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Conditions for aeronomic applicability of the classical electron heat conduction formula

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Abstract. Conditions for the applicability of the classical formula for heat conduction in the electrons in ionized gas are investigated. In a fully ionised gas ($\nu_{en} << \nu_{ei}$), when the mean free path for electron- electron (or electron - ion) collisions is much larger than the characteristic thermal scale length of the observed system, the conditions for applicability break down. In the case of the Venus ionosphere this breakdown is indicated for a large fraction of the electron temperature data from altitudes greater than 180 km, for electron densities less than 10^4 cm^{-3}. In a partially ionised gas such that $\nu_{en} >> \nu_{ei}$ there is breakdown of the formula not only when the mean free path of electrons greatly exceeds the thermal scale length, but also when the gradient of neutral particle density exceeds the electron thermal gradient. It is shown that electron heat conduction may be neglected in estimating the temperature of joule heated electrons by observed strong 100 Hz electric fields when the conduction flux is limited by the saturation flux. The results of this paper support our earlier aeronomical arguments against the hypothesis of planetary scale whistlers for the 100 Hz electric field signal. In turn this means that data from the 100Hz signal may not be used to support the case for lightning on Venus.

1. Introduction

Following the first version of the paper [*Cole and Hoegy* ,1996a] submitted for publication, an editorial referee disputed our estimates of the rise in temperature of joule heated electrons in the 100Hz electric fields observed in the ionosphere of Venus by the Pioneer Venus Orbiter (PVO). We were testing the validity of the hypothesis that the waves are due to whistlers on a planetary scale. This referee insisted that the authors take into account classical conduction of heat in the electron gas when calculating the temperature rise of joule heated electrons. Smaller, but physically significant, increases of electron temperature were still estimated [*Cole and Hoegy*, 1996a,b] when this was done. *Strangeway* [1996,1997a,b] argued strongly the case for including heat conduction, in its classical form (1), in the energy balance of electrons. Using similar aeronomical situations as *Cole and Hoegy* [1996a,b], he inferred negligible rises in electron temperature in the dayside ionosphere and high altitude night ionosphere. His estimate of electron temperature near 130km altitude at night was of the same order as ours, for reasons given in the text. Above 150 km, we predicted significant increases in electron temperature, while he claimed that heat conduction would nullify the effect of joule heating. Differences in the estimates of electron temperature resulted from the use of large scale lengths of the temperature field by us , and smaller scale lengths by him. As is shown in this paper, the breakdown of conditions for the applicability of the coulomb part of the conventional electron conductivity formula supports our case for estimates of elevated temperature and subsequent aeronomic effects [*Cole and Hoegy* ,1996a,b]. These large temperatures are unobserved. This is evidence that the hypothesis of planetary scale whistlers for the 100 Hz electric fields is false [*Cole and Hoegy*, 1996a,b]. Further this opposes the "whistler" arguments for lightning on Venus [*Russell*, 1991; *Strangeway*, 1991; *Grebowsky et al.*, 1997].

The issue of the appropriateness of short or long scale lengths for the electron temperature field above 150 km altitude can be approached by examination of the conditions for the validity of the coulomb part of the classical formula for heat conduction in the electron gas. Heat conduction in the electron gas is a topic of basic significance in aeronomy [e. g., *Banks and Kockarts*, 1973]. However, the conditions for its valid application are not always found in nature [*Cole*, 1965; *Merritt and Thompson*, 1980].

In the altitude range 130-150 km at night it is found that the conventional formula (1) leads to excessive estimates of electron cooling by conduction, thus invalidating *Strangeway's* [1996,1997a,b] criticism of our theory of joule heating of electrons by 100Hz electric fields in the Venus ionosphere.

Here, the conditions for the applicability of the classical heat conductivity formula in ionospheric theory are examined generally, and also with special reference to Venus. It will be found that they do not hold in vast segments of the Venus ionosphere. These segments contain regions where a large fraction of strong 100Hz signals is observed [*Strangeway et al.*, 1993a,b; *Strangeway*, 1996, 1997a,b; *Cole and Hoegy*, 1996a,b]. In such regions there would be significant aeronomic consequences [*Cole and Hoegy*, 1996a,b] given the validity of the whistler hypothesis for the strong100Hz signals of ac electric fields observed. The argument of the present paper favours our earlier inference [*Cole and Hoegy*, 1996a] that if one employs the classical formula with relatively long scale lengths for the electron temperature field in a large fraction of the 100Hz electric field events, one obtains much more realistic estimates of the temperature contrary to the estimates of *Strangeway* [1996, 1997a,b] who used short scale lengths. This supports our earlier aeronomic arguments against the whistler hypothesis for the 100Hz electric fields [*Cole and Hoegy*, 1996a,b]. and our contention that the 100Hz data may not be used to justify the hypothesis of lightning in the Venus ionosphere [*Russell*, 1991; *Strangeway*, 1991;*Grebowsky, et al.*, 1997]. C.G.S units are used except where otherwise stated.

In the lower thermosphere at night conditions for the validity of the classical heat conduction formula (including neutral collisions) are shown to be violated. This makes *Strangeway's* [1996, 1997a,b] criticism of our work incorrect.

1.2. Conditions for Applicability: The classical theory of heat conduction in the electron gas rests upon the existence of local thermodynamic equilibrium in each species of particle participating in the phenomenon [e.g., *Spitzer*, 1962; *Chapman and Cowling*, 1970]. The flux of heat by conduction in an ionised gas is then

$$F_{cond} = -K_e \nabla T_e,$$

where T_e is the electron temperature. The formula for the coefficient of heat conductivity in the electrons from *Banks and Kockarts* [1973], can be rewritten in terms of collision frequencies as

$$K_e = 1.23 \times 10^{-6} T_e^{5/2} \left(1 + \frac{\nu_{en}}{2\nu_{ei}}\right)^{-1} \tag{1}$$

in units of erg/cm/s/K, where ν_{en} and ν_{ei} are the electron-neutral, and the electron - ion , collision frequencies, respectively, for momentum transfer. Here the coulomb logarithm ln Λ has been put equal to 15. The classical formula (1) implicitly assumes that the mean free path of electrons is small compared to the scale of variation of the mass properties of the gas [*Chapman and Cowling*, 1970]

In the following λ_{ee}, λ_{ei}, λ_{en}, stand for the mean free path of electrons in electrons, ions and neutrals, respectively. Note that $\lambda_{ee} = \lambda_{ei}$ *[Banks and Kockarts*, 1973]. L_T , L_e, L_n, denote the scale lengths of the electron temperature, the elctron density, and the neutral gas density, respectively.

1.3 Breakdown of Applicability

When $\lambda_{ei} >> L_T$: Consider first the coulomb component of (1). The transport of heat, implied by (1) is dependent on electron-ion collisions, and the establishment of local thermodynamic equilibrium in the electrons is dependent on electron-electron collisions. Therefore it has been suggested that the conditions of applicability of (1) do not hold if the mean free path λ_{ei} is > scale sizes appropriate to the system under study [e.g., *Cole*, 1965; *Merritt and Thompson*, 1980]. In this case heat flux may be carried by a flux of hot electrons, modified by the development of secondary electric fields.

When λ_{ei}>> λ_{en}: We also investigate a second condition when the mean free path λ_{ei} , for *electron-electron* collisions, is >> λ_{en} for *electron-neutral* collisions. In the latter case the electrons would have little chance of interacting with each other to produce a Maxwell-Boltzmann distribution locally, nor to communicate among themselves information about their possible energy-density gradient.

These conditions would invalidate the use of equation (1) in theoretical analysis. It is of course seen that, formally, K_e approaches zero as the ratio ν_{en}/ν_{ei} approaches infinity, rendering conduction cooling of electrons ineffective; that is a special circumstance at the bottom of any planetary ionosphere. In section 2.2 we discuss the relationship of our work to that of *Merritt and Thompson* [1980] on the question of the coulomb part of the conductivity formula. In section 3 we extend the application of the concept of saturation flux to include e-n collisions. In sections 3.4 and 3.5 we investigate the implications of the variations of mass properties of the gas.

2 Breaking Conditions in a Gas with $\nu_{en} << \nu_{ei}$

2.1 λ_{ei} > scale sizes; in the case of $\nu_{en} << \nu_{ei}$

The electron-electron collision time interval, for momentum and energy transfer, is [*Banks and Kockarts,* 1973]]

$$\tau_{ee} = \frac{0.194}{n_e \ln \Lambda} T_e^{3/2} = \tau_{ei} / \sqrt{2}, \tag{2}$$

where the coulomb logarithm

$$\ln \Lambda = 8.96 + \ln\left(T_e^{3/2} / n_e^{1/2}\right)$$

The mean free path of an electron in the fully ionised gas is given incorrectly in equation 9.108 of *Banks and Kockarts* [1973] where there is a typographical error, since the coulomb logarithm should be in the denominator instead of the numerator. Then

$$\lambda_{ee} = \frac{0.194}{n_e \ln \Lambda} T_e^{3/2} \left(\frac{16kT}{\pi m_e}\right)^{1/2} = \lambda_{ei}, \tag{3a}$$

where the coulomb logarithm will be assumed to be 15 for our purposes. Therefore

$$\lambda_{ee} \approx 1.14 \times 10^4 T_e^2 / n_e. \tag{3b}$$

Note in passing that when the average speed of electrons is very much greater than that of the ions, $v_{ee} = \sqrt{2} v_{ei}$ This is usually the case in planetary ionospheres.

Figure 1 shows plots of λ_{ee} for ranges of values of n_e and T_e . Figure 2a shows a mass plot of λ_{ee} as a function of altitude derived from UADS (dayside data) for the first 900 orbits by the Pioneer Venus orbiter (PVO). Compare Figure 2b (night time data) and note that the altitudes have a lower limit of about 200 km in the daytime and 150 km at night. These figures will be referred to later in specific cases relevant to joule heating caused by ac electric fields of 100Hz. It can be seen from Figure 1 that for T_e > 3000K and n_e < 10^4 cm^{-3}, λ_{ee} > 90km. When T_e > 6000K and n_e < 10^3 cm^{-3}, λ_{ee} > 3,300km. It would not be valid to employ K_e in problems in which λ_{ee} >> scale length of the system being examined ; rather, the heat would be transported from the heat source by a stream of electrons. Figures 2a,b refer to the high altitude orbits of PVO. Even more restrictive conditions on the use of (1) are developed in Section 2.2.

A special region of interest is near 160 km altitude at night, which has bearing on the possibility of lightning on Venus. *Russell et al.* [1993; Figure 7] show the kinetic pressure of the ionosphere in this region, on orbits 5011-5055, to be on average about the same as that of the magnetic pressure. On orbit 5051 the magnetic field at 160 km, 80s after periapsis is ~ 18nT [*Strangeway et al.* 1993a]. Using these facts, for this orbit, we infer an estimate of the product $n_e T_e$ = 9.3x10^6, at 160km. Putting n_e < 10^3 cm^{-3} , as seen from the observations on orbit 5051, then T_e > 9,300K, and, from (3), λ_{ee} > 10,000 km. This is a demonstration of the breaking of the first condition.

It may be suggested that λ_{ee} sets a lower lower limit to the minimum scale length L_T for possible thermal gradients in the electron gas, unless collisions with neutral particles dominate energy transfer, see section 3.3. We show in section 2.2 that the work of Merritt and Thompson requires an even larger lower limit on $L_T$of about 8 λ_{ee}. Figures 1 and 2b provide support for the choice of long (~10^4 km) values for L_T [*Cole and Hoegy,* 1996a,b], but not for short values [*Strangeway* ,1996, 1997a,b]. λ_{ee} in excess of 10^4 km is encountered often near 160km altitude at night (see Fig 2b).

2.2 Relation to the Work of Merritt and Thompson [1980]

The saturated flux: These authors present results of their study of the breakdown of the Coulomb part of the classical heat conduction formula for an electron gas, in a non-magnetized spherically symmetric ionosphere, in which the mean free path for electrons is comparable to or greater than the scale length of the temperature field. Under conditions of such breakdown, they consider the flux of heat to be determined not by normal coulomb conduction, but to have an upper limit, called the "saturated" flux of electrons carrying heat energy given by

$$F_s = \pm\alpha\left(kT_e / m_e\right)^{1/2}\left(n_e kT_e\right), \tag{4a}$$

or,

$$F_s = \pm 5.2\times10^{-11}\alpha n_e T_e^{3/2} \tag{4b}$$

where α is a dimensionless parameter considered to be in the range

$$0.1 \le \alpha \le 1. \tag{4c}$$

Fs is inferred on the basis that, on average, electrons cannot travel faster than their thermal speed. It is a convection flux of particles and energy rather than a conduction flux of energy.

The classical conduction flux, after taking into account the generation of electrostatic field, and assuming zero electric current [*Spitzer*, 1962] is

$$F_c = -K_e \nabla T_e, \text{ with } K_e = 1.23\times10^{-6} T_e^{5/2}.$$

Merritt and Thompson review research on the value of α. There are some experimental conditions in which it is thought α << 1 in high density laser plasmas. However this result may not be transposable to the Venus ionosphere. For conditions of the quiet Venus ionosphere they argue the case for a "canonical" value of α = 0.25.

F_S represents a convection of electrons and does not take into account secondary electric field generated by them, nor the noise in the electric field which may affect transport properties of the electron gas. It is therefore likely to be an overestimate of the real upper limit to the energy flux. For example,putting the condition current density, j = 0, would demand an equal counterstreaming number flux of electrons, if they are available. If not an accompanying flux of ions would occur but these would cool the electrons by taking energy from them via the self-onsistent electric field.

The ratio s: Of considerable interest is the ratio

$$\sigma = F_c / F_s = 2.37 \times 10^4 T_e^2 / \alpha n_e L_T, \tag{5a}$$

where $L_T = T_e / \nabla T_e$. Alternatively,

$$\sigma = 2.375 \times 10^4 T_e^2 / n_e L_T \alpha, \text{ or} \tag{5b}$$

$$\sigma \approx 2.1 \lambda_{ee} / L_T \alpha \tag{5c}$$

which may be expressed as , $F_c / F_s >> 1$, if

$$L_T < 2.1 \lambda_{ee} / \alpha. \tag{6a}$$

We note that their L_T is related to λ_{ee} by the factor ~ 2.1/α. For α = 0.25, this factor is ~8. Let us call the value of L_T when σ = 1,

$$L_{T,crit} = 2.375 \times 10^4 T_e^2 / n_e \alpha. \tag{6b}$$

For α = 0.25,

$$L_{T,crit} = 9.58 \times 10^4 T_e^2 / n_e. \tag{6c}$$

It follows that $L_{T,crit}$ puts an even larger lower limit condition on breakdown for L_T than does λ_{ee}. The values of $L_{T,crit}$ would then be given by 8.4 times those of λ_{ee} given in Figure 1. Smaller values of α mean proportionally larger values of the upper limit to $L_{T,crit}$.

Merritt and Thompson illustrated the possible utility of the concept of saturated flux by reference to the normal Venus background ionosphere. They showed, by invoking a certain total heat flux at the top of the ionosphere, and a model of the electron density profile, and with α = 0.25, that a reasonable fit to ionospheric electron temperature can be obtained by employing a harmonic combination of the two fluxes. According to these authors the classical flux dominates in the lower ionosphere during sunlit times, and the saturated flux in the upper ionosphere, the transition region being at about 300 km altitude.

Our work is complementary to theirs in that it makes explicit the connection of λ_{ee} to $L_{T,crit}$ and (in later sections) discusses the influence of neutral particles on electron conductivity in the context of the Venus ionosphere. The full relationship of their work to ours is not yet clear, and we will pursue this in a future paper, especially the relationship of charge neutrality to the saturated flux. Our work adds some new facets to an old problem [*Cole*, 1965; *Merritt and Thompson*, 1980]. Our application here is to the vexed question of the whistler hypothesis for the 100 Hz signal observed in the Venus ionosphere by PVO. The problem has arisen in other contexts which are not persued here [*Hartle and Sturrock*, 1968; *Hartle and Barnes*, 1970]

2.3 Discussion: Interpretation of the Foregoing Results.

For an observed T_e and n_e, one can estimate λ_{ee} and $L_{T,crit}$. If λ_{ee} is taken as the actual thermal scale length of the system, then (6) is automatically satisfied, and F_C is overestimated, from (5),by a factor of about 8. Therefore the choice of λ_{ee} as the thermal scale length would provide, via(1), an over generous estimate of the conductive cooling of electrons. Noting figures 1 and 2a,b makes our estimates of electron temperature [*Cole and Hoegy*, 1996a,b] conservative.

On the other hand, the error factor σ in F_C caused by the arbitrary choice of L_{Tarb} as the thermal scale length, is, if $\sigma > 1$,

$$\sigma \approx 2.1\lambda_{ee} / \alpha L_{T,arb}. \tag{7a}$$

or , with $\ln\Lambda = 15$, and $\alpha = 0.25$,

$$\sigma \approx 9.58 \times 10^4 T_e^2 / n_e L_{T,arb} \tag{7b}$$

In the use of too small values of L_{Tarb}., (7b) is, in general, the "minimum over estimate" factor in evaluating conventional electron heat conduction. We consider (7b) to give a minimum value of the error because we expect the demand for electrical neutrality to reduce the convective flux (4a) below its maximum value.

There is clearly an error in estimating electron cooling when an L_T is assumed that is less than the critical value. In the use of small values of L_T this error is the ratio of the divergence of the heat flux assuming scale length L_T to that assuming scale length $L_{T,crit}$, or,

$$\frac{\nabla F_c}{\nabla F_{c,crit}}$$

The conventional flux becomes equal to the saturation flux, under a given *Te* when the temperature scale length is, putting $\alpha = 0.25$,

$$L_{T,crit} = 9.58 \times 10^4 T_e^2 / n_e$$

The ratio of the classical coulomb heating for an arbitrary L to that at the critical L_T is then given by

$$\sigma_1 = \frac{\nabla F_c}{\nabla F_{c,crit}} = \frac{L_{T,crit}^2}{L^2} = \left(\frac{9.58 \times 10^4 T_e^2}{n_e L} \right)^2 \tag{8}$$

Example 1: In general, this is the (over estimate) factor in using the conventional electron heat conduction formula when $\sigma > 1$. By his arbitrary choice of short thermal scale lengths, *Strangeway* [1996] has entered the domain of $\sigma > 1$, thus greatly overestimating the conductive cooling of joule heated electrons in his Figures 2a,b and 3a,b as we now demonstrate. From these figures and their captions one can calculate $\sigma 1$, assuming $\alpha = 0.25$, for example. Figures 3a,b and 4a,b are the figures 2a,b and 3a,b of *Strangeway* [1996] on which we have placed curves showing the reduction in conduction cooling due to saturation. We use the same physical parameters as he, to facilitate direct comparison of our work with his. Notice that the new curves lie below the joule heating. This is contrary to the conclusion of Strangeway that conduction would overwhelm joule heating, as his original figures portrayed. Therefore the core of his opposition to our thesis [*Cole and Hoegy*, 1996a,b] about the 100 hz signal observed by PVO is not valid.

The regime of saturation flux needs to be understood physically. The fact that it sets an upper limit on the classical coulomb flux is clear. What are its other physical manifestations? For example, the saturation flux, being convection and not conduction, may have important electrical and magnetic consequences; what are these? These and other questions will be covered in future work.

Example 2: Figure 1 of *Strangeway* [1997a] describes median conditions in the vicinity (+25 to -100 km) of the median ionopause. He has miscalculated the value of λ_{ee}, which is in fact greater than his L (= our L_T) at the ionopause. For valid application of the classical heat conduction formula, it should be less than L at his ionopause level which is a region of $\sigma > 1$ for the median values. A saturated flux region exists in the altitude interval +25 to -100 km from the median ionopause. It is clear that he has miscalculated and overestimated the conduction cooling in this region. Take, as an instance, the median values T_e = 7000K, n_e = 600 cm-3 at the ionopause. This yields a value of $L_{T,crit}$ = 7.8(4) km.Whereas Strangeway shows a value of thermal length scale of 3(3) km. It follows, using (8), that he has overestimated the conduction cooling by at least a factor of 680 at this place.

Though we also used the classical heat conduction formula [*Cole and Hoegy*,1996a,b], our choice of a large value of L_T, suggested empirically by data, gave us values of the conduction flux nearer to the saturation values. In the present paper, however, we are now giving fundamental physical arguments for much lower values of conduction cooling than those espoused by *Strangeway* [1996]. What is clear is that *Strangeway's* [1996] use of conventional conduction to critcise our theory [*Cole and Hoegy*, 1996a,b] on Joule heated electrons by 100Hz electromagnetic waves in the Venus ionosphere is not valid. Our arguments indicated that the 100 Hz data ought not to be used to support a case for lightning on Venus. Now they are vindicated and removed from the doubt engendered by *Strangeway's* [1996, 1997a,b] papers.

3. Breaking Conditions in a Gas with $\nu_{en} / \nu_{ei} >> 1$

3.1 A Discussion of the Condition: $\lambda^*_{ee} >> \lambda^*_{en}$.

This condition exists in the lower thermosphere of Venus in the special region of interest to this paper of 129-160km altitude. Here we define λ^*_{ee} to be the mean free path for electrons to exchange energy with other electrons. Note that $\lambda^*_{ee} = \lambda_{ee}$. λ^*_{en} is the mean free path for electrons to exchange energy with neutral particles. The classical coefficient of heat conduction (1) involves the ratio of momentum transfer collision frequencies ν_{en} / ν_{ei}. We argue here that in a partially ionised gas the cooling of electrons is controlled more by the ratio $\lambda^*_{en} / \lambda_{ee}$ than by ν_{en} / ν_{ei}.

The rate of loss of energy of an electron, of kinetic energy ε, to heavy particles is

$$\frac{d\varepsilon}{dt} = \sum f_s \frac{m_e}{m_s} \varepsilon \nu_{es}, \tag{9}$$

In the case of CO2, f_s is essentially constant over the energy range of interest. It is the factor of enhancement of energy transfer in an *e-s* inelastic collision over that in an elastic one [see e.g., *Morrison and Greene*, 1990]. ν_{es} is the electron collision frequency for momentum transfer to species *s*.

Therefore the characteristic time for loss of energy of an electron is

$$\tau^*_{es} = 1 \Big/ \left(\sum_s f_s \frac{m_e}{m_i} \nu_{es} \right). \tag{10}$$

It is noted in passing that, in a thermosphere consisting essentially of CO2 and O, CO2 will dominate in the *e-n* cooling processes wherever

$$f_{CO2} \nu_{eCO2} / m_{CO2} >> f_O \nu_{eO} / m_O \tag{11a}$$

or,

$$n_{CO_2} >> \frac{f_O}{f_{CO_2}} \frac{\sigma_{eO}}{\sigma_{eCO_2}} \frac{m_{CO_2}}{m_O} n_O \tag{11b}$$

where $\sigma_{\alpha\beta}$ refers to the appropriate collision cross section. Therefore CO_2 will dominate the *e-n* cooling processes even though its density may be a factor of more than 100 less than that of O. For example: if T_e= 2000K, $Ti = Tg$ = 1000K, $n_e = 10^4$ cm^{-3}, [O] = 10^8cm^{-3}, and [CO_2] = 10^6cm^{-3}, CO_2 cooling is 7 times that of O.

The condition $\lambda^*_{ee} >> \lambda^*_{en}$ will apply when

$$p = \tau_{ee} / \tau^*_{en} = \tau_{ee} \left(\sum_s f_s \frac{m_e}{m_s} \nu_{es} \right) >> !. \tag{12}$$

We could define a quantity

$$\nu^*_{equiv} = \sum_s f_s \frac{m_e}{m_s} \nu_{es} \tag{13}$$

which is an equivalent collision frequency for energy transfer from electrons to all neutrals and ions. In the case of a CO2 dominated partially ionised gas, (12) becomes

$$p = f_{co2} \nu_{eco2} / \nu_{ee} >> 1.$$

This ratio is to be compared with that in (1), namely, ν_{en} / ν_{ei}. Inelastic collisions soak up much energy that would otherwise go into heat conduction. on the other hand the classical formula would reduce the flux by only ν_{en} / ν_{ei}.

Figure 5a shows, for the first 900 orbits of PVO, plots of p for ionospheres at night. Figure 5b shows values of p above 150 km altitude during sunlit hours. It is seen that at the lowest altitudes at night $p >> 1$. In the daytime from 200 to 350 km altitude, $p >> 1$.

3.2 Comparison of Conductive Cooling with Inelastic Collision Cooling in the Lower Thermosphere:

From (1) and (9) the ratio of the two can be represented by

$$\left(\frac{8.61 \times 10^{-6} T_e^{7/2} \nu_{ei}}{\nu_{en} L_T^2} \right) \div \left(\nu_{en} f \left(\frac{m_e}{m_{co2}} \right) \frac{3}{2} nkT_e \right),$$

or, using (2),

$$1.85 \times 10^{14} T_e / L_T^2 \nu_{en}^2.$$

At 130 km altitude at night ν_{en}= 2x10^{4}s^{-1}, and we put f=1000 [*Morrison and Green*, 1980] and L_T= 2 km [*Strangeway*, 1996]. Then the ratio is 1.2x10^{-5} T_e. It follows that classical conduction cooling > inelastic collision cooling when T_e> 8.6x10^4 K or 7.4eV . Strangeway's figure 3b shows a much smaller ratio at this altitude for temperatures less than about 8 eV. Accordingly we consider our neglect of conduction cooling , when estimating electron temperature due to joule heating to yield a good estimate of T_e up to this value. It is shown below that other criteria militate against the use of the classical conduction formula for conditions at130 km at night (section 3.6).

3.3 Effect of e-n Collisions on the Saturated Flux

Here we apply the same principles as in section 2.2 to the discussion of a saturated electron flux taking into account *e-n* collisions in addition to *e-i* collisions. In the presence of significant numbers of both *e-i* and *e-n* collisions we must employ the full expression (1) for the coefficient of conductivity. If we invoke the concept of saturation flux (4) in this case, then we write

$$\sigma^* = F_c / F_s = 2.375 \times 10^4 T_e^2 / \alpha^* n_e L_T (1 + \nu_{en} / 2\nu_{ei}) \tag{14}$$

The value of α^* may well be different in this case from the value of α in the purely coulomb case, especially considering the necessity to preserve electrical neutrality. That is a matter for future research. The critical value of L_T for σ^* = 1 is

$$L_{T,crit} \approx 2.375 \times 10^4 T_e^2 / \alpha^* n_e (1 + \nu_{en} / 2\nu_{ei}), \tag{15a}$$

or,

$$L_{T,crit} \approx 2\lambda_{ee} / \alpha^* (1 + \nu_{en} / 2\nu_{ei}). \tag{15b}$$

In the absence of a better guess, put α^* = 0.25, as in the purely coulomb case. Then, the critical value of L_T, for transition to saturated flux is, using (2),

$$L^*_{T,crit} = 1 \times 10^7 T_e^{1/2} / \nu_{en}. \tag{15c}$$

The value of L_T is therefore decreased by dividing its purely coulomb value by the factor $(1 + \nu_{en} / 2\nu_{ei})$, which we approximate with $\nu_{en} >> 2\nu_{ei}$. Then, for an arbitrary value of L_T, when $\sigma^* > 1$, the overestimate of the conduction flux is

$$\sigma^* \approx 10^7 T_e^{1/2} / L_{T,arb} \nu_{en}. \tag{16}$$

This should be compared to the case (6b) when collisions with neutrals are negligible.

Assuming, as in the pure coulomb case, that α^* = 0.25, $\nu_{en} = 2\text{x}10^4 \text{s}^{-1}$, T_e = 116040K, then $L^*_{T,crit}$ = 1.7 km. Thus the choice of L_T = 2 km in Figure 3b of *Strangeway* [1996] of these parameters puts the conduction flux very close to saturation for these values of parameters. It may be doubted whether such an extreme condition, when subject to the requirement of electrical neutrality, will not produce unanticipated physical consequences. Uncertainty in the appropriate value of $L_{T,crit}$ is brought about by uncertainty in the value of α^*. However if the values taken from the laser field are any guide, the proper value of α^* may be a power of 10 less than the value used here. In this case $L^*_{T,crit}$ becomes 17 km, σ* = 8.5. Analagously to (8) it can be shown that

$$\sigma_1^* = \frac{\nabla F_c}{\nabla F_{c,crit}} = \frac{L^{*2}_{T,crit}}{L^2} = \left(\frac{1\times 10^7}{\nu_{en} L}\right)^2 T_e. \tag{17}$$

Figure 3b of *Strangeway* [1996] portrays conductive cooling, for *Te* in excess of about 7 eV, as overwhelming joule heating. However in this region the conduction is so close to saturation that new physics, involving preservation of electrical neutrality, may cause reduction of the heat flow and its divergence. Moreover there are other difficulties with the formula for conditions at 130km at night, still to be discussed. Figure 4b is to be compared with *Strangeway's* [1996, Figure 3b], to see the dramatic effect of saturated conduction.

3.3 The Self - Consistent Calculation of the Problem

Let us examine a "self-consistent" calculation of joule heating as portrayed, for example, in *Strangeway* [1996, Figure 7b]. Consider the region near the peak of the conduction cooling curve in the vicinity of 135 km altitude. From the information there and his Figure 6b we create Table 4. L_T is found by inspection of the temperature profile on the right hand side of the Figure 7b. On the bottom line Table 4 shows the minimum overestimate in the conduction cooling rate σ_1^*. This suggests that the self- consistent calculations of *Strangeway* [1996] are physically invalid.

Table 4

Alt	130	132	134	135	136
Te	8(5)	6(5)	4(5)	3(5)	2(5)
L_T	*5*	*3*	2	2	2
ν_{en}	*10(4)*	*2(3)*	900	700	600

σ*	3.2	167	31	31	37
σ_1^*	10	2.7(4)	1234	1530	1388

Caption: Table 4 shows the minimum overestimate σ_1^* in the conduction cooling rate.

3.4. The condition λ_{en} >> scale height of neutral gas:

Formula (1) is deduced for a gas of uniform composition. It breaks down when λ_{en} >> scale length of the neutral gas number density N, which we denote by L_N. This in turn requires that

$$\left(\frac{8kT}{\pi m_e}\right)^{1/2} \frac{1}{\nu_{en}} >> L_N, \tag{18a}$$

or

$$\nu_{en} << 6.2 \times 10^5 \frac{T_e^{1/2}}{L_N}. \tag{18b}$$

The scale height of the CO_2 (the dominant constituent of the lower thermosphere of Venus is about 2 km. In this case (18b) yields

$$\nu_{en} << 3T_e^{1/2}$$

The critical values of ν_{en} in (18b) are listed in Table 5, together with the approximate corresponding altitudes according to figures 4a,5b,6b and A2 of *Strangeway* [1996]. Above these altitudes in the lower thermosphere, the formula breaks down for the various temperatures stated provided $\nu_{en} >> 2\nu_{ei}$.

Table 5

T_e	1.16(5)	1.16(5)	1.16(5)	8.1(5)	1.16(6)
$\nu_{en,crit}$	102	323	1022	2700	3000
Alt(km)	142	137	135	133	132

It follows that the application of the classical heat conductivity formula (1) will not give reliable results in this region. *Strangeway's* [1996, Figures 4a-d,] paper therefore cannot be used as criticism of our work [*Cole and Hoegy*, 1996a,b]. This result has a bearing on the region of 5-10 eV in figure 3b of *Strangeway* [1996].

An example of a similar kind is in Figure A2 of *Strangeway* [1996]. Puting $\alpha^* = 0.25$, $T_e = 8\mathrm{x}10^5$K, $L_N = 2$ km (the scale height of the neutral gas), (18b) yields $\nu_{en} = 4.5\mathrm{x}10^4 \mathrm{s}^{-1}$, coresponding to an altitude of about 128 km. At all altitudes shown above this, $\lambda_{en} >> L_N = 2$ km applies, and there would be a breakdown of the implicit assumptions under which (1) is derived.

3.5 The Condition $\lambda_{en} >> L_e$

We consider that the condition $\lambda_{en} >> L_e$ violates the assumptions under which (1) is derived. Here L_e is the scale length of electron density. This may be expressed as

$$\left(\frac{8kT}{\pi m_e}\right)^{1/2} \frac{1}{\nu_{en}} >> L_e, \tag{19a}$$

or

$$6.2 \times 10^5 T_e^{1/2} / \nu_{en} >> L_e \tag{19b}$$

Values of L_e are shown in Table 6 for various values of T_e and ν_{en} taking data from figures 6a,b and7d of Strangeway [1996]. L_{eo} is the scale length L_e estimated from his Figure 7d

Table 6

Alt	130	135	140
T_e	8(5)	1.2(5)	5(4)
ν_{en}	2(4)	7(2)	1(2)
λ_{en}	0.3	3.2	14

L_{eo}	0.14	2	∞

It is evident from this table that the classical formula for conduction is being applied under conditions not envisaged in its derivation. at around 135km in the region of peak conductive cooling according to his Figure 7.

3.6 Special case: Venus Ionosphere at 130km Altitude at Night:

This region is of considerable interest in the debate over the relationship of the100Hz signal to whistlers [*Cole and Hoegy*, 1996a,b; *Strangeway*, 1996, 1997a,b]. This altitude is a crucial one in terms of refractive index [*Cole and Hoegy*, 1997b]. It has been supposed that whistlers get to higher altitudes (160 km and above) by passage through this highly dissipating region [*Strangeway*, 1996, 1997].

It is noted in passing that theoretically there is no guidance of whistlers by the magnetic field in this region [*Cole and Hoegy*, 1997], contrary to the view of *Strangeway et al.*, [1993]. In other words the 100 Hz signal does not appear to behave as a whistler in this region.

Considering first the role of saturation flux in the profiles of Figure7d, together with the data of *Strangeway* [1996]. We construct Table 7 using (15c).

Table 7

Alt	130	135	140
T_e	8(5)	1.2(5)	5(4)
ν_{en}	2(4)	7(2)	1(2)
$L_{T,crit}$	4.4	49	223
L_T	4	3	12
σ_1^*	1.25	272	347

It follows that even from the viewpoint of saturation flux there is overestimation by Strangeway of conductive cooling when using the classical formula. At these altitudes equating joule heating to inelastic collisional cooling should give a reasonsble estimate of electron temperature.

Estimating T_e: Let us compare τ_{ee}, involving elastic collisions, to the collision interval of electrons and CO_2,

$$\tau_{en} \approx 5 \times 10^{-5} s \ , \tag{19}$$

involving inelastic collisions [*Cole and Hoegy*, 1996a,b; *Strangeway*, 1996, 1997a,b]. According to *Morrison and Greene* [1978] the transfer of energy to the vibrational and rotational levels of CO_2 exceeds that transferred to translational kinetic energy by elastic collisions, by a factor of 1000, in the electron energy range of interest here. Now the transfer of kinetic energy between an electron and a CO_2 molecule per elastic collision compared to that between an electron and an electron is m_e / m_{CO2}. Then in a CO_2 thermosphere, the energy transfer rate to neutrals by electrons greatly exceeds that to electrons by electrons whenever

$$\frac{1000}{\tau_{en}} \frac{m_e}{m_{CO2}} >> \frac{1}{\tau_{ee}}. \tag{20a}$$

That is, the *e*- CO_2 energy transfer rate >> the *e*-*e* rate when

$$T_e^{3/2} >> 0.2 n_e. \tag{20b}$$

This is always the case at 130km at night. For example, if $n_e < 1000$ cm^{-3}, $T_e >$ 35 K. That is, the electrons do not get a chance to thermalize amongst themselves between collisions with neutrals. Local thermal equilibrium in the electron gas would not exist. It follows that conventional theory of electron conductivity cannot be used here. Electrons do not get a chance to convey information about a possible gradient in their "temperature" or rather their energy density. It follows further that electron-electron energy exchange is negligible compared to cooling by inelastic collisions with CO_2 (see also next section). We conclude that, in this case, the electron "effective" temperature is well approximated by the local balance of local heating and collisional cooling rates. This supports our earlier finding for this altitude range at night [*Cole and Hoegy*, 1996a,b]

In the case of the lower Venus ionosphere at night, for joule heating of the electrons by ac electric fields, and collisional cooling by CO_2, this means that the electrons have an average energy density ε characterized by an "effective" temperature. Thus $\varepsilon \approx (3/2) n_e k T_{eff}$, where

$$T_{eff} = \frac{e^2 m_{CO2}}{3000 m_e^2}\left\langle \frac{E_\perp^2}{\nu_{e,CO2}^2} \right\rangle, \quad (21)$$

independent of n_e [*Cole and Hoegy*, 1996b]. Putting $E^2 = 10^{-6}$ $V^2/m^2/Hz$, and a natural bandwidth of 100 Hz, we find T_{eff} ~1.2x 10^4 eV, by equating joule heating to vibrational cooling. See alaso Figure 4b. This is a factor of three less than the temperature estimated from *Strangeway* [1996, figure 3b] In order to reduce T_{eff} to a reasonable 500 K at 130 km altitude at night, we would need to limit E^2 to 4×10^{-8} $V^2/m^2/Hz$. This would exclude from interpretation as due to whistlers, over 25 of the highest intensity points on Figure 4 of *Strangeway et al.* [1993b]. This represents a large fraction of the data at and near this altitude. Heating the electrons would surely diminish their density, on account of the increased temperature and mean free path. We regard this heating as excessive and pursued its physically inconsistent outcomes elsewhere [*Cole and Hoegy*, 1996b].

Equation (10) produces the relations (20a) and (20b). Figures 3a,b demonstrate the altitudes at which the ratio $\lambda_{ee} / \lambda_{en} >> 1$. When the thermosphere is dominated locally by CO_2 neutrals, but has O^+ ions, this inequality is given, from (2) and (13), by

$$\tau_{en} << 9 \times 10^{-6} f_{inel} T_e^{3/2} / n_e A_n \quad (22a)$$

or,

$$\tau_{en} << 2 \times 10^{-4} T_e^{3/2} / n_e \quad (22b)$$

in which mass number A_n = 44, and , f_{inel} ~1000. Thus , for example, if T_e = 2000K, and n_e = 500 cm^{-3}, (22) requires that $\nu_{en} >> 27s^{-1}$. This is true below about 145km in the night thermospheric model of *Strangeway* [1996; figure 5]. This estimate of altitude does not take account of cooling by atomic oxygen which would raise it. This is the region which is especially important observationally for the whistler hypothesis for the 100 Hz signal [*Strangeway et al*, 1993b]. In this region the electron temperature caused by only local heating by 100 Hz waves can be estimated from Equation (21). Simply, the role of heat conduction in the electron gas is small, in determining T_e because K_e approaches zero when $\nu_{en} >> \nu_{ei}$. The bulk of the energy of joule heated electrons is lost locally, as was deduced in the argument leading to (21). The same conclusion applies if one assumes a large scale length in the electron temperature, such as was adduced from data earlier [*Cole and Hoegy*,1996a,b], using the classical heat conductivity formula.

4 Relevance to the Whistler Hypothesis for the 100 HZ Signal at Venus

The theory of heat conduction in electrons has a bearing on the question of whether there is lightning on Venus [*Cole and Hoegy*, 1996a; *Strangeway*, 1996]. A detailed case for lightning has been made [*Russell*, 1991; *Strangeway et al.*, 1993a,b]. The hypothesis that the 100 Hz signal observed in the Venus ionosphere is due to whistlers formed a most significant role in the support of the case for lightning. It is therefore important to subject the hypothesis to the closest scrutiny. We have attempted this in our series of papers.

The whistler hypothesis for the 100Hz signal observed by PVO in the Venus ionosphere has been examined and criticized [*Cole and Hoegy*, 1996a,b; 1997a] on the grounds that there would be excessive heating of the electrons, taking into account all the microscopic energy transfer processes. At the insistence of *R. L. Strangeway*, [see *Cole and Hoegy* ,1996a; acknowledgments], the latter authors included the conventional equation (1) in energy budget calculations for electrons, but argued for a long characteristic thermal conduction length scale of order 10^4km, above 150 km altitude, on the basis of data examined, thus limiting the local loss of electron energy by heat conduction. This was countered by *Strangeway* [1996] who argued for relatively short scale lengths. This left the question of the whistler hypothesis unresolved in this subject. At that time we had not appreciated the limitations imposed upon the use of (1), known at Earth [c.f., *Cole*, 1965], as they might apply in the Venus ionosphere, and now demonstrated in the present paper. We have shown above that these limits have a similar quantitative effect (albeit physically different) to the limitations imposed by the choice of a large scale length of conduction. These limitations, and the conclusions deduced from them above, add support to the thesis of *Cole and Hoegy* [1996a,b; 1997a] that the heating produced by the strongest 100Hz electric fields observed in the Venus ionosphere would cause excessive, unobserved, electron temperatures, thus invalidating the whistler hypothesis for them. The limitations certainly do not support the general argument of *Strangeway* [1996, 1997] that heat conduction in the electron gas would nullifiy the significant heating , and susequent aeronomic effects predicted by *Cole and Hoegy* [1996a,b].

Calculations of T_e in the Venus ionosphere involving the classical heat conductivity for electrons may lead to incorrect inferences as we believe has happened [*Strangeway*, 1996, 1997a,b], as we have demonstrated here. Strangeway's [1996a,b] criticism of our work is not justified. Though we also used the classical formula, at the insistence of an editorial referee, we at least used data to justify a very large scale length for the system [*Cole and Hoegy*, 1996 a,b]. This has similar physical consequences to those of the present paper which is more fundamental in its approach.

5 Conclusions:

General: The critical thermal scale length discussed in the text defines an upper limit to the classical conduction flux. It is probably not the real upper limit. We suggest that because of the demands of electrical neutrality a more realistic (longer) critical thermal scale length can be set. This is the subject of further research.

Conditions implying a very long thermal scale length occur frequently in vast regions of the Venus ionosphere [*Cole and Hoegy*, 1996a,b]. At these times it is not valid to apply the classical heat conduction formula (1) with a shorter thermal scale length to infer a significant cooling of electrons. It has been shown here that, in regions where 100Hz electric fields exist, there are found conditions for the breakdown of the classical formula. In particular they invalidate *Strangeway's* [1996] criticisms of *Cole and Hoegy's* [1996a,b] case against the hypothesis of planetary scale whistlers for 100 Hz signals observed on PVO. *Strangeway* [1996] found generally negligible rises in T_e in joule heated electrons on the assumption of the applicability of the classical formula together with short thermal scale lengths. This assumption is seen to be without physical support.

We have examined conditions under which the use of the classical formula for heat conductivity breaks down, and pointed out how the inappropriate use of the formula has led *Strangeway* [1996] to attack our criticism of the whistler hypothesis for 100 Hz signals observed in the Venus ionosphere. We have demonstrated that his criticism is not justified in all the specific examples he analyses. Heat conduction cooling clearly does not overwhelm joule heating, in these cases, contrary to his claim. This is clearly portrayed in our Figures 4a,b and 5a,b. Any differences in detail of these graphs and the corresponding ones in Figures 2a,b and 3a,b of *Strangeway* [1996] we believe are due to his use of approximate formulas somewhat (and mostly slightly) different from ours given in *Cole and Hoegy* [1996a].

We have extended the discussion of the concept of saturation flux to show its relation to the mean free path of electrons, and to the case of a partially ionised gas. This has been illustrated by means of observations in the ionosphere of Venus from the Pioneer Venus Orbiter. The following are some of the main conclusions relevant to Venus.

Around the ionopause during the daytime. Here we have violation of conditions of applicability of the conduction formula by virtue of λ_{ee} being very much greater than the scale length of the ionosphere. This suggests that calculations based upon the classical formula together with very "long" scale lengths for T_e would yield a good first approximation to T_e, as was reported in *Cole and Hoegy* [1996a,b]. We now appreciate that "long" means " of the same order or more", as the critical length scale of the electron temperature.

Below 145 km at night: The applicability of the formula (1) for heat conduction in the electron gas depends on the ratio ν_{en} / ν_{ee}, = $\lambda_{en} / \lambda_{ee}$. In the lower Venus ionosphere K_e is formally heavily reduced because of the ratio ν_{en} / ν_{ee}. It frequently becomes inapplicable because λ_{ee} >> scale height of neutral gas, in the altitude range below 145km. The critical thermal length scale can be very large.

Lightning: There are two important regions concerning the linkage of the whistler hypothesis for the 100 Hz signal to the hypothesis that the whistlers are due to lightning. One is in the vicinity of 160 km at night [*Strangeway et al*, 1993a]. Thus from figure 1, for $n_e = 10^3$ cm^{-3}, and T_e = 3000K,the electron mean free path would be 10^4km, and the heat conduction scale length would be at least 10^4 km and possibly 6.5x 10^4km, if we invoke the work of *Merritt and Thompson* [1980]. This is consistent with the data based argument of *Cole and Hoegy* [1996a,b] that there would be significant rises of electron temperature caused by strong observed 100 Hz. electric fields. The second is near 130 km altitude at night, where the strongest 100Hz signals are observed [*Strangeway et al.*, 1993b]. At these places the conditions for the validity of the classical electron heat conduction formula break down, for a variety of reasons on account of *e-n* collisions (see Table 7), and the conclusions of *Cole and Hoegy* [1996a,b] are vindicated.

Because of the conditions for breakdown of the heat conduction formula, estimates of physically significant, and aeronomically doubtful and unobserved values of T_e associated with a large proportion of electric field events casts doubt on the whistler hypothesis for electric fields of 100Hz. In turn this supports our contention that the observations of the 100Hz electric field signal may not be used to support the case for lightning on Venus [*Cole and Hoegy*, 1996a,b] which is in contrast to the view portrayed by *Strangeway* [1996, 1997a,b], and in the recent review by *Grebowsky et al.*,[1997]. The only substantial criticism of our conclusion on this question has come from *Strangeway* [1996, 1997a,b]. His argument invoking heat conduction in the electron gas to disperse and nullify the 100Hz electric field joule heating found by us has been shown here to be without foundation. Our conclusion that the 100Hz electric field data should not be used to substantiate a case for lightning on Venus still stands. Other data must be used for that purpose,

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Captions :

Figure 1. Plots of λ_{ee} for ranges of values of *ne* and *Te* . Note $L_{T,crit}$

is about $8\lambda_{ee}$.

Figure 2a. Mass-plot of λ_{ee} as a function of altitude derived from UADS, ne and Te at night, for the first 900 orbits by the Pioneer Venus orbiter (PVO). Note that the altitudes have a lower limit of about 180 km.

Figure 2b. Mass-plot of λ_{ee} as a function of altitude derived from UADS, ne and Te during daylight, for the first 900 orbits by the Pioneer Venus orbiter (PVO).

Figure 3a. Reworked figure 2a of *Strangeway* [1996] using concept of saturation flux, including his original conduction cooling graph (dot curve, with L = 1000 km = L_T) which is to be compared with ours (dot-dash curve, with $L_T = L_{T,crit}$). Note E = 10 mV/m. Bo = 50nT. The dashed line represents collisional cooling of electrons. The ions are O+.

Figure 3b Reworked figure 2b of *Strangeway* [1996], as in Figure 3a above.

Figure 4a Reworked figure 2a of *Strangeway* [1996] using concept of saturation flux, including his original conduction cooling graph (dot curve, with L = 10 km = L_T) which is to be compared with ours (dot-dash curve, with $L_T = L_{T,crit}$). Note E = 1 mV/m. Bo = 30 nT. The dashed line represents collisional cooling of electrons. The ions are O+. Neutrals are O with density of 4x10(8) cm-3.

Figure 4b Reworked figure 3b of *Strangeway* [1996], as in Figure 4a above, except that E = 10 mV/m. Bo = 5 nT, and n_e = 1000 cm-3 . Dot curve (L = 2 km = L_T) which is to be compared with ours (dot-dash curve, with $L_T = L^*_{T,crit}$).

The dashed line represents collisional cooling of electrons. Neutrals are CO_2 with density of 10(11) cm-3.

Figure 5a. Plots of *p* for night ionospheres, above 150 km altitude, for the first 900 orbits of PVO.

Figure 5b. Plots of *p* for day ionospheres, above 200 km altitude, for the first 900 orbits of PVO.

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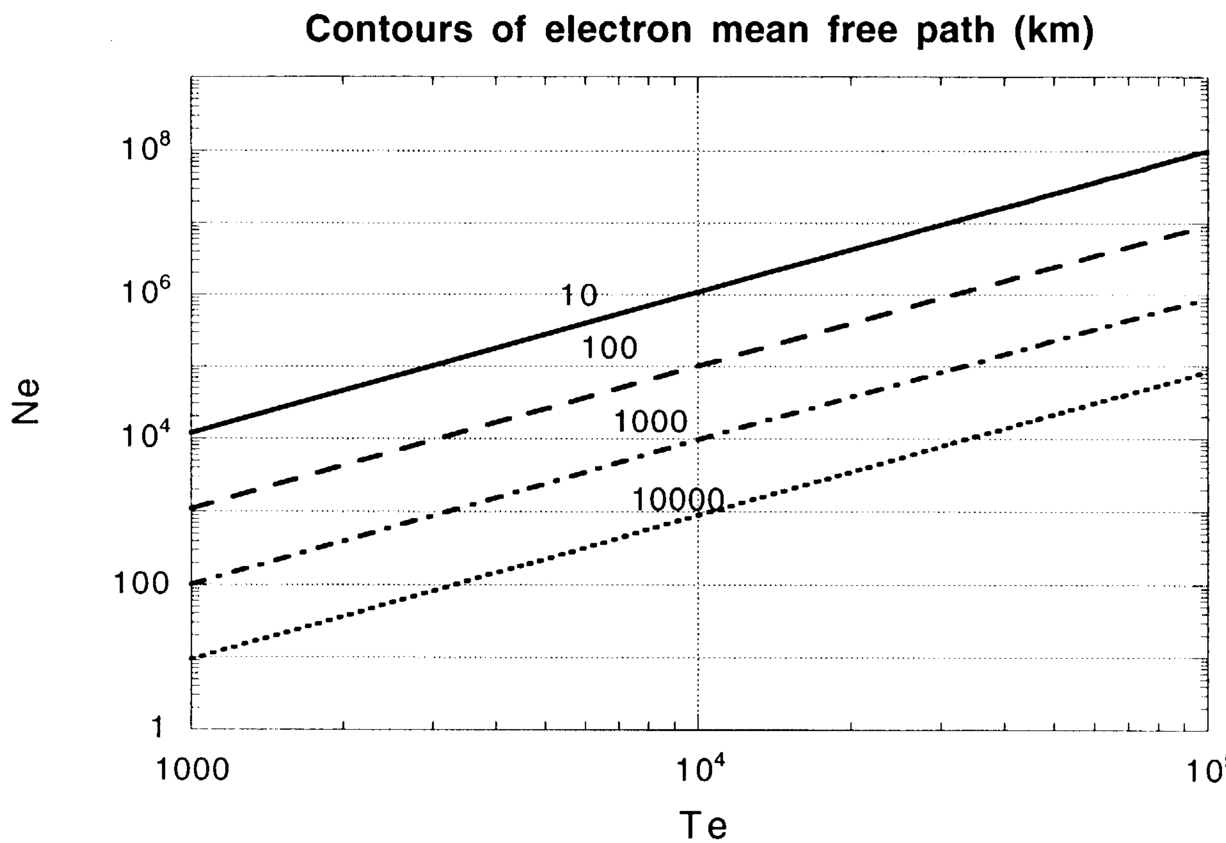


Contours of electron mean free path (km)
Ne
10^8
10^6
10^4
100
1
1000
10^4
10^5
Te
10
100
1000
10000

Figure 1

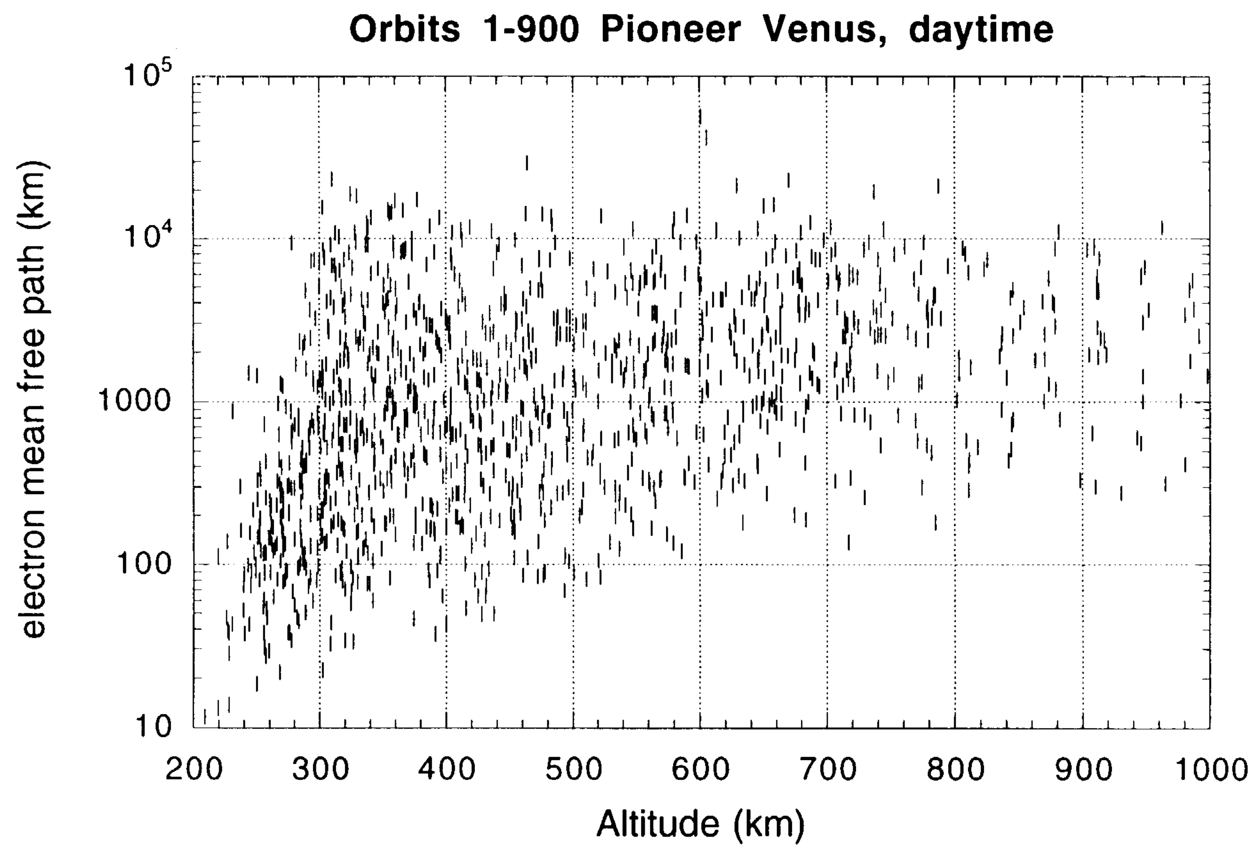

Orbits 1-900 Pioneer Venus, daytime
electron mean free path (km)
10^5
10^4
1000
100
10
200
300
400
500
600
700
800
900
1000
Altitude (km)

Figure 2a

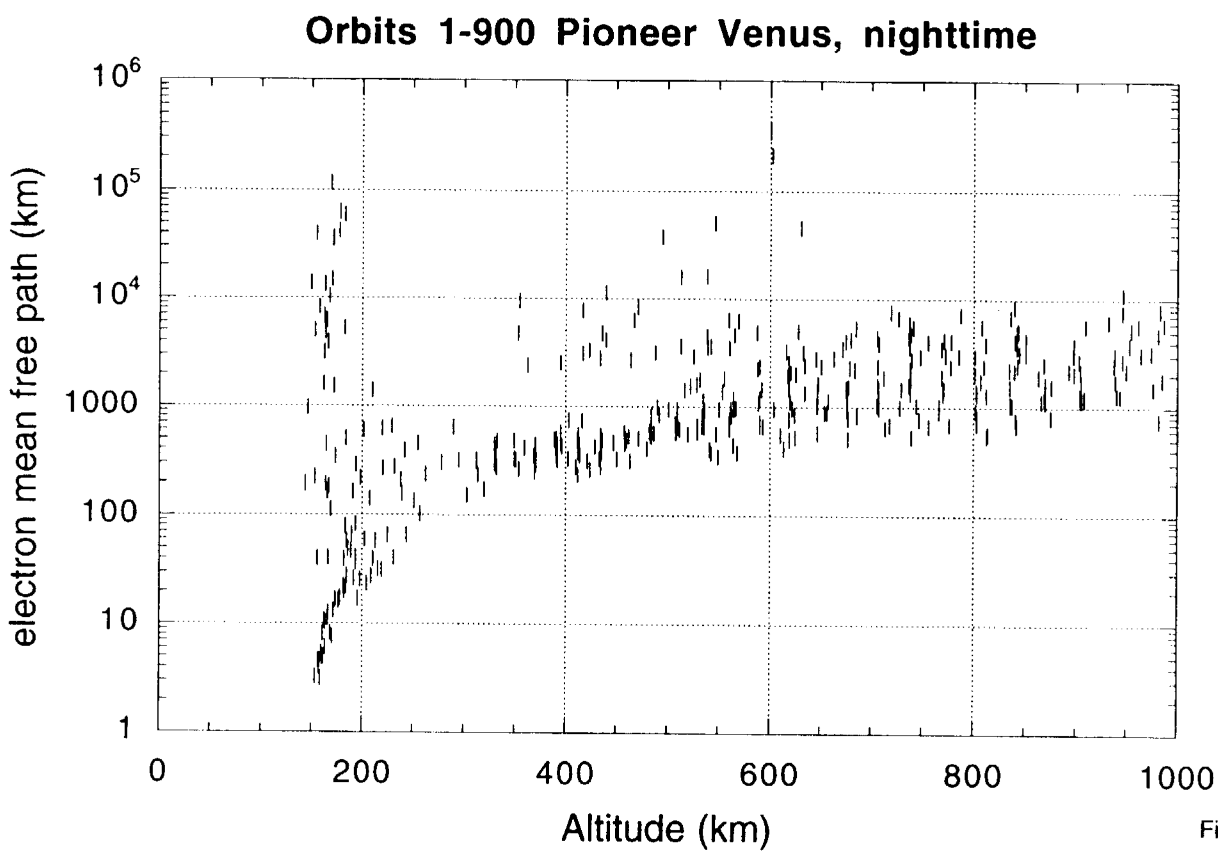
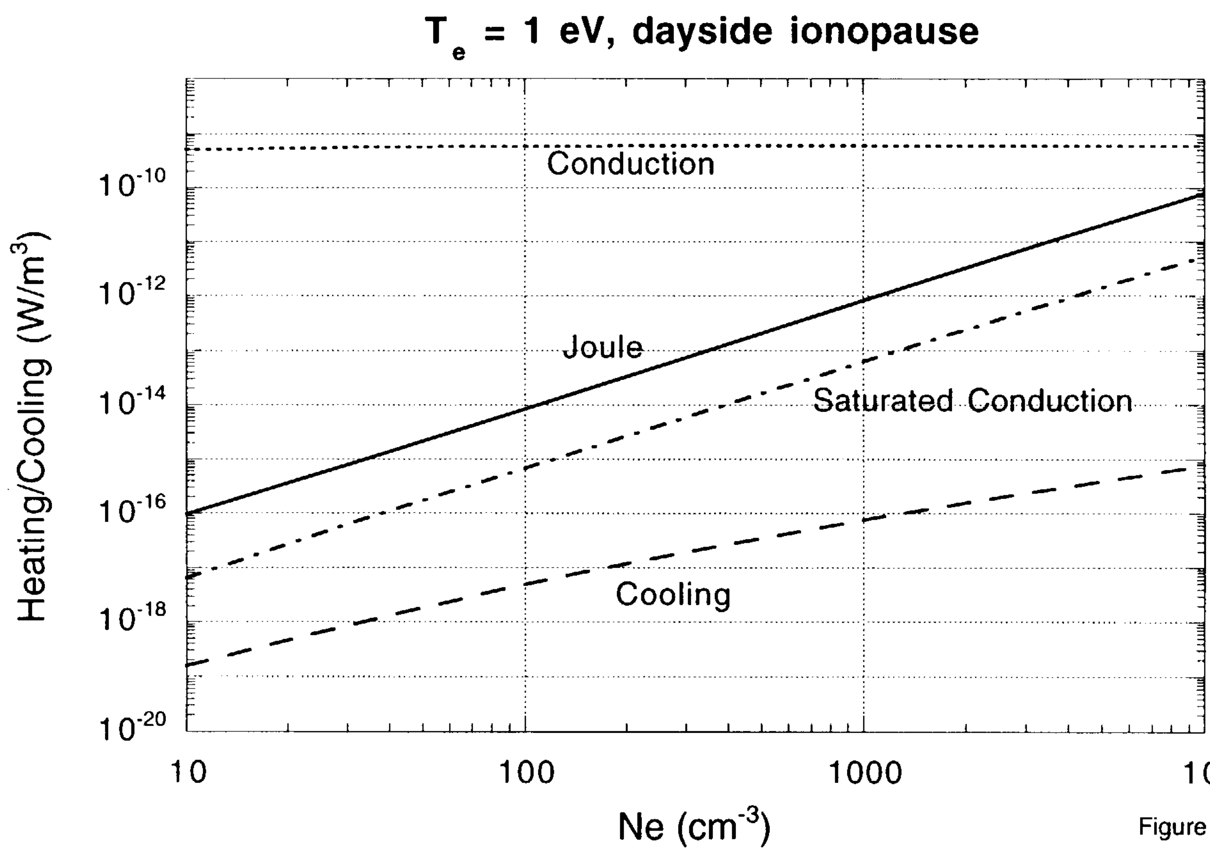

Orbits 1-900 Pioneer Venus, nighttime
electron mean free path (km)
10^6
10^5
10^4
1000
100
10
1
0
200
400
600
800
1000
Altitude (km)

Figure 2b



T_e = 1 eV, dayside ionopause
Conduction
Joule
Saturated Conduction
Cooling
Heating/Cooling (W/m^3)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10
100
1000
10^4
Ne (cm^{-3})

Figure 3a

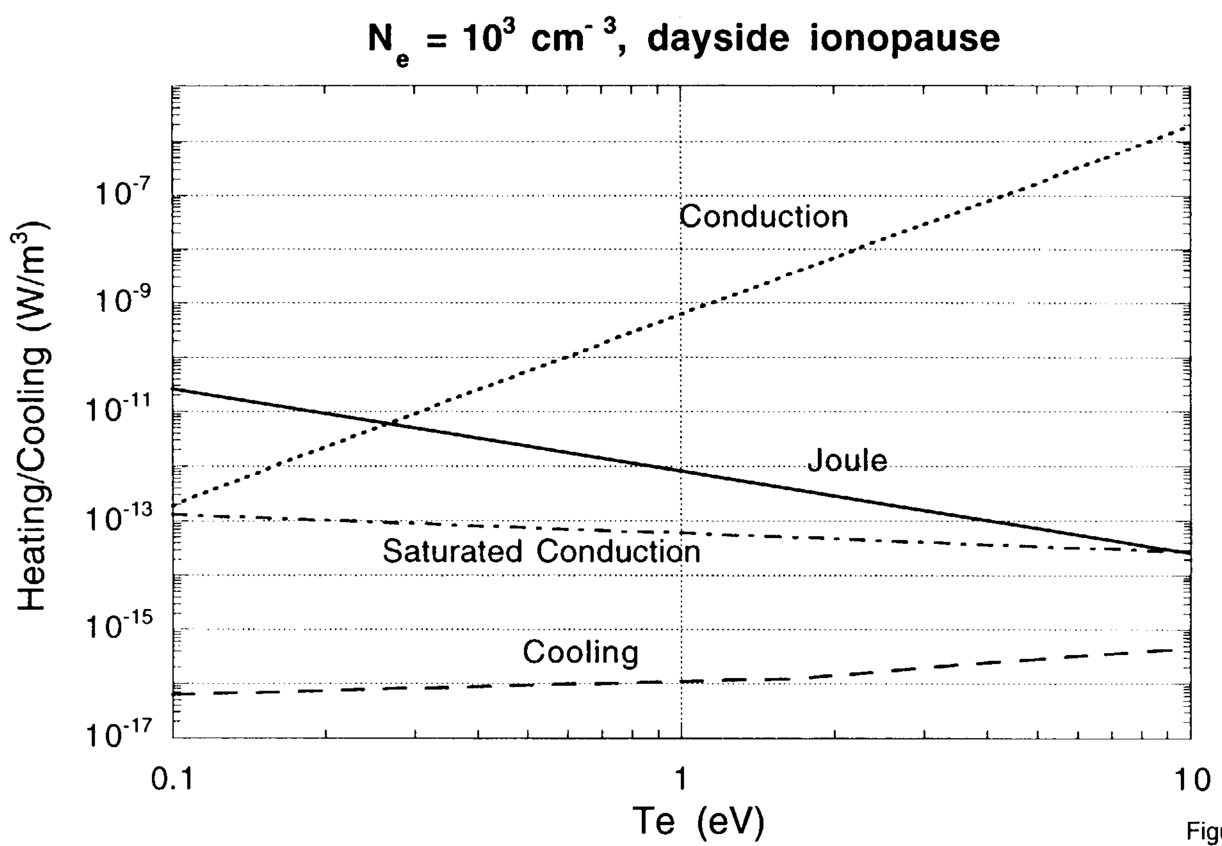
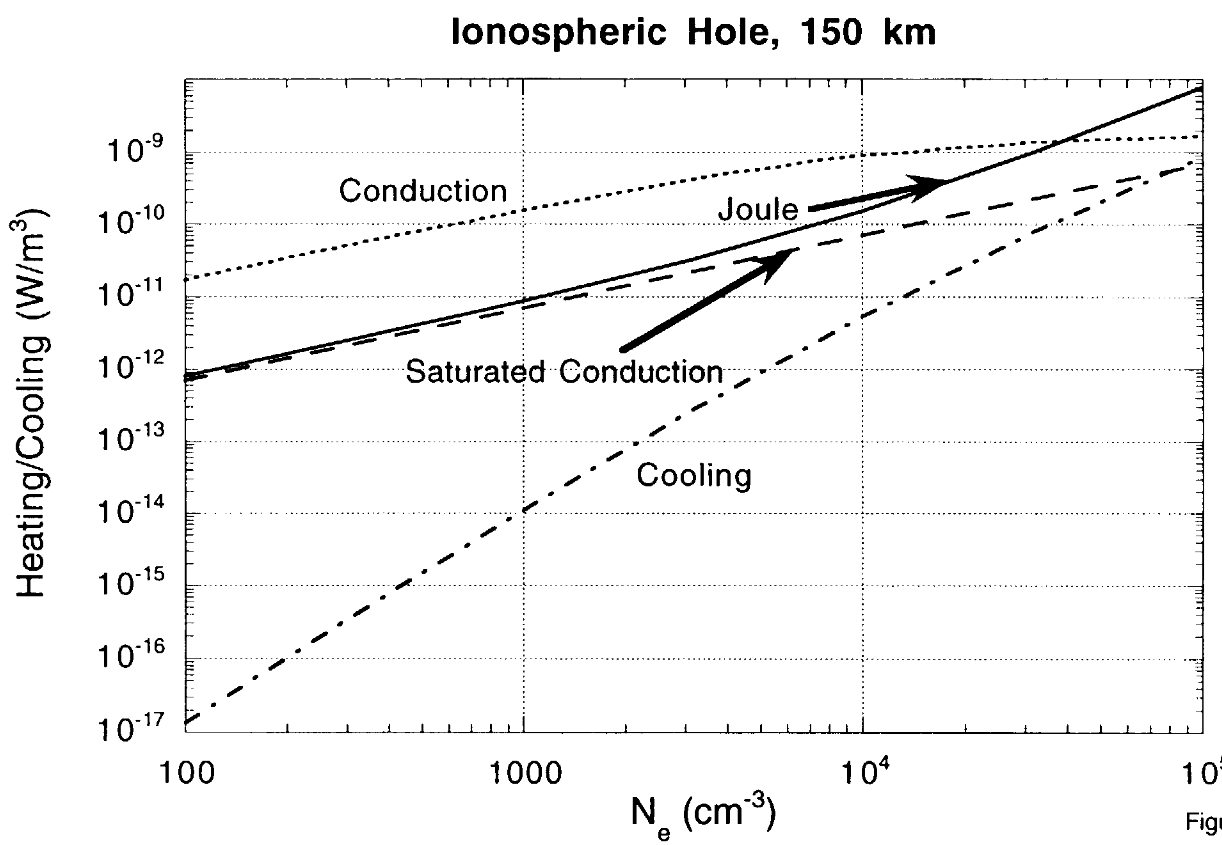

N_e = 10^3 cm^-3, dayside ionopause
Conduction
Joule
Saturated Conduction
Cooling
Heating/Cooling (W/m^3)
10^-7
10^-9
10^-11
10^-13
10^-15
10^-17
0.1
1
10
Te (eV)

Figure 3b



Ionospheric Hole, 150 km
Conduction
Joule
Saturated Conduction
Cooling
Heating/Cooling (W/m^3)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
100
1000
10^4
10^5
N_e (cm^{-3})

Figure 4a

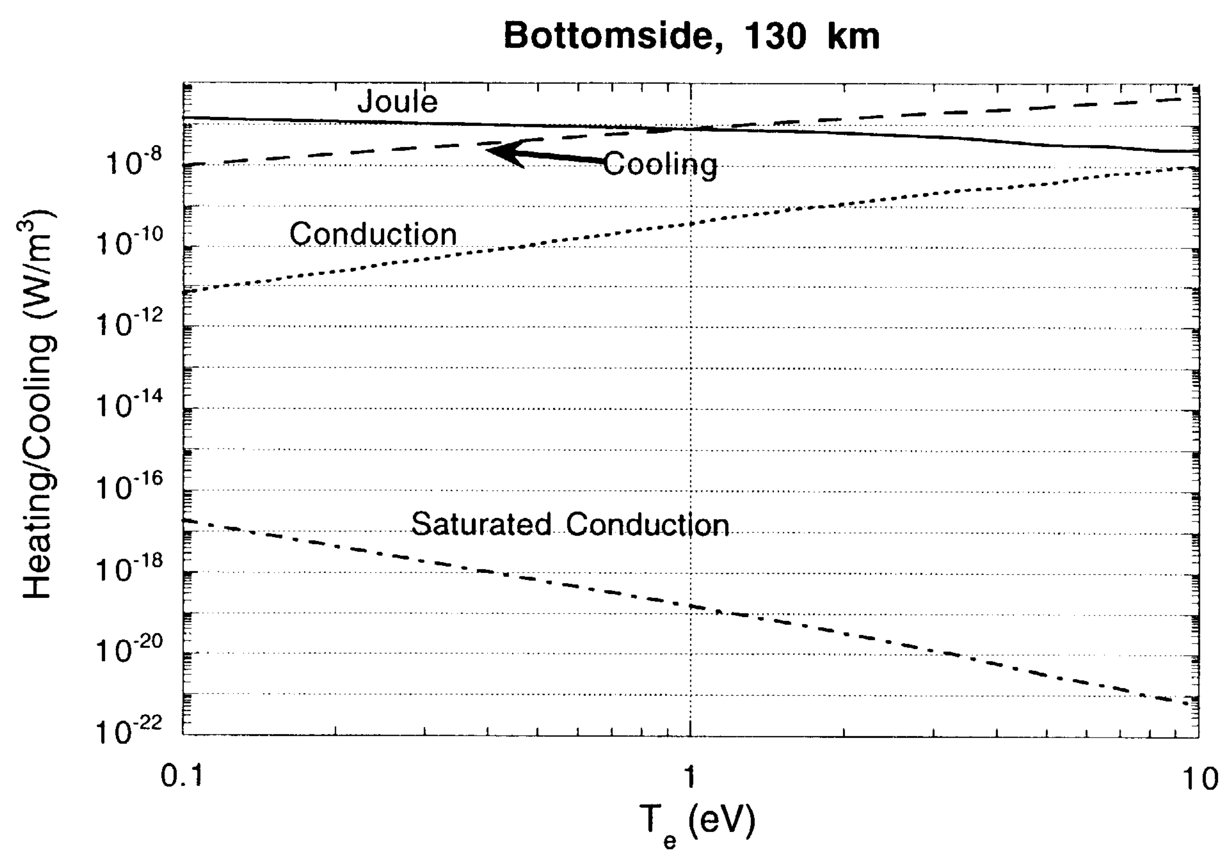
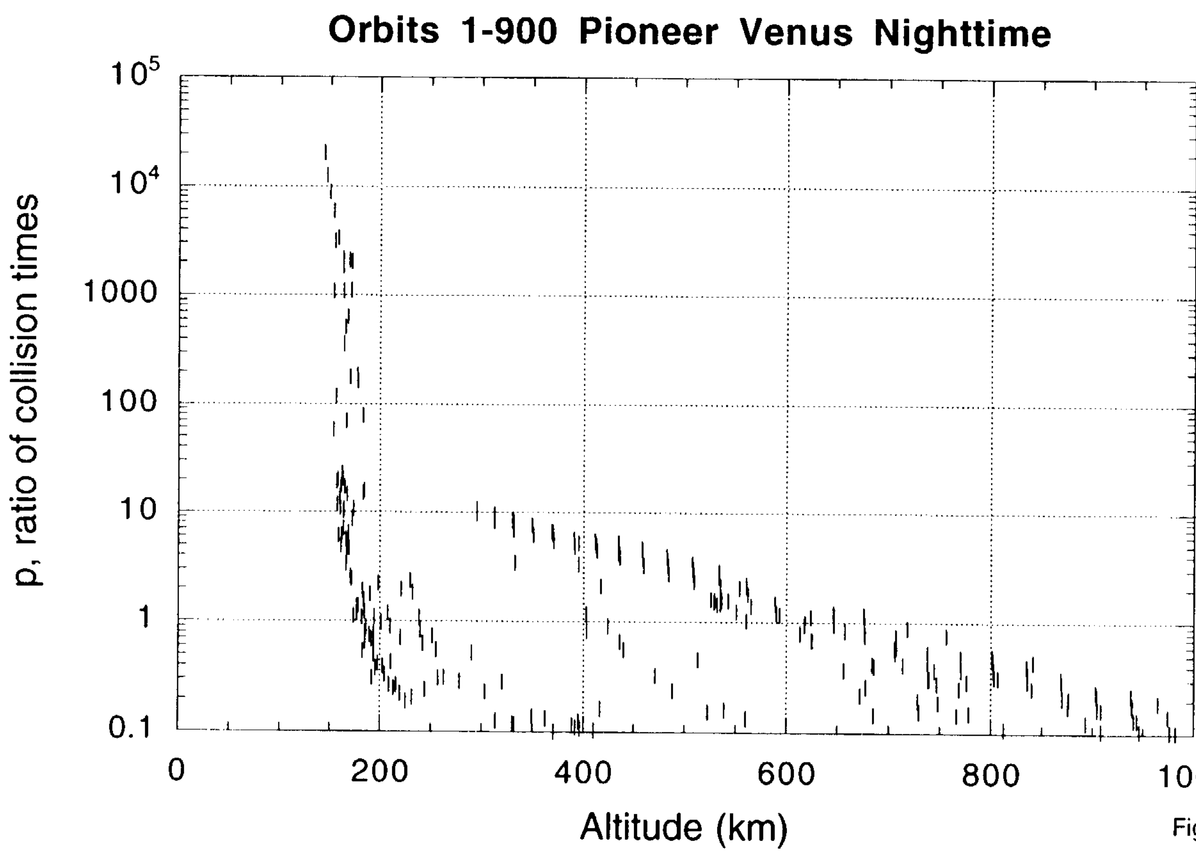

Bottomside, 130 km
Joule
Cooling
Conduction
Saturated Conduction
Heating/Cooling (W/m^3)
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
0.1
1
10
T_e (eV)

Figure 4b



Orbits 1-900 Pioneer Venus Nighttime
p, ratio of collision times
10^5
10^4
1000
100
10
1
0.1
0
200
400
600
800
1000
Altitude (km)

Figure 5a

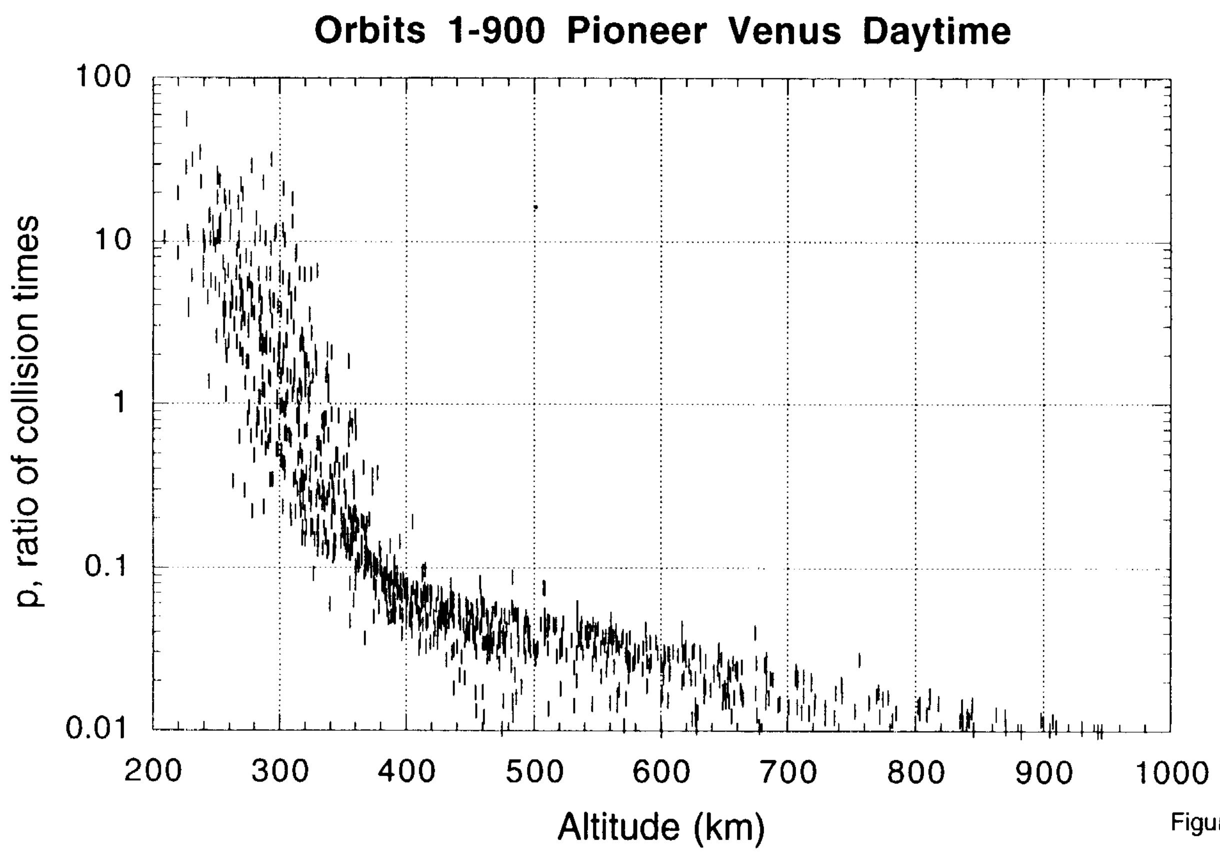

Orbits 1-900 Pioneer Venus Daytime
100
10
1
0.1
0.01
p, ratio of collision times
200
300
400
500
600
700
800
900
1000
Altitude (km)

Figure 5b