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Effective Energy Reception of the Electron Gas per Created Ion Electron Pair*

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Abstract. The effective energy reception of the electron gas per ionized neutral particle and per created photoelectron (PE) has been calculated from data of the Satellite AEROS and by use of the Multi Satellite and Incoherent Scatter (MSIS) neutral model. Our results show good agreement with the calculations of Nagy et al. (1969) and the model of Swartz and Nisbet (1972). The comparison with the results of Dalgarno et al. (1968) shows the importance of non-local energy loss of the PEs above 350 km. For a height of 400 km we calculated the portion of non-local photoelectrons to 30% and for 450 km to 50%. Finally, analytical model functions depending on height and Nisbet's density ratio have been approximated to the calculated energy reception.

Key words: Heating efficiency – Electron energy equation – Non-local heating – Photo-electron production – AEROS – Temperature gradient – Non-local photo-electrons – MSIS – Heat gain – Heat loss.

1. Introduction

The aeronomy satellite AEROS with its extensive measurement program meets the ideal requirements for a variety of investigations of the heat budget of the electron gas in the ionosphere. Three terms determine the heat (resp. energy) of the electron gas in the stationary case.

- The heat gain P_g/eV m^{-3} s^{-1} by collisions with the hot PEs, which are created by the ionization of the neutral particles by the solar radiation.
- The heat loss P_l/eV m^{-3} s^{-1} by collisions with the cold neutral particles and ions.
- The heat conduction P_c/eV m^{-3} s^{-1} in the electron gas.

As the electrons move along the magnetic field lines driven by the neutral winds, we have also to consider the amount of energy transported by directed move-

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* Dedicated to Professor Dr. K. Rawer on the occasion of his 65th birthday

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ment of the particles. Hoegy and Brace (1978) showed, by using experimental data of the satellite AE-C, that the three terms are sufficient to describe the measured electron temperature. Our special interest concerns the question, how much energy is given to the electron gas on the average per created PE. This factor ε/eV, named heating efficiency, gives us the connection between the PE production rate $q/\mathrm{m}^{-3}\,\mathrm{s}^{-1}$ and the heat gain rate P_g.

$$P_g(h) = \varepsilon(h) \cdot q(h). \tag{1}$$

However, above 300 km ε loses this clear explanation of an average energy input to the electron gas per PE. Because of the lower neutral density, the PEs created in such heights can travel several scale heights before they lose their suprathermal energy. That means the heat input to the electron gas is not only due to locally created PEs but also due to PEs cascading from other heights to the local level. In this case ε is the proportionality factor between the local PE production rate and the local heat gain rate of the electron gas.

2. Calculation of ε

The electron energy equation in our simplified form is

$$P_g = P_t + P_c \tag{2}$$

Using Eq. (1), one gets

$$\varepsilon = \frac{P_t + P_c}{q}. \tag{3}$$

P_t contains energy losses due to elastic and inelastic collisions with neutral particles and ions. The loss rates of the electron elastic collisions and excitation of rotational, vibrational and electronic states of molecular and atomic oxygen and molecular nitrogen are given by Rishbeth and Garriott (1969). By far most energy is lost by *fine-structure excitation of atomic oxygen.* Hoegy (1976) showed that the widely used analytical expression for this loss rate which was introduced by Dalgarno and Degges (1968) is almost twice the values he calculated based on a more involved theory. We have approximated the electron temperature dependence of the ratio of the new to the old value given by Hoegy (1976) in his Fig. 1. The following is our analytical expression.

$$\begin{aligned} P_t^{(\mathrm{new})}/P_t^{(\mathrm{old})} &= 0.432 + 0.1752 \cdot \exp[-1.07 \cdot 10^{-3} \cdot (T_e - 1000)] \\ P_t^{(\mathrm{old})} &= 3.4 \cdot 10^{-18} \cdot n(0) \cdot N_e \cdot (T_e - T_n)/T_n \cdot (1 - 7 \cdot 10^{-5} \cdot T_e) \end{aligned} \tag{4}$$

$n(0), N_e/\mathrm{m}^{-3}$ = atomic oxygen and electron density

$T_n, T_e/K$ = neutral and electron temperature.

The loss rate due to Coulomb collisions in an O^+-gas with assumed charge neutrality ($n(O^+) = N_e$) is (Risbeth and Garriott, 1969).

$$P_t^{(O^+)} = 4.8 \cdot 10^{-13} \cdot N_e^2 \cdot (T_e - T_i)/T_e^{3/2} \tag{5}$$

T_i/K ion temperature.

Using calculations of Chapman and Cowling (1970) and Spitzer (1956) the *heat conduction* of the electrons in a fully ionized neutral gas is given by

$$P_c = \sin^2 \psi \cdot 7.7 \cdot 10^7 \frac{d}{dh}\left(T_e^{\frac{5}{2}} \frac{dT_e}{dh}\right) \tag{6}$$

ψ = magnetic dip.

The factor $\sin^2 \psi$ considers the fact that the electrons are forced to move along the magnetic field lines. For the heights that are considered here, the influence of collisions with neutrals on the heat conduction can be ignored.

The *PE production* is calculated by the number of ionizing processes.

$$q(h) = \sum_k n_k(h) \cdot \sum_{\lambda_i} \sigma_k^{(I)}(\lambda_i) \cdot I_{\lambda_i}(h)$$

$$I_{\lambda_i}(h) = I_{\lambda_i}(h_{\mathrm{EUV}}) \cdot \exp\left[-\frac{1}{\cos\chi} \sum_k \sigma_k^{(A)}(\lambda_i) \cdot \int_{h_{\mathrm{RPA}}}^{h_{\mathrm{EUV}}} n_k(h')\, dh'\right] \tag{7}$$

$k = 1, 2, 3$ meaning O, O_2, N_2

$\sigma_k^{(A/I)}(\lambda_i)/\mathrm{m}^2$ absorption and ionization cross sections of the neutrals k for the solar radiation of wave length λ_i

χ = solar zenith angle

$I_{\lambda_i}(h)/\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ photon flux in height h of wave length λ_i

$h_{\mathrm{EUV/RPA}}$ satellite height for the EUV and RPA measurements, respectively.

3. Used Data

The neutral temperature and the densities of O_2, N_2 *and* O were taken from the MSIS-model (Hedin et al., 1977). The *electron density and temperature* was measured on board the AEROS-A by the Retarding Potential Anlyser (RPA) of Spenner and Dumbs (1974).

Furthermore we used the *photon fluxes* measured by the AEROS-EUV-Spectrometer of Schmidtke et al. (1974).

The *cross sections* were taken from the reviews of Huffman (1969) and Schoen (1969). The *ion temperature* was calculated by assuming thermal balance between heat gained by the ion gas from the hotter electrons [Eq. (5)] and heat lost to the colder neutrals (Risbeth and Garriott, 1969).

$$T_i = \frac{T_n + 6 \cdot 10^6 \cdot X \cdot T_e^{-\frac{1}{2}}}{1 + 6 \cdot 10^6 \cdot X \cdot T_e^{-\frac{3}{2}}} \qquad X = \frac{N_e}{\sum_k n_k}. \tag{8}$$

For this calculation we have not considered the heat conduction in the ion gas which is neglectable in our height range. As one notices from Eq. (6) we need *the first and second height derivatives of the electron temperature* to calculate P_c. From in situ measurements these values can be obtained only for large height

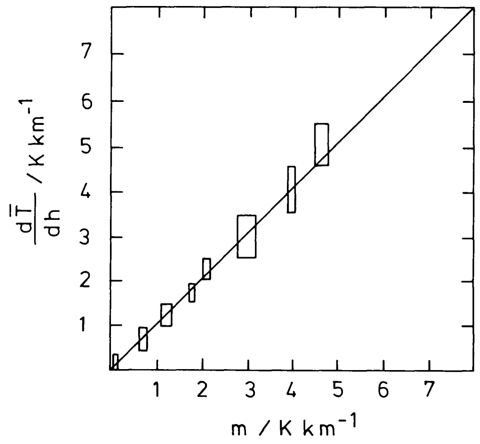

Fig. 1. Comparison of the gradients calculated in different ways (see text)

gradients of the satellite's orbit, as otherwise the results are influenced by the latitudinal and longitudinal gradients. To calculate ε for the global data base, we have gathered the temperatures of the whole AEROS-A mission in 10 degree intervals of geomagnetic latitude (beginning with $-60 \ldots -50$) and have approximated these group profiles by a function explained in Appendix I.

For the nighttime when no PEs are produced ($P_g = 0$), the temperature gradient can be calculated from the balance between heat conduction and heat loss in the following way. The height profile of the electron temperature can be divided into regions within which the temperature is nearly linear (Appendix I).

$$T_e = T_{e0} + m \cdot (h - h_0). \tag{9}$$

By differentiating Eq. (9) and substituting in Eq. (6) we get

$$P_c = \sin^2 \psi \cdot 7.7 \cdot 10^7 \cdot \tfrac{5}{2} \cdot T_e^{\frac{3}{2}} \cdot m^2. \tag{10}$$

Finally, using Eq. (2), bearing in mind that $P_g = 0$, and solving for m we get

$$m = 7.2075 \cdot 10^{-5} \cdot \frac{\sqrt{P_t}}{\sin \psi \cdot T_e^{\frac{3}{4}}} K\,\mathrm{km}^{-1}. \tag{11}$$

This gives us the possibility to compare the single gradients m with the derivative of the approximated mean function. Figure 1 shows that the mean values of gradient m calculated by using our theoretical considerations fits very well with the empirical approximation, thus justifying our gradient determination. That is obviously also valid for the lower height range where high gradients occur at night.

4. Results

Figure 2 shows the height behaviour of ε, averaged over all latitudes, and the mean absolute deviation from the median value. Figure 2 contains also ε as

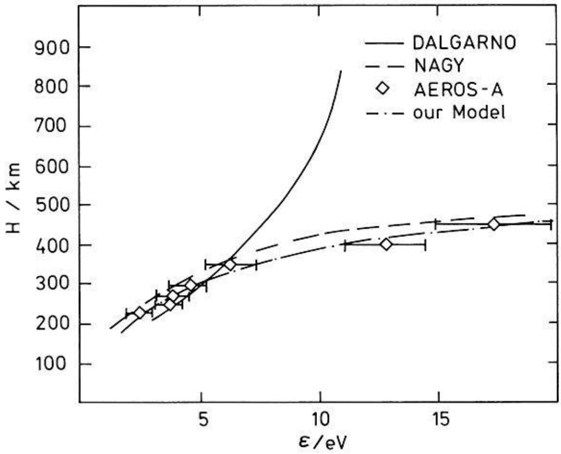

Fig. 2. Height dependance of ε and $\bar{\varepsilon}$ compared to results of other authors

calculated by Nagy et al. (1969) for data of the incoherent scatter station Millstone Hill/USA. The agreement with our values is rather good. The solid line in Fig. 2 represents the energy given to the electron gas per PE, $\bar{\varepsilon}$, which was calculated by Dalgarno et al. (1968) for data from Millstone Hill. Below 350 km the PEs lose their energy totally local, and one can identify the proportionality factor ε as the energy given to the electron gas per PE.

If one wants to extend the energy-input-per-PE-interpretation above 350 km, one has to replace the local PE production rate q by the total amount $\bar{q}$ of PEs per unit volume and second

$$P_g = \bar{\varepsilon} \cdot \bar{q}. \tag{12}$$

Conversely one can calculate the proportion p of non-local PEs q_n with respect to the total rate $\bar{q}$ to zero order by equalizing Eqs. (1) and (12):

$$\begin{aligned} &q/\bar{q} = \bar{\varepsilon}/\varepsilon \quad \text{with} \quad \bar{q} = q + q_n \\ &p = q_n/\bar{q} = 1 - q/\bar{q} = 1 - \bar{\varepsilon}/\varepsilon. \end{aligned} \tag{13}$$

Using the values of Fig. 2 one gets at a height of 400 km a portion of non-local PEs of 30% and at 450 km even 50%.

Figure 3 shows ε depending on the ratio of electron to neutral density and the model for $\bar{\varepsilon}$ established by Swartz and Nisbet (1972). Their model reproduces the fact that the energy of the PEs is divided mainly between electrons and neutrals. That means the energy given to the electron gas depends on the ratio of electron to neutral density. But the losses of the PEs to the electron gas are important only for low PE energies (<1 eV). The main competitors in this energy range are molecular nitrogen and oxygen with their low-lying vibrational states. Therefore the atomic oxygen with higher excitation states is weighted with 0.1. Swartz and Nisbet (1972) restricted their model to the region indicated in Fig. 3, as with decreasing neutral density more and more PEs escape into the protonosphere.

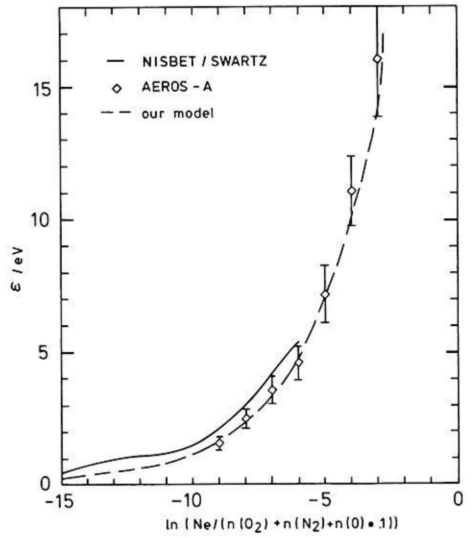

Fig. 3. Density ratio dependance of ε and $\bar{\varepsilon}$ compared to Nisbet's model

This is about the same region for which we can equalize ε and $\bar{\varepsilon}$. This is confirmed by our calculations as shown in Fig. 3. As the concept of the proportionality factor ε simplifies heat budget calculations, we have approximated our values by analytical functions (see Figs. 2 and 3):

$$\varepsilon(h) = 0.307 \cdot \exp(0.00916 \cdot h)$$

$$\varepsilon(x) = 44.7 \cdot \exp(0.364 \cdot X)$$

$$X = \ln \frac{N_e}{n(\mathrm{O_2}) + n(\mathrm{N_2}) + 0.1 \cdot n(\mathrm{O})}.$$

Both models are valid within the ranges given in Figs. 2 and 3.

Appendix I

Model for the Electron Temperature

For all latitudes we can divide the electron temperature profile in regions with constant height gradient

$$\frac{dT_e}{dh} = \begin{cases} ST_0 & h \ll XS_1 \\ ST_1 & XS_1 \ll h \ll XS_2 . \\ \vdots \quad \vdots & \vdots \quad \vdots \end{cases} \qquad \text{(A7)}$$

By connecting these regions with an Epstein step function, that means functions of the following kind

$$f(x)=y_1+\frac{y_2-y_1}{1+\exp\left(-\dfrac{x-x_1}{d_1}\right)} \tag{A8}$$

with

$$f(x) \begin{array}{l} \nearrow y_1 \quad x \ll x_1-d_1 \\ \searrow y_2 \quad x \gg x_1+d_1 \end{array}$$

we get the analytic function

$$\frac{dT_e}{dh}=ST_0+\sum_{k=1}^{M}\frac{ST_k-ST_{k-1}}{1+\exp\left(-\dfrac{h-XS_k}{D_k}\right)}. \tag{A9}$$

M = number of different regions.
Height integration gives us

$$T_e(h)=\bar{T}+(h-\bar{h})\cdot ST_0$$
$$+\sum_{k=1}^{M}(ST_k-ST_{k-1})\cdot D_k\cdot\ln\left[\frac{1+\exp\left(\dfrac{h-XS_k}{D_k}\right)}{1+\exp\left(\dfrac{\bar{h}-XS_k}{D_k}\right)}\right]$$

with the temperature $\bar{T}$ at the reference height $\bar{h}$. The parameters M, $ST_{0\ldots M}$, $XS_{1\ldots M}$ and $D_{1\ldots M}$ have been varied to get the optimum fit to the data.

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