\infty \sigma_{0v}(x)x\exp(-x)\,dx, \qquad (2)$$

where E_v is the energy of vibrational level v, E is the energy of the electron and $x = E(kT_e)^{-1}$. Pavlov states that the sum of Q_{0v} for $v = 1,2,\ldots,10$, is equivalent to Stubbe and Varnum's transfer rate (at $T_n = 500$ K) and this is found to be the case in our calculation, shown by the dashed line in Fig. 5. The results are distinguishable from each other only at low electron temperatures. Newton et al. (1974) give formulae (their equations (A1) and (A2)) to predict the reaction rates I_{ij} of N_2 with electrons. The most important of these formulae is denoted (Newton et al., 1974) as

$$I_{ij} = 1.26574\times10^{-6}\pi\left(\frac{2}{\pi kT_e}\right)^{3/2}\frac{1}{(m_e)^{1/2}}\cdot\int_0^\infty E\sigma_{ij}(E)\exp(-E/kT_e)\,dE. \qquad (3)$$

Note that Newton et al. used de-excitation cross sections and detailed balance to obtain the low-energy tails of the excitation cross sections.

Assuming that Eq. (3) can be converted to an energy transfer rate by multiplying by the gain or loss of energy in the transition in N_2, the present calculation gives the values shown by the circles in Fig. 5. The agreement between the 3 methods (all using our recommended set of cross sections) suggests that the three formulations are being correctly interpreted and implemented.

4. Results and discussion

Electron energy transfer rates for the transitions $0\rightarrow1$, $0\rightarrow2,\ldots,0\rightarrow10$, calculated using Eq. (2) with the recommended cross sections, are shown in Fig. 6. Also shown is the transfer rate summed for all of the vibrational transitions. It is clear from this figure that for $T_e \leqslant 1500$ K Q_{01} dominates. For electron temperatures greater than 1500 K, however, higher order excitation processes, particularly Q_{02},

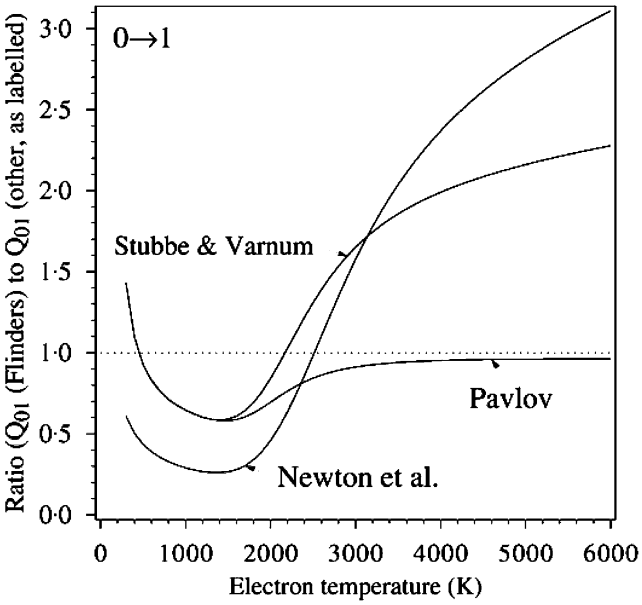

Fig. 7. Ratio of the rate determined using the recommended cross sections to that using those of previous workers, as labelled, for the $0 \rightarrow 1$ transition.

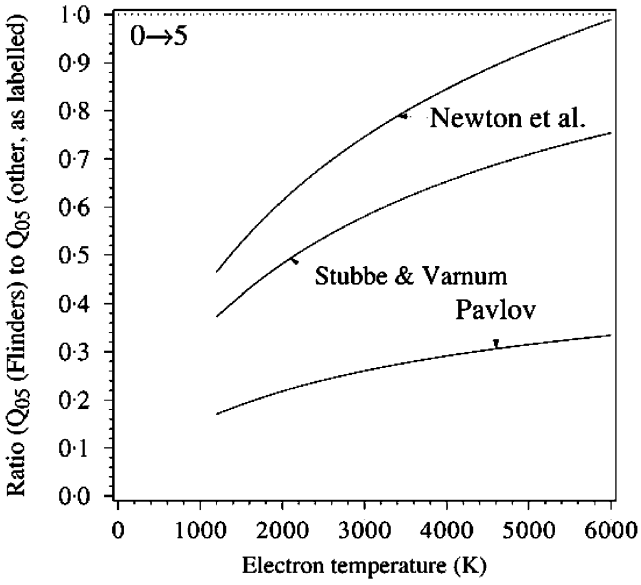

Fig. 9. Ratio of the rate determined using the recommended cross sections to that using those of previous workers, as labelled, for the $0 \rightarrow 5$ transition.

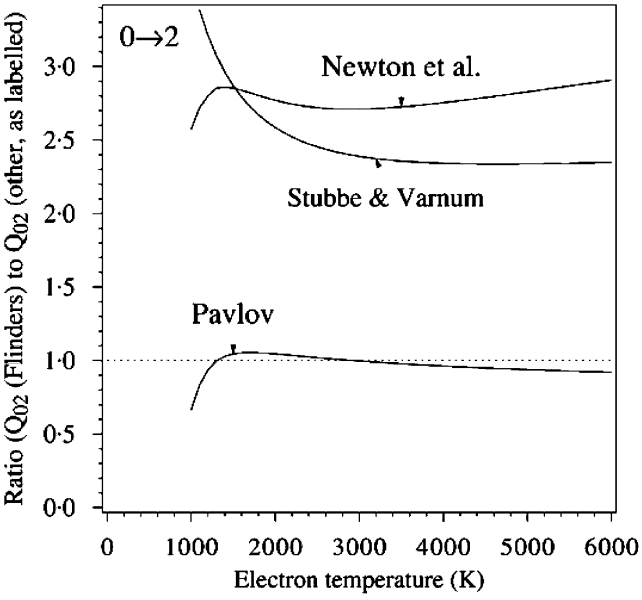

Fig. 8. Ratio of the rate determined using the recommended cross sections to that using those of previous workers, as labelled, for the $0 \rightarrow 2$ transition.

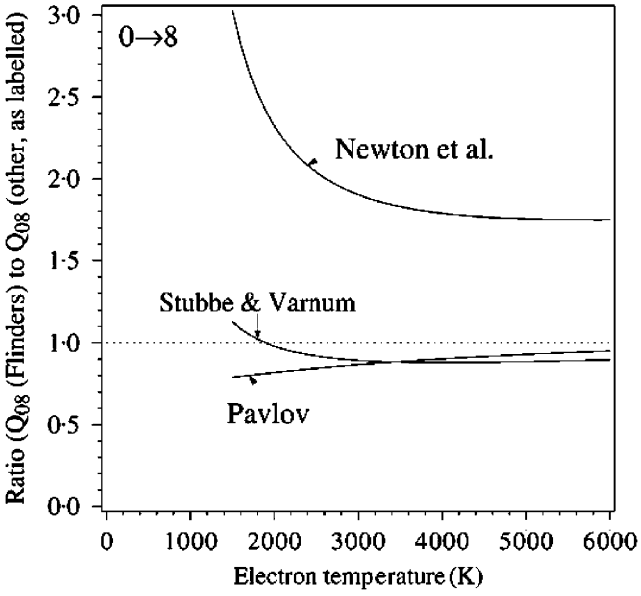

Fig. 10. Ratio of the rate determined using the recommended cross sections to that using those of previous workers, as labelled, for the $0 \rightarrow 8$ transition.

also begin to make important contributions to the overall electron energy transfer rate in N_2.

To illustrate the importance of the cross sections used in these calculations, we compare in Figs. 7–10 the ratio of the present electron energy transfer rates to those of the previous workers (Stubbe and Varnum, 1972; Newton et al., 1974; Pavlov, 1998) for a subset of the relevant vibrational processes, again as a function of T_e. It is clear from Figs. 7–10 that there are significant discrepancies between the present calculation for Q and those from the earlier studies. These discrepancies are a direct result of the different cross section data bases used in the respective calculations. Thus this work provides a transparent link between behaviour at the nanoscale (cross sections) to the macroscopic behaviour of the ionosphere (through Q) as a whole.

Considering Fig. 7 in more detail we note that the current Maxwell-averaged rate for the $0 \rightarrow 1$ transition is

Table 1
Coefficients A_{iv} for the approximation to $\log_{10}Q_{0v}$ given in Eq. (4), plus the maximum fractional discrepancy δ_v, for $v = 1, 2, \ldots, 10$, given in the sequence shown at the top

$0 \to v$	A_{0v}	A_{1v}	A_{2v}
δ_v	A_{3v}	A_{4v}	A_{5v}
	A_{6v}	A_{7v}	A_{8v}
$0 \to 1$	-20.53338	2.232010×10^{-2}	-2.788177×10^{-5}
0.054	1.928050×10^{-8}	$-7.718809 \times 10^{-12}$	1.854619×10^{-15}
	$-2.647034 \times 10^{-19}$	2.072139×10^{-23}	$-6.859584 \times 10^{-28}$
$0 \to 2$	-34.26962	3.381645×10^{-2}	-2.377044×10^{-5}
0.022	1.019910×10^{-8}	$-2.775980 \times 10^{-12}$	4.793986×10^{-16}
	$-5.059731 \times 10^{-20}$	2.951543×10^{-24}	$-7.197135 \times 10^{-29}$
$0 \to 3$	-35.48243	3.222374×10^{-2}	-2.061168×10^{-5}
0.009	7.963622×10^{-9}	$-1.906802 \times 10^{-12}$	2.767044×10^{-16}
	$-2.228996 \times 10^{-20}$	7.646298×10^{-25}	
$0 \to 4$	-27.15243	1.058009×10^{-2}	3.925376×10^{-6}
0.044	-7.431033×10^{-9}	3.917439×10^{-12}	$-1.085827 \times 10^{-15}$
	1.706720×10^{-19}	$-1.440022 \times 10^{-23}$	5.076359×10^{-28}
$0 \to 5$	-20.53292	-8.916443×10^{-3}	2.452598×10^{-5}
0.036	-1.913251×10^{-8}	7.907546×10^{-12}	$-1.929100 \times 10^{-15}$
	2.790345×10^{-19}	$-2.216591 \times 10^{-23}$	7.458488×10^{-28}
$0 \to 6$	-37.82918	3.307371×10^{-2}	-2.012980×10^{-5}
0.005	7.406585×10^{-9}	$-1.695386 \times 10^{-12}$	2.362236×10^{-16}
	$-1.834737 \times 10^{-20}$	6.091531×10^{-25}	
$0 \to 7$	-36.86810	3.100290×10^{-2}	-1.852920×10^{-5}
0.007	6.722730×10^{-9}	$-1.520620 \times 10^{-12}$	2.096600×10^{-16}
	$-1.613160 \times 10^{-20}$	5.310360×10^{-25}	
$0 \to 8$	-34.52000	2.329070×10^{-2}	-1.112690×10^{-5}
0.009	3.094860×10^{-9}	$-5.032050 \times 10^{-13}$	4.435710×10^{-17}
	$-1.637750 \times 10^{-21}$		
$0 \to 9$	-34.44360	2.160660×10^{-2}	-9.804670×10^{-6}
0.004	2.608400×10^{-9}	$-4.077370 \times 10^{-13}$	3.470410×10^{-17}
	$-1.241880 \times 10^{-21}$		
$0 \to 10$	-31.65800	1.519400×10^{-2}	-5.250400×10^{-6}
0.007	9.974600×10^{-10}	$-9.909600 \times 10^{-14}$	4.025500×10^{-18}

substantially smaller than the results of Pavlov for $T_e < 3000$ K. In practice this means using the Pavlov method and cross sections may result in overestimating the effect on the ionosphere of direct excitation of the $0 \to 1$ vibrational level of N_2 in the lower half of the ionosphere. The $0 \to 1$ energy transfer rates of both Newton et al. and Stubbe and Varnum are similar in form, for $T_e > 3000$ K, and both are substantially smaller than the corresponding present results. For $T_e < 3000$ K, we note that the $0 \to 1$ rates of Stubbe and Varnum and Newton et al. are also generally in poor agreement with the present results.

In contrast to the comparison for $0 \to 1$, Fig. 8 shows that for the $0 \to 2$ N_2 transition the calculated Q of Pavlov is in good agreement with the present for all electron temperatures $T_e \geqslant 1200$ K. This agreement confirms the validity of Pavlov's work for the N_2 $0 \to 2$ excitation process at $T_e \geqslant 1200$ K. Fig. 8 shows that the calculated Q of both Newton et al. and Stubbe and Varnum significantly underestimate the transfer rates for $0 \to 2$ for all T_e.

The results in Fig. 9, for the $0 \to 5$ transition, show that the previous studies significantly overestimate the magnitude of Q at all T_e. The consequence of this comparison is that having used the previously reported Q-value for the $0 \to 5$ excitation may have resulted in overestimating the associated energy loss.

Finally in Fig. 10 we consider the energy loss associated with direct excitation of the $0 \to 8$ transition in N_2. We see from this figure that the Q_{08} of Newton et al. underestimates the magnitude of this energy transfer rate. This again reflects the inadequacy of the cross section data base employed by Newton et al. in their studies. On the other hand, however, the result of Stubbe and Varnum for Q_{08} is

in good agreement with the present for most T_e, while that reported by Pavlov agrees with our work to within 10% for $T_e > 3500$ K.

To make the new cooling rates easily accessible, coefficients are presented in Table 1 to allow approximate values for $\log_{10} Q_{0v}$ to be calculated using the equation

$$\log_{10} Q_{0v} = A_{0v} + \sum_{i=1}^{n} A_{iv} T_e^i. \quad (4)$$

In this table, δ_{0v} is the maximum of the fractional difference between the approximation and the calculated value over the range of values plotted in Fig. 6 for Q_{0v}.

5. Conclusions

New electron-energy transfer rates Q, as a function of electron temperature, for vibrational excitation of N_2 have been calculated using an improved array of excitation and deexcitation cross sections. A comparison of the present Q against those reported from earlier calculations indicated significant differences, reflecting the sensitivity of the transfer rates to the respective cross section data employed in the various studies. Given these limitations in Q from the earlier work, we can only conclude that previous calculations of the electron cooling rate are also likely to be inaccurate. Results from this study highlight the importance of employing the most accurate excitation and deexcitation cross sections in order to reliably model macroscopic electron-energy transfer rates in the ionosphere.

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