On the role of electron-driven processes in planetary and cometary atmospheres

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Abstract.
Electron impact excitation plays an important role in the upper atmospheres of planets and their satellites and also in the comae of comets, in both energy transfer and chemistry. Emissions produced by electron impact excitation are vital in remote sensing of these atmospheres. Modeling of the processes and emissions requires knowledge of both the plasma parameters and accurate cross sections or rates for the electron impact processes. This modeling is illustrated by four examples: electron cooling by CO\textsubscript{2} in the atmosphere of Mars, infrared emissions from CO in the atmosphere of Venus, fourth positive emissions from CO in the coma of comet Hale-Bopp and emissions due to excitation of the higher-energy states of molecular oxygen in the atmosphere of Europa. In each case the assembly of the plasma parameters and accurate electron impact cross sections is described, together with the modeling techniques applied and the significant results. These include a possible explanation for low temperatures in part of the upper atmosphere of Mars, evidence that the abundance of CO in comet Hale Bopp has been overestimated and identification of a useful parameter for remote sensing of Europa.

1. Introduction
Sunlight produces photoionization and hence a low-density plasma in upper planetary atmospheres and in the comae around comets. Electrons in the solar wind, often accelerated in magnetospheric processes, produce localised ionisation. In both cases a flux of secondary electrons is produced, leading to further ionization, plus dissociation and excitation, before the electrons recombine with the ions. The excited atoms and molecules can release energy in radiative decay (as aurora, dayglow or nightglow) or by taking part in chemical reactions. Hence plasma processes drive energy transfer and the composition of minor constituents in cometary and planetary atmospheres.

In order to model these processes, it is necessary to know the composition and temperature of the neutral species, the electron impact cross sections for the ionization, dissociation, and excitation processes, recombination rates and the plasma conditions. The latter are usually characterised either by the electron temperature and density of a Maxwell-Boltzmann distribution, or by a differential electron flux spectrum.

The simplest of such calculations is of “electron cooling”, i.e. energy transfer from a Maxwell-Boltzmann distribution of ionospheric electrons to neutral species by electron impact excitation.
of the neutrals [1]. If there are multiple paths for excitation or deexcitation, such as radiative cascades through different excited states, collisional processes and chemical reactions, then a “statistical equilibrium” calculation [2] is required.

2. Methods
Using the formulation of Pavlov [3] the electron energy transfer rate \( Q_{0\nu} \) per molecule is:

\[
Q_{0\nu} = E_{\nu} \left(8kT_e(\pi m_e)^{-1}\right)^{0.5} \int_0^\infty \sigma_{0\nu}(x) \exp(-x)dx,
\]

where \( x = E(kT_e)^{-1} \), \( E \) is the electron energy, \( E_{\nu} \) is the energy of vibrational level \( \nu, m_e \) is the electron mass, \( T_e \) is the electron temperature, \( k \) is Boltzmann’s constant, and \( \sigma_{0\nu} \) is the integral cross section (ICS) for excitation from ground(0) to vibrational level \( \nu \). If excitation leads to only one possible radiative transition, the emission rate per molecule is \( Q_{0\nu}/E_{\nu} \). The electron cooling rate for a unit volume due to a particular molecule is determined by multiplying \( Q_{0\nu} \) by the electron density \( n_e \) and the density of the molecule.

The statistical-equilibrium calculation assumes that the gain and loss rates are equal for each excited species, producing equilibrium populations that are determined by the processes involved and thus are generally not in thermal equilibrium [4]. Continuity equations are written for each species and then the whole set is solved iteratively [2]. An example that includes radiative cascade among excited electronic states of a molecule is represented by the statistical-equilibrium equation [5]:

\[
k_{\nu'0}^{\alpha} n_0^{\beta} + \sum_{\beta} \sum_i A_{i\nu'}^{\alpha\beta} n_i^{\beta} = \left\{ \sum_{\gamma} \sum_{\nu} A_{\nu\nu'}^{\alpha\gamma} Q_{\nu'}^{\alpha} + Q_{\nu'}^{\beta} \right\} n_0^{\nu'},
\]

where \( A_{i\nu'}^{\alpha\beta} \) is the Einstein spontaneous transition probability \( (s^{-1}) \) for the radiative transition from the \( i \)th vibrational level of electronic state \( \alpha \) to the \( j \)th vibrational level of electronic state \( \beta \); \( n_0^{\alpha} \) is the number density of the \( k \)th vibrational level of state \( \alpha \); and \( Q_{\nu'}^{\alpha} \) is the quenching rate \( (s^{-1}) \) of the \( i \)th level of state \( \alpha \). \( k_{\nu'}^{\alpha} \) is the electron impact excitation rate \( (s^{-1}) \) of the \( i \)th level of state \( \alpha \) from the \( j \)th vibrational level of the ground electronic state. The volume emission rate (VER) from a unit volume due to a particular transition is \( A_{i\nu'}^{\alpha\beta} n_i^{\beta} \) photons s\(^{-1}\).

Photo- and auroral electrons produce secondary electron distributions which are not Maxwell-Boltzmann and so need to be specified as a function of \( E \). For ionospheric calculations the most common approach is to specify a differential flux distribution \( F(E) \), being the number of electrons with a particular energy crossing an area per unit time. The excitation rate \( k_{\nu'0}^{\alpha} \) is then given by:

\[
k_{\nu'0}^{\alpha} = \int_0^\infty \sigma_{\nu'0}^{\alpha}(E)F(E)dE,
\]

where \( \sigma_{\nu'0}^{\alpha} \) is the rotationally averaged electron impact excitation cross section from the ground state to the \( \nu' \) level of electronic state \( \alpha \). The higher-energy electrons lose energy and end up as a population of “thermal” electrons in a Maxwell-Boltzmann distribution. They can be included by converting the speed distribution of thermal electrons to a differential flux spectrum, using \( F(E) = n_m(E)\nu = n_m(E)\sqrt{2E/m_e} \), where \( n_m(E) \) is the number of electrons with speed \( \nu \).

3. Applications
Calculations of electron cooling by CO\(_2\) and CO in the atmospheres of Mars and Venus are described below. For CO more detailed calculations using statistical equilibrium were made to include stepwise vibrational transitions, quenching and cascade from excited electronic states. Applications of the statistical-equilibrium method are then described for electron-driven processes in comet Hale-Bopp and in the atmosphere of the Galilean moon Europa.
3.1. Electron cooling by CO$_2$ in the atmosphere of Mars

As the neutral atmosphere of Mars is dominated by CO$_2$, Morrison and Greene [6] calculated electron energy transfer rates ($Q_{0\nu}$) due to excitation of CO$_2$. A more accurate calculation [7] of these rates became possible due to new experimental measurements [8, 9, 10] and theoretical [11] cross sections for electron impact vibrational excitation of CO$_2$. These new cross sections were combined with others from a compilation [12] of earlier values [13, 14, 15] to produce the set of cross sections [7] shown by solid lines in Fig. 1. The cross sections [16, 17] used by Morrison and Greene are shown in the two cases where they reported transfer rates for individual modes. As expected and as shown in Fig. 2 the larger cross sections used by Morrison and Greene produced larger transfer rates for electron temperatures above \(\sim 1000\) K, but the larger values of the updated cross sections at very low energies produced larger transfer rates at lower temperatures.

The plasma conditions in the upper atmosphere of Mars are shown by electron densities in Fig. 3 and electron temperatures in Fig. 4. Due to the limited height range of the measured electron temperatures, a calculated profile by Choi et al. [18] was used for $T_e$ in equation (1) to calculate energy transfer rates. The electron densities in the atmosphere of Mars were assembled from in situ measurements by the Viking I lander [19] and maxima and minima of profiles measured remotely by the Mars Global Surveyor (MGS) satellite [20], to give the “Fit to measurements” [7] shown in Fig. 3. These were combined with CO$_2$ densities [21] to calculate the cooling rates due to CO$_2$ as a function of altitude for Mars, as shown in Fig. 5.

It can be seen in Fig. 5 that calculated cooling rates with the more recent cross sections are...
considerably larger than those calculated with the cross sections used by Morrison and Greene [6] at altitudes below 140 km. That difference when using the updated cross sections is larger than the difference due to day-to-day variability in electron density, shown by the maximum and minimum values in Fig. 5. These higher values of electron cooling by CO$_2$, which imply higher rates of infrared radiation going to space, may explain the very low neutral temperatures observed below 140 km in altitude by both the “SPICAM” (Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars) spectrometer on Mars Express [22] and Viking I, shown in Fig. 4, which are much lower than the temperatures calculated by Chen et al. [23].

### 3.2. Infrared emissions from CO in the atmosphere of Venus

A study of electron cooling by CO in the atmospheres of Mars and Venus [27] found that rates by CO were greater than by CO$_2$ at upper altitudes. This motivated new absolute integral cross section (ICS) measurements [24] for electron impact excitation of the ground state vibrational levels of CO, as plotted in Fig. 6. Also plotted are previous experimental measurements [25] which were put on an absolute scale using the value at 1.91 eV from an earlier study [26]. The main differences between the two sets of measurements are the larger cross sections for the (0→1) excitation around 2 eV and below 0.6 eV in the most recent measurements. The new cross sections [24] were applied in a study [28] of electron-driven infrared emissions from CO in the upper atmospheres of Mars and Venus.

While for Venus a calculation of a photoelectron flux spectrum was available [29], it was necessary to assemble an auroral spectrum for Venus, based on measurements by Spenner et al [30]. These measurements, consisting of flux spectra at various altitudes, were subject to considerable time variation, which masked the variation with altitude. However, we found that taking averages of spectra for 2 lower heights and for 4 upper heights gave base spectra at 168 km and 600 km (as plotted in Fig. 7) that were similar in shape to each other. To interpolate

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![Figure 3](image1.png)  
**Figure 3.** Martian electron densities as a function of altitude: (○) in situ measurements by the Viking I lander [19], (—····) maximum and (······) minimum of values measured by the MGS [20] and (——) the fit to all these measurements by Campbell et al. [7].

![Figure 4](image2.png)  
**Figure 4.** Martian electron temperatures: (○) measured by Viking I [19] and (—····) calculated by Choi et al. [18]. Neutral temperatures: measured by (⊙) Viking I [21] and (——) Mars Express [22], and (······) calculated by Chen et al. [23].
Figure 5. Electron cooling rates as a function of altitude in the atmosphere of Mars, calculated with (— — —) the cross sections used by Morrison and Greene [6] and with the new cross sections for (———) the fit to electron density measurements, and the (- - - -) minimum and (———) maximum densities observed by the MGS [20].

Figure 6. Measurements of ICSs for electron impact of vibrational levels of CO by (——) Allan [24], (— — —) Poparič et al. [25] and (□) Gibson et al. [26]. (- - - -) Extrapolation at low energies for \( \nu=1 \).

or extrapolate from these two “base” spectra to any other height, we assumed that the rate of flux reduction at any height at each energy was proportional to the sum of the densities of O, CO and \( \text{N}_2 \) at that height. Examples of spectra produced by this procedure are shown for 150 km and 139 km in Fig. 7. The maximum rate of flux loss is predicted at 145 km, which is close to the value of 139 km found by Gérard et al. [29], providing some validation for this procedure. As the spectra of Spenner [30] had no values below 8 eV, the shape of the low-energy part of the spectrum was taken from the calculated spectrum by Gérard et al. [29] (shown in Fig. 7) and spliced to the 168-km “base” spectrum as shown in Fig. 7, by scaling it to match its slope in the range 8–10 eV to that in the measured spectra. For other heights the added low-energy section is scaled to be proportional to the loss rate in the higher-energy part of the spectrum.

Calculated electron-driven VERs for daytime in the atmosphere of Venus for the \((2^1 \rightarrow 1)\) and \((3^2 \rightarrow 2)\) transitions in the ground electronic state of CO are plotted in Fig. 8. The “Gronoff day” cases apply equation (1) to thermal electrons with parameters as specified by Gronoff et al. [32]. Comparison with previous calculations by Crovisier et al. [31] for emissions produced by fluorescence and photolysis show that electron-driven \((3^2 \rightarrow 2)\) emissions dominate above 200 km. Results for a “full model”, being a statistical-equilibrium calculation incorporating quenching, cascade from excited states, step-wise transitions in the ground state and a flux spectrum including auroral input, are shown by symbols. The agreement with the thermal-equilibrium model for \((3^2 \rightarrow 2)\) emissions at higher altitudes (where auroral input is small) confirms the method of converting the Maxwell-Boltzmann distribution to a flux distribution. The higher values of \((2^1 \rightarrow 1)\) emissions in the full model are due to input to level \( \nu'=2 \) from the \((3^2 \rightarrow 2)\) transition.

Other interesting results shown in Fig. 8 are that auroral excitation dominates over that due
to thermal electrons below about 180 km, particularly using the auroral spectrum of Gérard et al., and photoelectron-driven emissions dominate over fluorescence plus photolysis at 250 km.

3.3. Fourth positive emissions from comet Hale-Bopp

McPhate et al. [33] measured a far ultraviolet spectrum from comet Hale-Bopp, identified particular lines as CO fourth positive emissions \(A^1\Pi \rightarrow X^1\Sigma^+\) and, assuming these were due to sunlight fluorescence, calculated the abundance of CO in the comet. No contribution to the emissions from electron-impact excitation was included. The determination [34] of electron impact cross sections for excitation of levels 0–7 of the \(A^1\Pi\) state of CO allowed a calculation [35] of the electron-impact component of the fourth positive emissions.

The plasma environment for the comet was based on a calculated flux spectrum for another comet [36], multiplied by 7.63 to scale the electron density implied by this flux (26.2 electrons \(cm^{-3}\)) to that of 200 cm\(^{-3}\) calculated for 160,000 km from Hale-Bopp [37]. This calculated flux spectrum (shown in Fig. 9) was applied in a statistical-equilibrium calculation of excitation of the \(^5S^0\) state of O atoms and vibrational levels 0–7 of the \(A^1\Pi\) state of CO. The O I emission at 1356 Å is believed to be produced by electron impact [33].

Electron impact excitation cross sections from the ground state of O(\(2p^4\ 3P\)) were given by Laher and Gilmore [38] for O(\(4p\ 3P\)), while those for O(\(3s\ 5S^0\)), O(\(3p\ 3P\)) and O(\(3p^2\ 3P\)) are averages of values calculated by Zatsarinny and Tayal [39] and Barklem (preprint, P. S. Barklem, 2006, http://arxiv.org/abs/astro-ph/0609684v1). Using transition probabilities from the NIST data base [40], a statistical equilibrium calculation was applied to determine the VERs due to the transitions \(3s\ 5S^0 \rightarrow 2p^4\ 3P(0)\) and \(3s\ 5S^0 \rightarrow 2p^4\ 3P(1)\), giving the calculated brightness for the 1356 Å and 1358.5 Å lines plotted in Fig. 10. The calculated brightness at 1356 Å

**Figure 7.** Spectra of auroral electrons for Venus. Base spectra at (- - - -) 168 km and (-----) 600 km deduced from the profiles of Spenner et al. [30]. The shape at low energy of a (---) spectrum at 139 km of Gérard et al. [29] is spliced onto the (- - -) base spectrum at 168 km. Calculated spectra are shown for (----) 139 km and (· · · ·) 150 km.

**Figure 8.** Comparison of electron-driven CO (2→1) and (3→2) VERs to those of Crovisier et al. [31] for Venus. Calculations are labelled: “Gronoff day” for using equation (1), “Full” for statistical-equilibrium, “Gerard aur.” for the auroral spectrum of Gerard et al. [29] and “Gerard P.E.” for the photoelectron spectrum of Gerard et al.
compares fairly well with the measurement. While this is somewhat fortuitous considering the approximations involved, it shows that the model of the plasma environment in comet Hale-Bopp is physically plausible. The assumed flux was then scaled up by a factor of 1.17 to match the calculated O I emissions with the observations and applied in the calculation of the CO fourth positive emissions. It was found that electron impact produced 40% of the emissions and fluorescence 60%. This is illustrated in Fig. 11 for the subset of CO fourth positive lines selected by McPhate et al. [33], comparing their fit to the measurements (solid line) with the cumulative sum of the electron-driven and fluorescent emissions calculated by Campbell et al. [35].

![Figure 9.](image1.png) **Figure 9.** Calculated flux of photoelectrons as a function of energy in the coma of comet Hale-Bopp.

![Figure 10.](image2.png) **Figure 10.** Calculated brightness of O I emissions for (---) \(^5\)S\(^o\) \(\rightarrow\) \(^3\)P(0) and (-- --) \(^5\)S\(^o\) \(\rightarrow\) \(^3\)P(1) transitions, (---) their sum and (-----) the sum scaled to the (shading) observations.

![Figure 11.](image3.png) **Figure 11.** Brightness as a function of wavelength of CO fourth positive emissions for (-----) the fit to measurements made by McPhate et al. [33] and calculations by Campbell et al. [35] of (red shading) electron impact excitation and (green shading) fluorescence.

3.4. Excitation of molecular oxygen in the atmosphere of Europa
Europa, a Galilean moon of Jupiter, has a thin transitory atmosphere believed to be produced predominantly by sublimation and ion impact on its icy surface [44], with O\(_2\) the dominant
species below 150 km [45]. As new measurements [41] for electron impact excitation of the higher-energy states of $O_2$ had become available, a study [46] was made of such excitation in the atmosphere of Europa. The new measurements were for electron impact excitation of the Schumann-Runge (SR) continuum, longest band (LB) and second band (SB) of $O_2$. These ICSs are shown in Fig. 12 along with BE$_f$-scaled theoretical calculations [41] and earlier measurements [42, 43]. In the calculations the BE$_f$-scaled cross sections were used for the SR continuum and SB, but were adjusted upwards to fit the measurements for the LB.

The electron fluxes used for Europa were sums of 3 Maxwell-Boltzmann distributions, as illustrated in Fig. 13. As described by Saur et al. [47] and Hall et al. [44], electrons in the magnetosphere of Jupiter at the orbit of Europa can be modeled as the sum of two Maxwell-Boltzmann distributions with characteristic temperatures of 20 and 250 eV and densities of 38 and 2 electrons/cm$^3$ respectively. As only half of this flux impacts on the atmosphere (with the other half shielded by the planet) the quoted densities were halved in the conversion to an isotropic flux spectrum. In addition, ionisation of $O_2$ produces a distribution of secondary electrons in the atmosphere which is assumed to be isotropic and has a temperature of 0.5 eV [47]. The density of these secondary electrons is given by a fit [48] to experimental measurements of electron density. The fluxes deduced for the sum of these three distributions are plotted for various heights. The reduction in the low-energy distribution with increasing height is a result of the decreasing $O_2$ density with height, although the change in electron (i.e. $O^+_2$) density is much less than that of $O_2$, presumably due to ambipolar diffusion of $O^+_2$ and electrons upwards.

Most of the excitation of the SR continuum, LB and SB results in predissociation, generally including one excited O($^1D$) atom [49] which radiatively decays to produce a 630.0-nm photon.

Figure 12. ICSs for excitation of the SR continuum, LB and SB of $O_2$: (I) measurements [41], (____) BE$_f$-scaling calculations [41], (---) adjusted BE$_f$ and (- - -) previous values [42, 43].

Figure 13. Electron flux spectrum for Europa, at (---) 300 km, (· · · · · ·) 200 km, (- - - -) 100 km and (——) 10 km.
The other excitation processes (direct electron impact on O atoms and recombination of O$_2^+$) produce both O($^1D$) and O($^1S$) atoms and hence both 630.0-nm and, from O($^1S$)$\rightarrow$O($^1D$), 557.7-nm radiation. The results of a statistical-equilibrium calculation of these three excitation processes are shown in Fig. 14 as production and VER rates as a function of altitude. We find that 630.0-nm emissions due to excitation of the SR, LB and SB dominate below 90 km.

As the higher-energy states (SR, LB and SB) of O$_2$ can only be excited by the magnetospheric electrons (above $\sim$8 eV) and as they produce only 630-nm photos, the ratio of 630.0-nm to 557.7-nm radiation will be sensitive to the details of the different electron processes. This ratio is shown in Fig. 15, calculated both with and without the contribution from the O$_2$ excitation. The ratio is much larger when the contribution from O$_2$ excitation is included, thus it is a possible indicator for remote sensing of the plasma conditions within the atmosphere of Europa.

4. Conclusions
Examples of calculations of electron impact excitation have been presented, for electron cooling or prediction of emissions in the upper atmospheres of Mars, Venus and Europa and the coma of comet Hale-Bopp. In each case the calculations used recent measurements of accurate cross sections for electron impact excitation and the assembly from multiple sources of a model of the plasma environment. These studies produced significant results, such as a possible explanation for very low neutral temperatures in the atmosphere of Mars, predictions of infrared emissions from CO in the atmosphere of Venus, a reduction of 40% in the estimated abundance of CO in comet Hale-Bopp and identification of a possible indicator for remote sensing of electron parameters in the atmosphere of Europa.

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5. References

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