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A NECESSARY CONDITION FOR THE
CRITICAL IONIZATION VELOCITY
INTERACTION

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1. Introduction

In his theory on the origin of the solar system, Alfvén (1954) proposed that a strong interaction should occur when the relative velocity between a magnetized plasma and a neutral gas exceeds the critical ionization velocity

$$v_c = (2eU_i/m_n)^{1/2}, \quad (1)$$

where m_n and U_i are the mass and the ionization potential of the neutral atom or molecule, and e is the electron charge. Since Alfvén's original proposal, the effect has been repeatedly observed in laboratory experiments in a wide range of parameters (e.g. Danielsson, 1970; Axnäs, 1972, 1978; Danielsson and Brenning, 1975; Piel and Möbius, 1978 and Mattoo and Venkataramani, 1980). The central aspect of the interaction is a rapid ionization of the neutral gas through electron impact; momentum exchange between the ionized neutrals and the plasma stream results in a decrease in the relative velocity between the plasma and the neutral gas. Simultaneously, the plasma electrons are heated so that they can keep up the ionization. The phenomenon is not yet completely understood, but theoretical models exist for some configurations. A review of the theoretical work was made by Sherman (1973). Raadu (1978) has discussed the role of electrostatic instabilities in the interaction.

The clear establishment of the phenomenon in the laboratory has been followed by a number of proposed applications in the ionospheres and magnetospheres of the planets, and in the solar wind (e.g. Lindeman *et al.*, 1974; Srnka, 1977; Cloutier *et al.*, 1978; Petelski *et al.*, 1980). The aim of the present work is to derive a condition, which can be used in such applications to quickly assess the possibility of v_c -interaction. The proposed applications usually concern a highly ionized plasma with supercritical velocity, which penetrates into a limited region with neutral gas. The most interesting feature is in most cases electron heating and subsequent electron impact ionization. We therefore concentrate on this aspect on the interaction, and examine under what conditions it is possible to heat the electrons so much that they can start ionizing the neutrals efficiently.

The approach is based on the observation that there has to exist some energy-transferring mechanism in the interaction. This mechanism must tap the energy source—the kinetic energy in the relative motion between the plasma and the neutral gas—and transfer part of the energy to the electrons. We will here calculate how efficient this unspecified energy-transferring mechanism has to be, if the interaction is to occur in a given situation. We will not discuss the possible mechanisms for the energy transfer; this is a problem which must be studied separately in each individual case. The result of this work will therefore not answer the question if v_c -interaction actually will occur; we will only get an answer to the question if the interaction is energetically possible.

Often one might be satisfied with this result, for example in cases where the interaction turns out to be either impossible, or possible with a very wide margin. Another case is when the v_c -interaction actually is observed; the condition for v_c -interaction then gives a measure of the efficiency in the interaction.

The model and the outline of the calculations are described in Section 2. In Section 3 the calculations are performed, and the condition for v_c -interaction is derived. The approximations and assumptions that are made in this derivation are listed and discussed in Section 4. The use of the condition is summarized in Section 5, and illustrated by two examples in Section 6. Section 7, finally, contains a short discussion of the results.

2. The energy flow in the interaction

We consider a uniform plasma with initial temperature T_{eo} and velocity v , which streams from vacuum into a region with neutral gas, see Fig.1. (There are reasons to believe that the interactions requires the presence of a magnetic field transverse to the stream direction, but for a discussion of the energy aspect it is not necessary to assume that there is such a field.) We want to know under which circumstances so much energy can be transferred to the electrons that they can start ionizing the neutrals efficiently. The problem is split up in two parts: first (Section 3.1) we examine when there is enough energy in

the energy source (the kinetic energy in the relative motion between the plasma stream and the neutrals). This will lead to a condition on the initial velocity and the mass ratio $m_{\text{ion}}/m_{\text{neutral}}$. The second step (Section 3.2) is to examine the tapping of this energy source. Not all the energy in the relative motion is readily available; the neutrals have to be ionized before they can be involved in collective processes that can increase the electron temperature. The instantaneously available energy for electron heating in a volume of the gas-plasma mixture is therefore limited to the kinetic energy in the relative motion between the original plasma and the new ions created by ionization of the neutral gas. It increases as the ionization increases. When electron impact is the dominating ionizing process we can calculate the ionization rate, and hence the rate of release of energy, from the electron temperature. This will lead to a second condition on the parameters, which has to be fulfilled if the plasma shall be able to tap the energy source fast enough during the penetration into the neutral gas. This second condition contains also the neutral gas density and spatial extension, and the electron impact ionization cross section of the neutrals.

Both these conditions will be expressed as conditions on the energy transfer factor K . K is the fraction of the energy released in an element of plasma, that is transferred to the electrons in that same element during its penetration into the neutral gas. The rest of the energy can be picked up by other particles, conducted away, or simply remain with the ionized neutrals. (The last alternative covers the possibility that no energy transfer mechanism can operate.) K must always lie between 0 and 1; the value in the individual case is determined by a combination of the microscopic aspects of the interaction (the energy transfer mechanism) and the macroscopic (energy loss through heat conduction).

3. Calculations

The electron impact ionization rate increases very steeply with temperature when the mean electron energy is around the ionization energy. We here choose the temperature $kT_e = eU_i$ to signify the

threshold of efficient ionization. (The choice of this temperature is not a sensitive parameter for the end result; this will be discussed in Section 4.4).

3.1 The available energy in the plasma stream

We now disregard the problem of how fast the energy can be released through ionization, and only consider the total amount of energy available in the plasma stream. We take a volume of plasma originally containing n_1 ions of mass m_i , which moves into the neutral gas with the velocity v . The boundaries of the volume are taken to follow the stream, so that the number of original ions remains constant. Due to electron impact ionization within the volume, n_2 new ions of mass m_n are picked up during the penetration into the neutral gas, and as a result the velocity decreases from v to v_1 . When no momentum is exchanged across the boundaries of our volume element, momentum conservation gives

$$m_i n_1 v = (m_i n_1 + m_n n_2) v_1, \quad (2)$$

while the released energy is given by the change of energy in the directed motion,

$$W_{rel} = m_i n_1 v^2 / 2 - (m_i n_1 + m_n n_2) v_1^2 / 2. \quad (3)$$

For simplicity, we disregard electron energy loss through other inelastic collisions than ionization (see Section 4.1).

When a fraction K of the released energy is transferred to the $(n_1 + n_2)$ electrons, their temperature is given by

$$\frac{3}{2} kT_e (n_1 + n_2) = K W_{rel} - n_2 eU_i. \quad (4)$$

We now consider heating to $kT_e = eU_i$. Eqs (1) - (4) can be combined to give

$$K = \left(\frac{v}{v_c} \right)^2 \frac{(3m_n/m_i + 5(v/v_1 - 1))}{2(1 - v_1/v)}. \quad (5)$$

The ions in the original plasma stream have given up slightly more than half of their energy, when the velocity has decreased

with 33%. If we require that the velocity decrease shall be smaller than this during the initial heating of the electrons to $kT_e = eU_i$, we get the following condition on K :

$$K \geq \left(\frac{v_c}{v} \right)^2 \left(4.5 \frac{m_n}{m_i} + 3.75 \right) \quad (6)$$

A more detailed study reveals that this result does not depend sensitively on the choice of $kT_e = eU_i$, or on the choice of 33% as the limit for the velocity decrease. More important is the assumption that no momentum is exchanged between different volumes of plasma. This might not always be true; consider, say, the case when we want to know if v_c -interaction can occur in a limited neutral gas cloud situated in a magnetized plasma stream of much larger extension. (This resembles the proposed experiment on v_c -interaction in the ionosphere discussed by Axnäs, 1980). The plasma which penetrates into the neutral gas can then, by $\underline{i} \times \underline{B}$ forces, exchange momentum with the surroundings. The energy required to heat the electrons locally in the neutral gas cloud can then be provided by the deceleration of a larger volume of surrounding plasma. Equation (6) is therefore a sufficient, but not always necessary condition on the initial energy in the plasma stream.

3.2 The tapping of the available energy

The rate of production of stationary ions per m^3 and second is

$$Q = n_n n_e S_i + Q_o, \quad (7)$$

where S_i is the ionization rate coefficient for electron impact ionization. Q_o is the production of stationary ions due to other processes, e.g. photoionization or charge exchange collisions. There are two cases, depending on whether Q_o initially is larger or smaller than $n_n n_e S_i$. We will treat these cases separately.

3.2.1 Electron impact dominates from the beginning

A fraction K of the released energy per ionization, $m_n v^2/2$, is transferred to the electrons. We assume that the electron energy distribution remains maxwellian during the interaction. (This assumption will be discussed in Section 4.2.) The rate of change of the average electron energy is then given by

$$\frac{d}{dt} \left(\frac{3kT_e}{2} \right) = \frac{Q}{n_e} \left(K \frac{m_n v^2}{2} - eU_i - \frac{3kT_e}{2} \right), \quad (8)$$

where $(-eU_i - 3kT_e/2)$ is the energy required to first ionize, and then heat the new free electrons to the average electron energy. When electron impact ionization dominates, Q_0 can be dropped from Eq. (7), and Eq. (8) becomes

$$\frac{d}{dt} (kT_e) = \frac{2}{3} n_n S_i \left(K \frac{m_n v^2}{2} - eU_i - \frac{3kT_e}{2} \right). \quad (9)$$

The $3kT_e/2$ term can be neglected in the initial phase of the interaction, when this term is small compared to eU_i . The ionization rate coefficient S_i is approximated by an analytical expression given by Raadu (1980), see Section 4.3,

$$S_i(X) = S_{i,max} \frac{0.987 X^{\frac{1}{2}} \exp(-1/X)}{1 + 0.183 X}, \quad (10)$$

where $X = kT_e/eU_i$, and $S_{i,max}$ is the maximum value of S_i .

The velocity v will decrease as new ions are picked up by the plasma. Since we want to follow the interaction only during the initial phase, we neglect this velocity decrease and treat v as a constant (see Section 4.4).

With these approximations, Eq. (9) becomes

$$\frac{dX}{dt} = \frac{2}{3} \frac{n_n}{eU_i} \left(K \frac{m_n v^2}{2} - eU_i \right) S_{i,max} \frac{0.987 X^{\frac{1}{2}} \exp(-1/X)}{1 + 0.183 X}. \quad (11)$$

We now substitute $t = L/v$, where L is the penetration depth into the neutral gas. A heating to $kT_e = eU_i$ from the original temperature T_{e0} corresponds to an integration of Eq. (11) from $X_0 = kT_{e0}/eU_i$ to $X = 1$,

$$\int_0^L n_n dL = \frac{3}{2} veU_i \frac{1}{S_{i,max} (K m_n v^2/2 - eU_i)} \int_{X_0}^1 \frac{(1 + 0.183 X) dX}{0.987 X^{\frac{1}{2}} \exp(-1/X)}. \quad (12)$$

In this equation, K is the dependent variable; the smallest value of the energy transfer factor, that can give v_c -interaction during the penetration to the depth L . The integral over X has to be evaluated numerically; the result is a function f of kT_{eo}/eU_i , which is given in Fig.2. Combining Eq:s (1) and (12), we find that v_c -interaction is only possible when

$$K \geq \left(\frac{v_c}{v} \right)^2 \left(1 + \frac{fv}{S_{i,max} \int (n_n dL)} \right). \quad (13)$$

This, together with Eq. (6), is our condition for v_c -interaction.

3.2.2 Electron impact does not dominate from the beginning

When the initial electron temperature is very low, one must consider other mechanisms than electron impact for the initial production of stationary ions, e.g. photoionization or charge exchange. When such sources are important, the electron temperature can increase more rapidly to the value at which electron impact starts to contribute. When the temperature has become so high that electron impact ionization dominates, the heating will proceed according to Eq. (9).

We assume that Q_0 is independent of the electron temperature. It is then straightforward to keep the Q_0 term in Eq. (9) and carry out the calculations as above. The result is that the actual value of the initial electron temperature T_{eo} is of minor importance. Instead another parameter appears: the temperature T_{e1} , at which electron impact and the other processes contribute equally to the ionization. The end result in the calculations can still be expressed in a form similar to Eq. (13). The result has therefore been reduced to a form which makes it possible to use that equation also in this case; the effect of the additional ionization is taken into account by the following procedure:

- (1) First one has to calculate the rate of production of quasi-stationary ions Q_0 due to the other mechanisms (charge exchange, photoionization etc.). The ionization rate coefficient, Eq. (10), is then used to calculate the electron temperature T_{e1} at which electron impact would give the same rate of ionization as these other mechanisms.

- (2) If $T_{e1} < T_{eo}$, Eq. (13) is used directly with the true initial electron temperature T_{eo} . Otherwise, T_{eo} has to be replaced by a value T_{eo}^* , which always lies closely below T_{e1} . T_{eo}^* is found from Fig.3, which gives T_{e1}/T_{eo}^* as a function of kT_{e1}/eU_i .

The result obtained by the use of T_{eo}^* corresponds to an exact calculation with the initial temperature $T_{eo} = 0$. This is usually a very good approximation also for values of $T_{eo} \neq 0$; only when T_{eo} is rather close to T_{e1} (in the range $0.3 T_{e1} < T_{eo} < T_{e1}$) does the exact result depend on T_{eo} to some degree.

4. Approximations and assumptions

The most important approximations and assumptions made in Section 3.2 are:

- (1) Other collisions than electron impact ionization of the neutral gas are neglected.
- (2) The electron energy distribution is assumed to remain Maxwellian during the interaction.
- (3) An approximate analytical expression for the ionization rate coefficient is used.
- (4) The electron temperature $kT_e = eU_i$ is somewhat arbitrarily chosen.

These four points will be discussed in the following four subsections. We will find that the condition for v_c -interaction is rather insensitive to such effects, provided that

- (1) the plasma is highly ionized,
- (2) the initial velocity of the plasma is well above the critical velocity, say, $v \gtrsim 4 v_c$, and
- (3) the initial ionization rate is high enough, either because the initial electron temperature $kT_{eo} \gtrsim 0.3 eU_i$, or because other ionization mechanisms give a correspondingly high ionization rate. (This requirement on the ionization rate only has to be fulfilled when one can suspect that the electron energy distribution can become strongly non-Maxwellian.)

4.1 Other collisions than electron impact ionization

The most important collisional processes that have been dis-

regarded are (1) inelastic collisions other than ionizations between electrons and neutrals or ions (which will cool the electrons and counteract electron heating), (2) resonant charge exchange collisions between neutral gas atoms and ionized neutrals that have been accelerated (which will increase the rate of production of stationary ions and hence enhance the interaction), and (3) collisions involving neutrals moving with the plasma stream (which have to be considered if the plasma stream is not fully ionized).

In situations where these processes might play a role, their importance should be checked by order-of-magnitude estimates. Even in situations where these types of collisions are frequent, they might influence the result only marginally. This is illustrated by the calculations of Axnäs (1980), who investigated under what conditions v_c -interaction is possible between a xenon cloud, released from spacelab, and the ionospheric plasma. Such an experiment has been proposed by Möbius *et al.* (1979). Axnäs found that, in spite of a low degree of ionization of the ionospheric plasma, collisions of type (3) has little influence on the result. Collisions of type (2), resonant charge exchange involving ionized neutrals, were explicitly included in his calculations. They were found to influence the calculated values of K with not more than 20%.

4.2 Non-maxwellian electron energy distribution

We have assumed that the electron energy distribution remains maxwellian during the interaction. This is not necessarily true; for example, one could imagine a situation where the energy-transferring mechanism heats only a fraction of the electrons and leaves the rest of the electrons unaffected. The error that follows from the assumption of a maxwellian energy distribution can be estimated from a study of the following extreme case: we assume that the energy transferred to the electron population is used to create a population of high-energy electrons, all with the same energy. This energy is chosen so that the rate of ionization is maximized. Such a rather artificial distribution would represent the most efficient way of using the transferred energy for ionization, and will therefore give a limit to how much the ionization can be underestimated by the assumption

of maxwellian electrons. It is straightforward to rewrite the equations in Section 3.2 in accordance with this assumption.

As could be expected, the interaction is found to require smaller values of the energy transfer factor K than when the electron energy distribution is assumed to remain maxwellian. The difference between these two cases depends strongly on the value of the initial temperature T_{eo} (or T_{eo}^* , in the case when electron impact does not dominate from the beginning). This is most conveniently expressed with the use of the normalized initial electron temperature $\chi_o = kT_{eo}/eU_i$ (or kT_{eo}^*/eU_i). For values of χ_o below $\chi_o \approx 0.1$, the difference in K can be several orders of magnitude. When χ_o approaches unity, the difference rapidly becomes smaller, i.e. a factor of 2.5 for $\chi_o = 0.2$, a factor of 1.5 for $\chi_o = 0.3$, and a factor of 1.3 for $\chi_o = 0.5$. It should be kept in mind that these are the highest possible errors, calculated under the assumption of a rather unlikely, strongly non-maxwellian electron energy distribution. Even so, the error turns out to be small, provided that the initial electron temperature is high enough ($kT_{eo} \gtrsim 0.3 eU_i$). One example of particular interest is the interaction between the solar wind and neutral gas; in this case, the error can usually be neglected, provided that the solar wind temperature kT_e is above 5 eV.

4.3 The analytical approximation of the ionization rate coefficient

We use the expression for the ionization cross section given by Raadu (1980),

$$\sigma_i = \sigma_{\max} \frac{a}{\alpha E} \left[1 - \exp(-\alpha(E-1)) \right], \quad (14)$$

where a and α are adjustable parameters, and E is the electron energy measured in units of the ionization energy:

$$E = mv^2/2eU_i. \quad (15)$$

Eq. (14) has the advantage over the usual approximations of cross sections (see e.g. Drawin, 1966) that it can be integrated

analytically over a maxwellian distribution of electron energies. With use of the normalized electron temperature $\chi = kT_e/eU_i$, this integration yields the rate coefficient

$$S_i(\chi) = S_{i,\max} \cdot \frac{0.567 a \chi^{\frac{1}{2}} \exp(-1/\chi)}{1 + \alpha \chi} \quad (16)$$

where $S_{i,\max}$ is the maximum value of $S_i(\chi)$. In Eq. (10), we have chosen $a = 1.73$ and $\alpha = 0.183$, which gives a good fit to most experimentally determined cross sections, with a maximum at four times the threshold energy. The corresponding rate coefficient agrees well with rate coefficients calculated from experimentally obtained cross sections, usually within 20%, from zero electron temperature up to $kT_e = 10 eU_i$.

$S_i(\chi)/S_{i,\max}$ is given in Fig.4 as a function of χ . Values of $S_{i,\max}$ are given for a number of species in Table I. For other species, $S_{i,\max}$ can be found from the maximum of the ionization cross section by the approximate formula (in MKSA units)

$$S_{i,\max} = 1.2 \cdot 10^6 U_i^{\frac{1}{2}} \sigma_{\max} \quad (17)$$

The uncertainty in S_i then becomes larger, but almost always lies below 30%.

4.4 The choice of $kT_e = eU_i$

As can be seen on Fig.4, the ionization rate decreases rapidly with electron temperature below $kT_e = eU_i$, while it varies much more slowly above that value. The choice of a temperature around $kT_e = eU_i$ to signify efficient ionization is therefore quite natural. The precise value to choose, however, has to be somewhat arbitrary; fortunately, this does not influence the result much. This is illustrated in Fig.5, which shows the temperature, ionization rate and velocity in a hydrogen plasma that penetrates into a uniform helium cloud. The solid curves show a numerical solution of Eq. (8) together with a simple form of the momentum equation,

$$\frac{d}{dt} (\langle m_i \rangle n_i v) = -n_e n_n \langle \sigma_i v_e \rangle m_n v \quad (18)$$

The upper curve shows that the electron temperature increases rather rapidly, once it has begun to rise. The penetration depth L , at which a certain temperature has been reached, is therefore rather insensitive to the precise value of that temperature (provided that the value is chosen around $kT_e = eU_i$). Inspection of Eq. (13) shows that this also makes the limit on K insensitive to the value of T_e ; a small relative variation in $\int n_n dL$ corresponds to an equally small relative variation in the limit on K .

The curves in Fig. 5 also illustrate the effect of two approximations made in Section 3.2.1, namely the dropping of the $3kT_e/2$ term from Eq. (9) and the approximation of constant velocity used in the integration of Eq. (11). The solid curves in Fig. 5 are calculated without these approximations, while the dotted curves are calculated from the approximate equations. Clearly, the important parameter, the penetration depth before $kT_e = eU_i$ is reached, is not much influenced by the approximations.

5. Summary

It is found that v_c -interaction is energetically possible when two conditions on K are fulfilled,

$$K \geq \left(\frac{v_c}{v} \right)^2 \left(4.5 \frac{m_n}{m_i} + 3.75 \right) \quad = \quad (6)$$

and

$$K \geq \left(\frac{v_c}{v} \right)^2 \left(1 + \frac{f(kT_e/eU_i) \cdot v}{S_{i,max} \int n_n dL} \right) \quad = \quad (13)$$

This result applies in situations where a highly ionized plasma stream impacts on a region with neutral gas. Both equations give values of the energy transfer factor K which must be exceeded if v_c -interaction shall occur (or, more specifically, if the electrons shall be heated above $kT_e = eU_i$).

Eqs (6) and (13) reflect two different conditions on the energy. Eq. (6) follows from the requirement that the total amount of energy in the plasma stream before the interaction

shall be sufficient to heat the electrons. In situations where the energy for electron heating in one volume of plasma can be taken (e.g., by $\underline{i} \times \underline{B}$ forces) from the deceleration of a larger volume of surrounding plasma, Eq. (6) is too restrictive. It can therefore be seen as a sufficient, but not always necessary condition on the energy in the plasma stream. Eq. (13) follows from the requirement that it shall be possible to tap the energy source fast enough (through electron impact ionization) during the penetration of the plasma to the depth L in the neutral gas. The parameters in Eq. (13) are:

- (1) The relative velocity v between the plasma and the neutral gas, and the critical ionization velocity $v_c = (2eU_i/m_n)^{1/2}$ of the neutral gas.
- (2) The density and the spatial extension of the neutral gas. These are combined in the quantity $\int n_n dL$, which is the integrated gas density along the plasma stream from the edge of the gas cloud to the penetration depth.
- (3) The initial electron temperature T_{eo} , which appears in the argument of the function $f(kT_{eo}/eU_i)$. This function is given in graphical form in Fig.2. T_{eo} is an extremely sensitive parameter. If the temperature is very low, one has to consider initial ionization by other mechanisms than electron impact; this is discussed in Section 3.2.
- (4) $S_{i,max}$, finally, is the maximum of the ionization rate coefficient for ionization of the neutrals by thermal electrons. Values of $S_{i,max}$ for some species are given in Table I together with values of v_c and U_i .

Together, Eq:s (6) and (13) give a smallest value K_{min} of K (the greater of the values from the two equations), which must be exceeded if v_c -interaction shall occur. K_{min} can be interpreted as follows:

$K_{min} > 1$: v_c -interaction is energetically impossible

$K_{min} \leq 1$: v_c -interaction is possible (or even easily possible if $K \ll 1$), as far as available energy is concerned.

In the latter case, $K_{min} \leq 1$, one might want to go into more detail. One way is to identify and study possible mechanisms of energy transfer, and to examine the effect of energy loss through heat conduction to the surroundings. The role of instabilities

in the critical ionization velocity mechanism has been discussed by e.g. Lehnert (1967), Raadu (1978), and Formisano *et al.* (1981). Important quantities to determine are the fraction of the energy which can be transferred to the electrons, and the time required for this transfer. This time should be short compared to the penetration time $t = L/v$.

6. Applications

We will now apply the condition for v_c -interaction to two examples, one from the laboratory and one from space.

6.1 The laboratory experiment

In the experiments by Danielsson (1970) and Danielsson and Brenning (1975), a stream of hydrogen plasma was made to collide with a cloud of neutral helium with a diameter around 5 cm. At a helium density of 10^{20} m^{-3} , both electron heating (from 5-10 to typically 85 eV) and braking to the critical ionization velocity (from $4 \cdot 10^5 \text{ ms}^{-1}$ to $3.5 \cdot 10^4 \text{ ms}^{-1}$) were observed in the gas cloud.

With these parameters, Eq. (6) gives $K > 0.17$. For Eq. (13), we first have to consider the role of the charge exchange collisions ($\text{H}^+ + \text{He} \rightarrow \text{H} + \text{He}^+$) for the initial ionization of helium atoms. The proton impact charge exchange rate coefficient is $1.6 \cdot 10^{16} \text{ m}^3 \text{ s}^{-1}$ for protons with a velocity of $4 \cdot 10^5 \text{ ms}^{-1}$. An electron temperature $kT_{e1} \approx 6.3 \text{ eV}$ would give the same rate of He^+ ion production. The uncertainty in electron temperature makes it necessary to consider the limits of the estimated initial temperature, (1) when T_{eo} is 10 eV, so that charge exchange collisions can be disregarded, and (2) when T_{eo} is 5 eV, for which case the procedure described in Section 3.2.2 must be used. The corresponding conditions on the energy transfer factor from Eq. (13) are, for these two cases, $K \geq 0.15$ and $K \geq 0.7$.

Combining the results from Eq. (6) and Eq. (13), we find that K_{\min} lies in the range 0.17-0.7. This should be compared to the results from the theoretical model of Sherman (1970) and Raadu (1978), who argue that the energy transfer in this particular experiment is due to a modified two-stream instability.

In computer experiments on the non-linear development of this instability, Ott et al. (1972) and McBride et al. (1972) found that a fraction of 0.28 of the energy was transferred to the electrons; this is in good agreement with our range of K_{\min} values.

6.2 The Apollo 13 stage lunar impact

Critical ionization velocity interaction was suggested by Lindeman et al. (1974) as an explanation of observations in connection with the Apollo 13 S-IV B stage impact on the Moon on April 15, 1970. The equipment at the Apollo 12 Lunar Surface Experiments Package (ALSEP), located 140 km from the impact point, recorded:

1. A flux of hot (50 eV) electrons.
2. A flux of heavy ions that was higher, by more than a factor of three, than the flux that could be expected from photoionization of the impact-produced gas cloud.

Lindeman et al. concluded that both these observations can be consistently explained by the existence of a rapid interaction between the solar wind and the neutral gas cloud, which heats the solar wind electrons above the ionization energy. They estimate that the gas cloud consists of around 10^{28} heavy molecules ($m \approx 80$ amu) of vaporized plastic from the rocket stage, with an average ionization cross section corresponding to $U_i = 15$ eV and $S_{i,\max} = 8 \cdot 10^{-14} \text{ m}^2 \text{ s}^{-1}$. We approximate the solar wind parameters with $v = 3.3 \cdot 10^5 \text{ ms}^{-1}$ and $kT_{e0} = 10$ eV.

Eq. (6) gives $K < 0.12$. This might well be a too strict limitation, since the surrounding solar wind could be coupled to the plasma that penetrates into the neutral gas (compare the discussion in Section 3.1).

For the calculation of the second condition of K from Eq. (13), we first disregard the effects of charge exchange and photoionization (which usually can be expected to be of importance in the solar wind). This simplification will be justified a posteriori; even without photoionization, Eq. (13) puts a lower limit on K than Eq. (6).

In order to get a value of $\int n_n dL$, we must consider the geometry of the problem (Fig. 6). Lindeman et al. have from kinetic theory calculated the vertical column density at the ALSEP site as a function of time, obtaining a peak around $5 \cdot 10^{16} \text{ m}^{-2}$ at a time 50-100 seconds after the impact; this time corresponds to peaks in the fluxes of both hot electrons and heavy ions. In the present geometry, this is a fairly good approximation for the column density upstream in the solar wind, which is the relevant parameter.

These values in Eq. (13) give $K \leq 0.05$. From $K \leq 0.12$ and $K \leq 0.05$ we get $K_{\min} = 0.12$, and therefore conclude that the critical ionization velocity interaction can explain the observations, if a suitable mechanism for energy transfer exists, and if the energy is not conducted away more rapidly than the electrons are heated.

7. Discussion

The v_c -interaction, as observed in the laboratory, shows two effects, (1) heating of the electrons to so high energies that they can ionize the neutrals and (2) braking of the plasma stream to the critical ionization velocity. We have here limited the discussion to the heating of the electrons, and only briefly touched upon the question of the braking of the plasma (Section 3.1 and 4.4). As pointed out by Srnka (1977), one can expect the interaction to develop in stages as the plasma penetrates into the neutral gas. In the first stage, the plasma electrons are heated to such energies that they can contribute to the ionization. In the next stage, corresponding to a deeper penetration into the neutral gas, newly ionized neutrals are picked up by the plasma stream, which is slowed down. Finally, the velocity decreases to the critical ionization velocity, and the whole process switches off. These three stages are easily distinguished in the numerical calculation shown in Fig. 5. The condition for v_c -interaction corresponds only to the first of these stages; it might therefore be seen as a condition for the start of v_c -interaction.

It has not been necessary to include a magnetic field in this analysis, which concerns only the energy flow in the interaction. However, there are reasons to believe that the

interaction requires a magnetic field transverse to the plasma flow. A magnetic field can be necessary for the operation of instabilities that can transfer energy to the electrons. It also greatly reduces the energy loss through heat conduction, at least in the transverse direction. The importance of a transverse magnetic field is illustrated by the fact that although there are many reports of v_c -interaction in a wide range of parameters, it has never been observed in flow-parallel or zero magnetic field. Experiments in transverse magnetic fields of varying strength (Danielsson and Brenning, 1975; Venkataramani and Mattoo, 1980; Brenning, 1981) also indicate that the interaction disappears if the magnetic field is below some critical value.

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	H	He	Ne	Ar	Kr	Xe	Li	Na	Mg	Ca
$S_{i,max}$ ($m^3 s^{-1}$)	$3.4 \cdot 10^{-14}$	$2.8 \cdot 10^{-14}$	$1.0 \cdot 10^{-13}$	$1.7 \cdot 10^{-13}$	$2.0 \cdot 10^{-13}$	$3.0 \cdot 10^{-13}$	$1.4 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$3.0 \cdot 10^{-13}$
v_c ($km s^{-1}$)	51.0	34.3	14.4	8.72	5.66	4.26	12.2	6.56	7.77	5.42
U_i (eV)	13.45	24.5	21.5	15.7	13.9	12.13	5.36	5.12	7.6	6.09

Table I Some atomic data. Maximum electron impact ionization rate coefficients (from Freeman and Jones, 1974), and values of the critical ionization velocity.

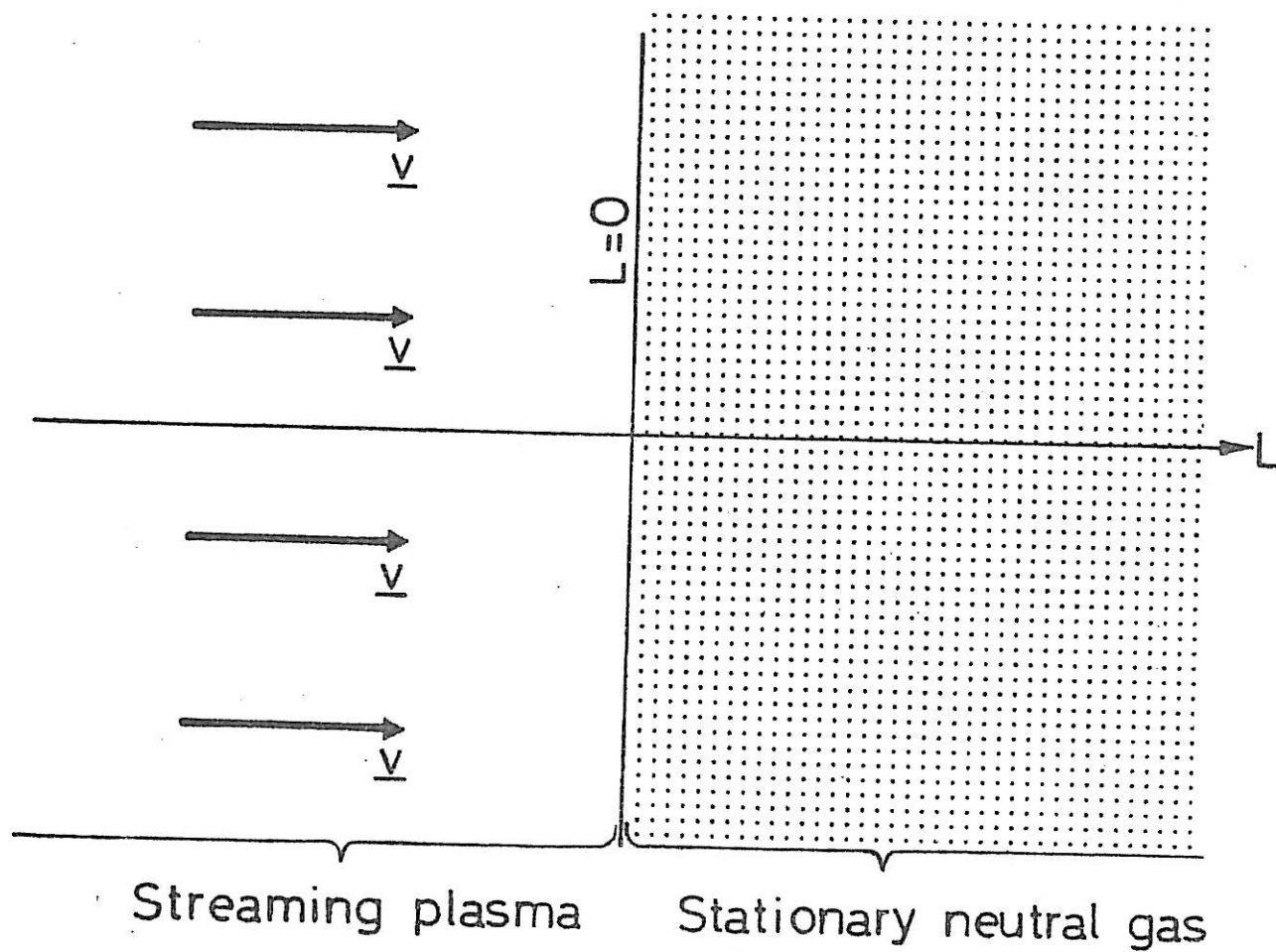


Figure 1. The model of the interaction. A plasma which for $L < 0$ has the velocity v and temperature T_{eo} penetrates into a region with neutral gas of density $n_n(L)$, which fills the half-space $L \geq 0$.

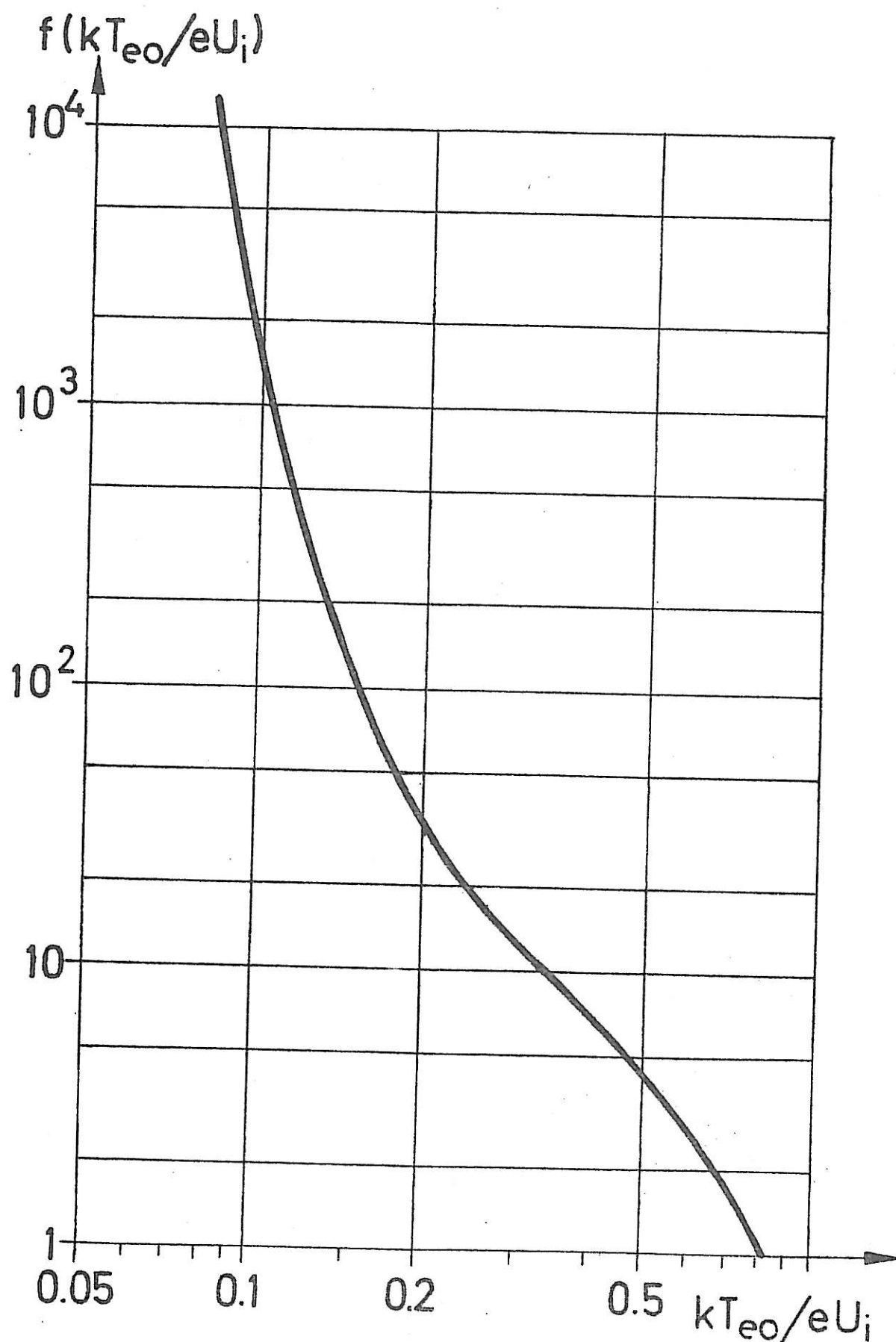


Figure 2. The parameter f in Eq.(13), as a function of the normalized initial electron temperature $X_0 = kT_{eo}/eU_i$. Some examples for lower X_0 values than those shown in the figure are: $f(0.07) = 5.2 \cdot 10^4$, $f(0.05) = 9 \cdot 10^6$, $f(0.04) = 9 \cdot 10^8$ and $f(0.03) = 2.5 \cdot 10^{12}$.

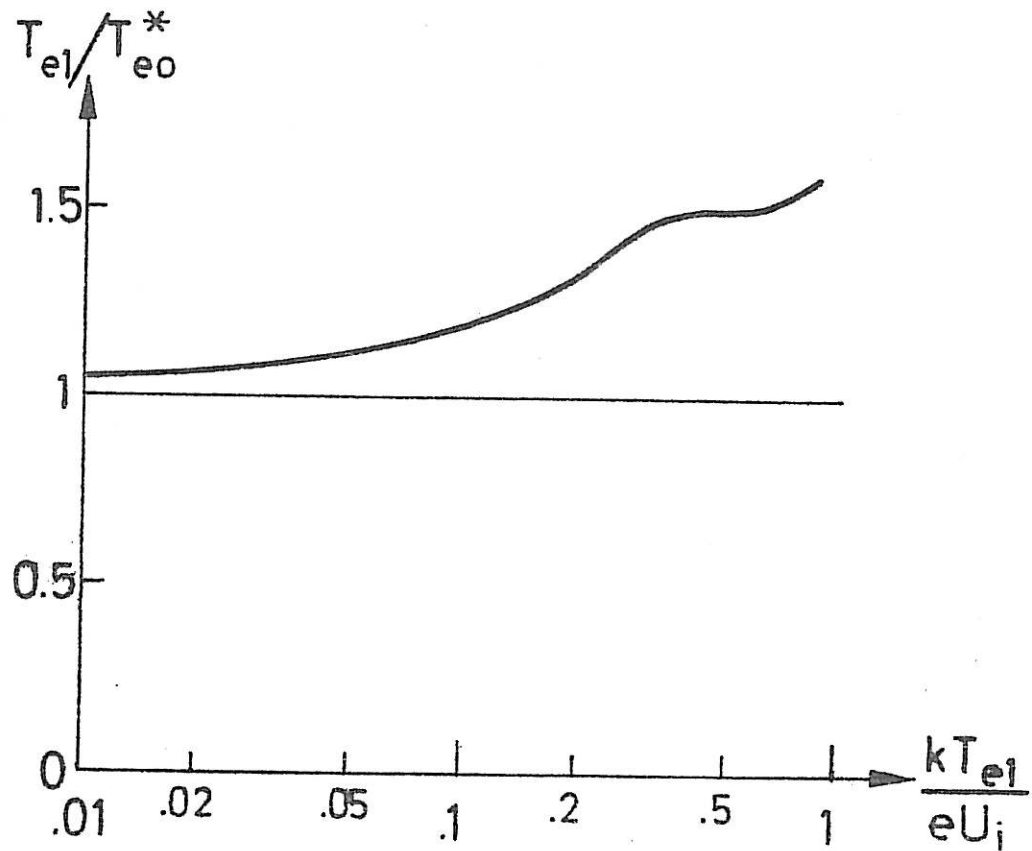


Figure 3. The ratio between the following electron temperatures: T_{e1} is the electron temperature at which electron impact and other sources of ionization contribute equally to the total ionization. T_{eo}^* is a value of the temperature which can be used to take into account the effect of these other sources of ionization in the condition for v_c -interaction. This is done by replacing T_{eo} with T_{eo}^* in Eq. (13).

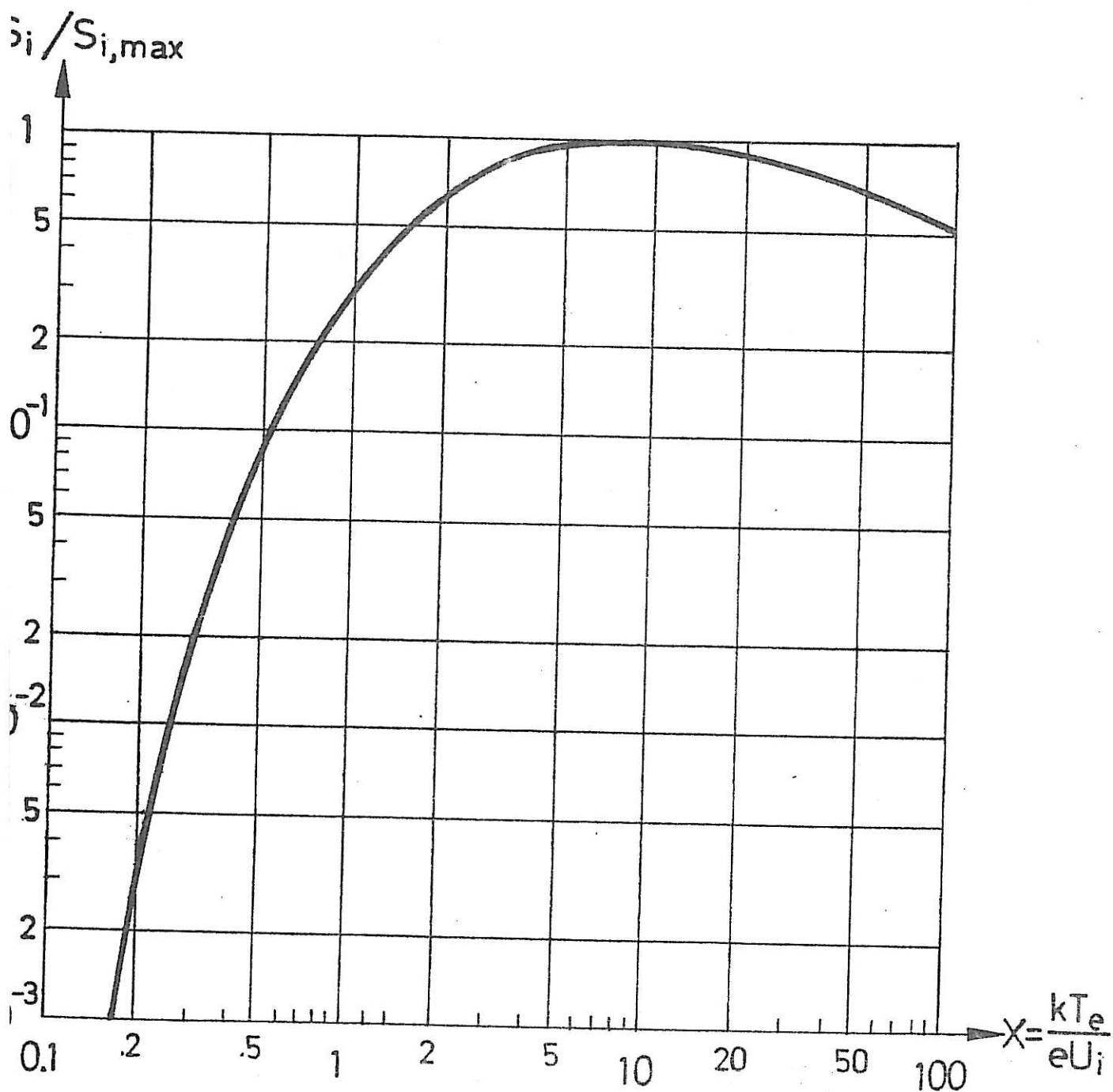


Figure 4. The normalized rate coefficient $S_i(X)/S_{i,max}$ for ionization by electron impact, as a function of the normalized electron temperature $X = kT_e/eU_i$. $S_i(X)$ is also given in analytical form in Eq. (10).

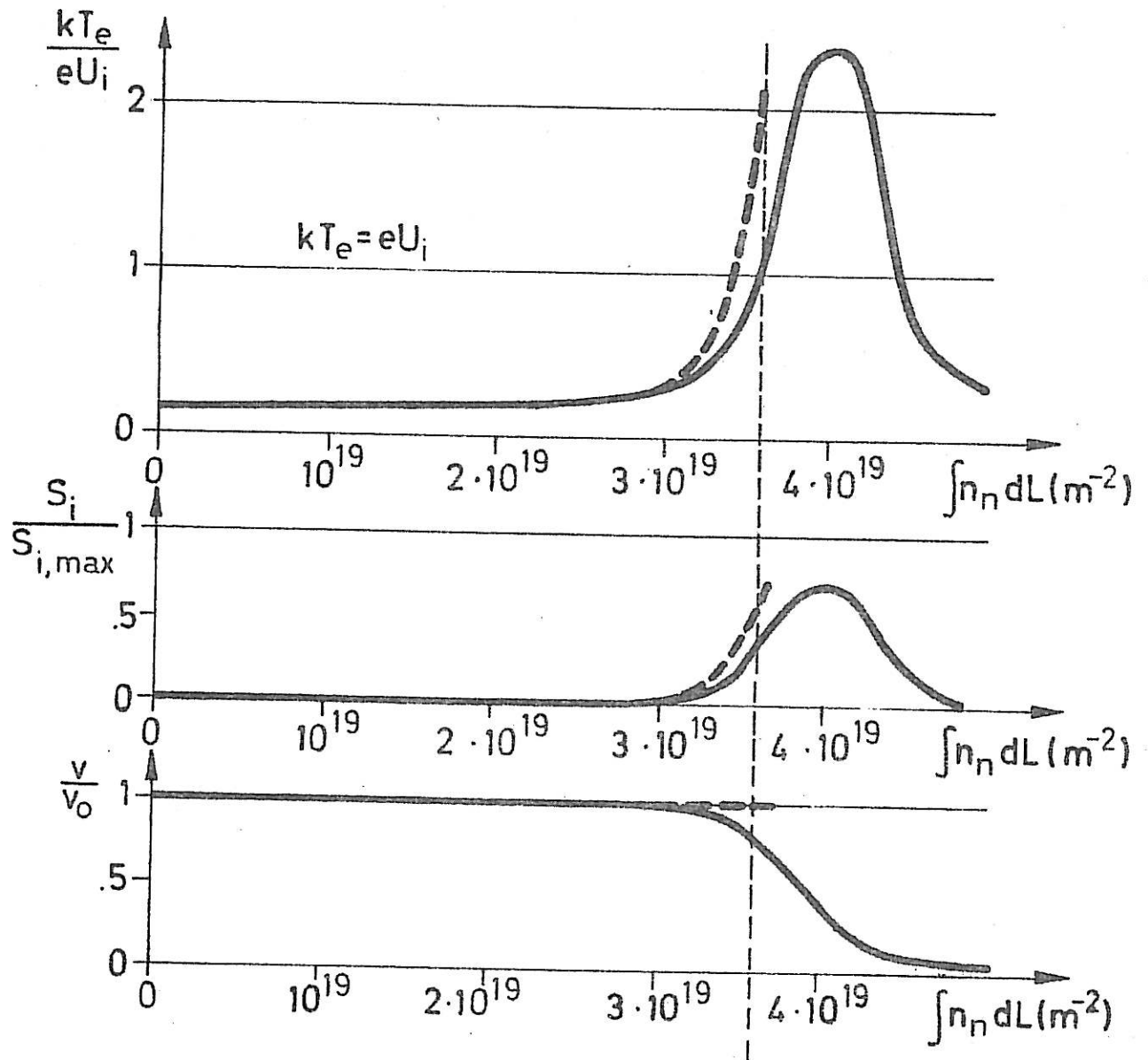


Figure 5. The variations in electron temperature, ionization rate and velocity in a hydrogen plasma that penetrates into a uniform helium cloud. The solid curves are obtained by a numerical solution of the energy and momentum equations for the following parameters: $v=4 \cdot 10^5 \text{ ms}^{-1}$, $n_n=10^{20} \text{ m}^{-3}$, $kT_{e0}=4 \text{ eV}$, $K=0.25$. The dotted curves are obtained with use of the approximate form of the energy equation used in Section 3.2. The graphs show that the penetration depth before efficient ionization starts is insensitive, both to the approximations in the energy equation and to the precise value of kT_e (provided that it is around $kT_e=eU_i$) which is chosen to signify the threshold of efficient ionization.

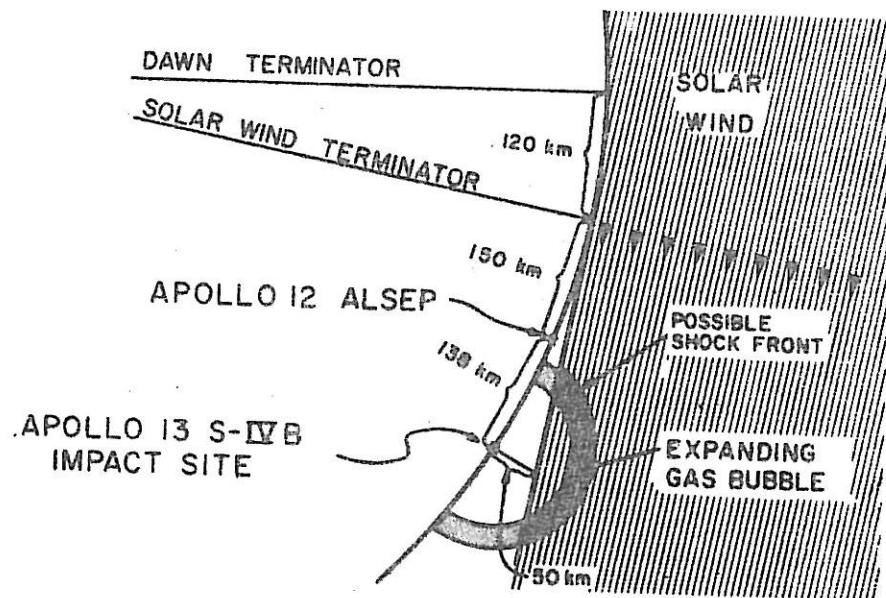


Figure 6. An equatorial cross-sectional view of the Moon (not to scale) showing the S-IVB impact point with respect to the ALSEP site and the dawn and solar wind terminator (from Lindeman et al. 1974).

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A NECESSARY CONDITION FOR THE CRITICAL IONIZATION VELOCITY
INTERACTION

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The possibility of critical ionization velocity (v_c) interaction is discussed in a configuration often encountered in astrophysical situations, with a highly ionized plasma streaming into a region with neutral gas. The energy flow in the interaction is studied and a condition is derived, which can be used to determine whether v_c -interaction is energetically impossible, just possible or easily possible. The parameters used are: the molecular mass, ionization potential and ionization cross section of the neutrals, the number density in and spatial extension of the region with neutral gas, and the velocity and initial electron temperature of the plasma stream. The use of the condition is illustrated by two examples.

Key words: Plasma flow, Critical velocity, Critical ionization velocity, Electron energization.