Energy Per Ion Pair In Planetary Upper Atmospheres

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Introduction

The mean energy expended in a collision by an electron in atmospheric gazes, called the W value, is a useful parameter for fast aeronomy computations. Its inverse represents the overall efficiency of a particle or an electromagnetic radiation in ionising a gas or a mixture of gas and is thus characteristic of the species considered.

Following a method proposed by Rees **[1]**, the ion and electron production height profiles can be calculated to derive the luminosity height profiles without having to solve a kinetic transport equation. Although computers are nowadays much faster than some decades ago when the energy per electron-ion pair was first computed, transport codes are still sparse especially when dealing with comparative planetology. Therefore, recent works still use the Rees method.

The value of 35 eV has often been used for this energy per electron-ion pair although many authors have shown that it depends on the energy of the precipitated particle and on the atmospheric composition. In the present paper, we use a kinetic transport code adapted to Mars **[2]**, Venus **[3]**, Earth **[4]** and, although not in the scope of this meeting, Titan **[5]** and Jupiter to compute the energy per ion pair. We show that this parameter depends on the planet and propose different average values for each of them. We also show the study of this parameter for different pure gases of interest for planetary atmospheres.

Historical overview

- 1927 — First experimental work by **Lehmann & Osgood**
- 1930-37 — Theoretical calculations by **Bethe** (1930). **Bagge** (1937) derives an expression for secondary ionisation ~ 30 eV depending on species.
- 1948 — **Fano** derives a simple formula
- 1958 — **Dalgarno et al.** build the first consistent model for electron and proton degradation. **Valentine & Curran** perform experimental work for several gases and ionising radiations. *W* spans from 27 (Ar) to 38 eV (H_2).
- 1963 — **Rees** uses a method to retrieve the ion and electron production height profiles using the average *W* value of 35 eV. This approach is still used for instance in tomography-like techniques of auroral fluxes.
- 1965-67 — **Green & Barth** (1965) and **Stolarski & Green** (1967) use a semi empirical method based on known inelastic collision cross sections.
- 1973 — **Edgar et al.** compute 38 eV for protons in N_2 at 100 keV using updated cross sections, a value close to that for electrons.
- 1977-78 — **Khare & Kumar** show the importance of Auger ionisation
- 1977 — **Jackman et al.** and **Green et al.** use a discrete-energy bin algorithm to compute the *W* values for several gases: 36.3 (H_2), 35.3 (N_2), 30.9 (O_2), 27.4 (O), 32.5 (CO_2), 33.5 (CO).
- 1981 — Kinetic transport methods begin to be used more and more (e.g., **Bretagne et al.**, 1981; **Slinker et al.**, 1990; **Basu et al.**, 1993) who find *W* to be around 28 eV for electrons in O and 34 eV in N_2.
- *Present* — No studies have been performed so far within a planetology context.

Calculating the *W* value

The energy expended in the creation of an electron-ion pair is defined as:

$$W = \frac{E_i}{N_i} \equiv \frac{Q}{\sum P_i}$$

where E_i is the input energy and N_i is the number of electron-ion pairs created. It is equivalent to the second formula where Q is the total energy flux in eV cm^{-2} s^{-1} and $\sum P_i$ is the total column ion production rate including ionisation, excitation and heating, expressed in cm^{-2} s^{-1}.

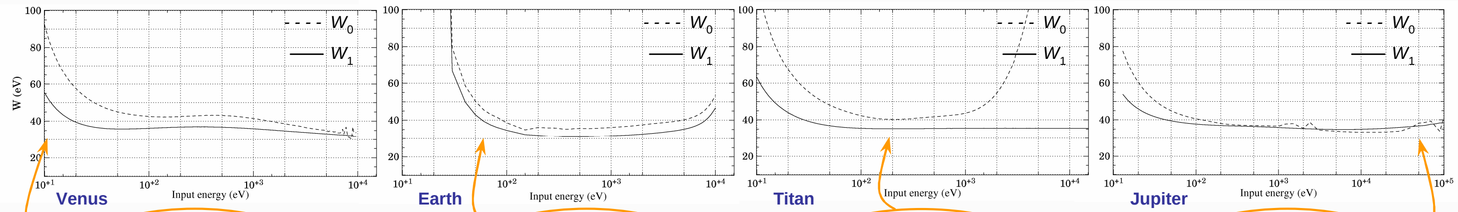
To compute *W*, we use kinetic transport models in the TRANS-* family and adapted to Mars **[2]**, Venus **[3]**, Earth **[4]**, Titan **[5]** and now also to Jupiter. These codes are based on a formalism which solves the Boltzmann equation for suprathermal electrons, yielding the ionisation rates and productions of excited states of neutrals and ions. The inputs of the codes are essentially ionisation and excitation cross sections, the neutral atmosphere and the electron precipitated fluxes.

We distinguish two different W values. When $Q = Q_0$, i.e., the total input flux at the top of the ionosphere, the *W* value is noted W_0. When $Q = Q_1$, i.e., the total absorbed energy flux in the ionosphere, the *W* value is noted W_1.

While W_0 is directly linked with experimental measurements, W_1 is the significant quantity in a numerical model where energy conservation issues are of crucial importance.

Results on the Earth, Venus, Titan and Jupiter

- Series of runs performed on different planets for the two parameters W_0 and W_1.
- Gaussian distribution (precipitated electron fluxes) centered on the input energy E_0 with total energy of 1 erg.
- Energy conservation in the numerical scheme better than 12%. For an ideal energy conservation of less than 1%, $Q_1 = Q = Q_0$ – backscattered energy flux.
- Evolution consistent with previous experimental and theoretical studies (see for instance Edgar et al., 1973). At low energies, typically under 100 eV, the *W* values are quickly decreasing to reach an asymptotic value around 1 keV.
- A systematic difference is seen between W_0 and W_1. W_0 is usually higher at lower energies. This is due to the fact that at low energies, the energy deposition occurs at higher altitudes: the backscattered term is more important and energy escapes from the atmosphere, which is not taken into account in W_0. Hence, at low E, $W_0 > W_1$. At higher energies (for E > 100 eV), the electrons penetrate deeper in the atmosphere and the backscattered fluxes tend to be redistributed in the atmosphere, taking part i n the energy balance, hence $W_0 \to W_1$.



Start-up phase: very few e-ion pairs are created under 60 eV as excitation and heating are more efficient at these energies

'Recovery' phase: when ionisation processes become important (compared to excitation), the decreasing trend starts to invert as more pairs are created.

Equilibrium phase: the decrease of the cross sections is compensated by the increase in energy input. A sudden increase is seen for Titan for Q_0 (also seen on Earth) due to the shape of the N_2 cross sections

For Jupiter, shown here as comparison, the curves remain constant until 100 keV, yielding a W value of about 37 eV for a (H,He) atmosphere

Main results and the example of Mars

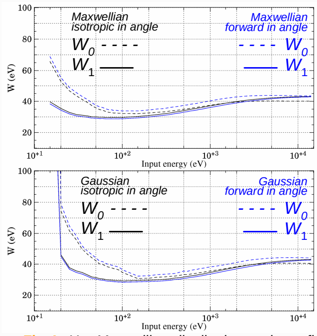


Fig 1. *Up: Maxwellian distribution as input flux. Down: Gaussian distribution. For each, the energy flux can be redistributed in angles, either isotropically or forward (gaussian shape).*

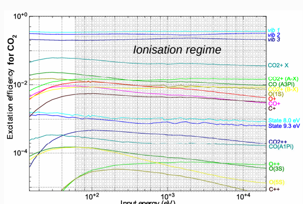
We study here the variation of the *W* values for Mars (*Mariner atmosphere conditions*, $f_{10.7}$ = 200, $d_{S\text{-}M}$ = 1.45 AU), depending on the input energy flux distribution (Fig. 1).

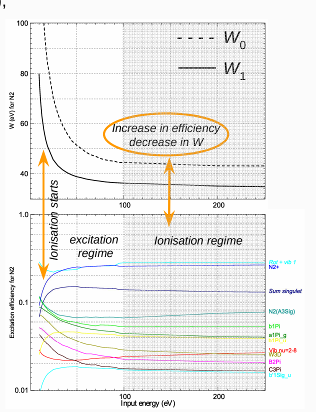
- Gaussian and Maxwellian distributions show different results at low energies (E < 300 eV).
- The *W* values in the equilibrium phase do not depend on the choice of the distribution
- W_0 values appear to be sensitive to the angular redistribution of the precipitated fluxes: backscattered fluxes are more important when the distribution is isotropic and more pairs are created than in the forward case.

In Fig. 2, excitation and ionisation efficiencies, i.e., $P_i / \sum P_i$, are plotted for single constituent atmospheres.

- It explains the shape of the *W* curves as a compromise between cross sections and energy input.
- Ionisation becomes a major mechanism at high E. While cross sections decrease regularly with E, the energy input increases: the contribution of ionisation to the total degradation of the energy flux remains constant with E.
- Two main regimes can be inferred: an *excitation regime* where most processes lead to excitation, and an *ionisation regime* where ionisation becomes dominant and lead to a flat *W* curve (higher E).
- The ionisation regime begins at 100 eV for N_2 and 60 eV for CO_2.

Fig 2. *Left: Excitation and ionisation relative efficiency computed for CO_2. Up right: W values between 0 and 200 eV for N_2. Down right: Efficiencies for the main excited/ionized states of N_2.*





Conclusion

The mean energy of an electron-ion pair is a parameter that depends on the species composition of the neutral atmosphere and to a lesser degree, on the angular distribution of the precipitation fluxes. Studying the excitation efficiency excitation shows that for each gas an ionisation regime begins to take place at a specific energy value. Table 1 summarises recommended *W* values for typical atmospheres of Mars, Venus, Earth, Titan and Jupiter. We also computed the degradation and the *W* values for single-constituent gases such as N_2, O, CO_2, CO. A systematic study of efficiency mechanisms for different species and on different planets will follow this work.

Atmosphere/Gases	Average *W* value at 2 keV
Mars (Viking 1)	40 eV
Venus (VTS3)	37 eV
Earth (MSIS-90)	35 eV
Titan (N_2, CH_4)	36 eV
Jupiter (H, H_2, He, CH_4)	38 eV
N_2	35 eV
O	27 eV
CO_2	42 eV
CO	30 eV

Table 1. *Energy per ion pair in planetary atmospheres*

References

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