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THE CRITICAL IONIZATION VELOCITY

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Abstract

The critical ionization velocity effect was first proposed in the context of space plasmas. This effect occurs for a neutral gas moving through a magnetized plasma and leads to rapid ionization and braking of the relative motion when a marginal velocity, "the critical velocity", is exceeded. Laboratory experiments have clearly established the significance of the critical velocity and have provided evidence for an underlying mechanism which relies on the combined action of electron impact ionization and a collective plasma interaction heating electrons. There is experimental support for such a mechanism based on the heating of electrons by the modified two-stream instability as part of a feedback process. Several applications to space plasmas have been proposed and the possibility of space experiments has been discussed.

1. Introduction

Fully ionized plasmas have been found to support a large variety of complex phenomena, largely due to the collective interactions of groups of particles through electric and magnetic fields. In addition to these, further qualitatively new phenomena appear in the interaction between plasmas and neutral gas. These can arise from a combination of plasma collective effects and binary processes such as ionizing collisions. This is the case for neutral gas moving through a magnetized plasma. If there is relative motion across the magnetic field an interaction leading to the ionization of the neutral gas can occur, provided that a marginal velocity, v_c, the critical ionization velocity, is reached. This velocity, often referred to in the literature as "the critical velocity", is defined by the condition that the kinetic energy of a neutral atom with mass m_n, moving with velocity v_c relative to the plasma, is equal to its ionization energy eV_i (V_i is the ionization potential in Volts), so that

$$\frac{1}{2} m_n v_c^2 = eV_i \ .$$

Typical values of the critical ionization velocity are displayed in Table 1. In speaking of a critical velocity effect one has in mind that the ionizing interaction between neutral gas and magnetized plasma sets in at the critical ionization velocity v_c and not at higher velocities such as follow if only simple binary collisions between neutral atoms and plasma ions are considered. The rapid ionization of neutral gas increases the plasma density and tends to brake the relative motion, so that the critical ionization velocity acts as a limiting velocity for the relative motion between neutral gas and plasma.

		Ionisation Potential, V_i	Atomic Weight, A	Critical velocity, V_c [km/s]
Hydrogen	H	13.6	1	51.0
Helium	He	24.6	4	34.3
Oxygen	O	13.6	16	12.8
Nitrogen	N	14.5	14	14.1
Neon	Ne	21.6	20	14.4
Sulphur	S	10.4	32	7.9
Carbon	C	11.3	12	13.4

$$\frac{1}{2} A m_H V_c^2 = e V_i$$

(m_H: atomic mass unit)

Table 1. The critical ionization velocity v_c for a selection of elements in atomic form.

The critical velocity effect was originally predicted by Alfvén (1954) and has subsequently been amply confirmed by numerous experiments (see, for example, the review by Danielsson (1973)). Alfvén considered the accretion of interstellar matter by the primeval sun and the formation of the solar system. The sun's gravitational field accelerated the incoming neutral gas through a surrounding dilute plasma which was held in place by the solar magnetic field. When the kinetic energy of infalling neutral atoms reached their ionization energy (i.e. at the critical ionization velocity, v_c) Alfvén proposed that an interaction should occur leading to their ionization. The newly produced ions should then be stopped by the magnetized plasma. As a consequence accreting neutral gas should give rise to bands of increased plasma density at specific distances from the sun depending on the composition of the gas. This explanation of the "band structure" for the distribution of matter within the solar system has been further developed by Alfvén and Arrhenius (1975, 1976).

The critical ionization velocity effect has not only been found in experiments specially designed for its investigation but it has even raised serious practical problems in plasma fusion experiments which rely on the production of a rotating plasma(cf Lehnert et al., 1966). Traces of neutral gas near electrode surfaces are often sufficient to produce the critical velocity effect limiting the rotational motion of a significant volume of the plasma.

2. Critical Velocity Experiments

In the majority of experiments which have shown the critical velocity effect, an external power supply has been used to drive a magnetized plasma through a neutral gas. Different configurations have been used so that limitations in rotational motion (Fahleson, 1961; Angerth et al., 1962; Lehnert et al., 1966; Srnka, 1974; Babický and Koláček, 1975) and in directed velocity (Wilcox et al., 1964; Eninger, 1966; Axnäs, 1972; Danielsson, 1970) have been demonstrated. The relative motion between magnetized plasma and neutral gas in such experiments has been found from Doppler shift measurements and probe measurements. If it is assumed that the plasma has the drift velocity E/B in the magnetic field B, electric field measurements give an indirect measurement of the relative velocity. In general these experiments demonstrate that the relative velocity is indeed limited to the critical ionization velocity for the neutral gas used. To exceed the critical velocity sufficient power must be applied so that the neutral gas becomes highly ionized (Fahleson, 1961; Eninger, 1966). The interpretation is that for low velocities plasma may be accelerated through the neutral gas without increasing the ionization, but that at the critical ionization velocity v_c there is a rapid increase in ionization so that the power supplied goes to ionization rather than acceleration (Alfvén, 1960). Further acceleration is then only possible when full ionization is approached.

If the ion-neutral collision frequency ν_{in} is greater than the ion gyrofrequency ω_{ci} ion collisions are important and the plasma velocity is expected to be different from the drift velocity $u_D = E/B$ deduced from electric field measurements. In such a situation the coaxial plasma gun experiments of Eninger (1966) show that it is then the drift velocity u_D that is limited to the critical ionization velocity v_c. In this experiment the electron gyrofrequency ω_{ce} greatly exceeds the electron-neutral collision frequency ν_{en} so that the electrons may still be expected to move with the drift velocity u_D. This suggests that it is the relative motion between electrons and the neutral gas which is significant for the critical velocity effect. Considerations of the generalized Ohm's law and experimental results indicate that the electron and ion velocities are approximately equal if the product of the Hall parameters is greater than unity $\omega_{ce}\,\omega_{ci}/\nu_{en}\,\nu_{in} > 1$ (Eninger, 1966). Using the condition that the electron drift velocity u_D equals the critical velocity v_c, the generalized Ohm's law may also be used to determine the distribution of the density and ionization rate for the coaxial gun experiments of Eninger (Raadu, 1978a).

Critical velocity experiments using a coaxial gun may be run with a high degree of reproducibility and have been used to confirm the critical velocity effect for a great variety of gases (Axnäs, 1972). Axnäs (1978b) has found that molecular gases have a systematically larger critical ionization velocity than predicted and attributes this to the presence of additional mechanisms for energy loss. In the case of gas mixtures an intermediate value of the critical velocity is found (Axnäs, 1978a). This value is close to that given by a natural generalization of the critical velocity given by equating the kinetic energy of ionized atoms produced per unit time interval with the energy required to ionize them (Raadu, 1976). Thus for a mixture of two neutral gases with atoms of mass m_1 and m_2, ionization potentials V_1 and V_2 we have

$$\frac{1}{2} m_1 v_c^2 \alpha_1 + \frac{1}{2} m_2 v_c^2 \alpha_2 = eV_1 \alpha_1 + eV_2 \alpha_2$$

where the ionization rates α_1 and α_2 must be found from the plasma parameters and considerations of the ionizing mechanisms (Axnäs, 1978a).

3. Experimental Indications of the Critical Ionization Velocity Mechanism

The experimental confirmation that the critical velocity effect does occur at the value predicted by Alfvén (1954) is very significant. As mentioned above direct ionizing collisions between ions and neutral atoms cannot be used as an explanation. In an ion-neutral collision only the kinetic energy in the centre of mass frame can be released. This would imply a critical velocity expression in terms of the reduced mass rather than the mass of the neutral atom alone. Thus the experiments clearly indicate that the actual mechanism is likely to be complicated.

Further evidence for the underlying mechanism is provided by the plasma-gas impact experiment (Danielsson, 1970; Danielsson and Brenning, 1975). A special feature of this experiment is that there is no continuous external power supply. Plasma is produced impulsively with a conical θ-pinch and then expands freely along a guiding magnetic field. In the downstream region the magnetic field is curved abruptly to produce a plasma flow across the magnetic field within an interaction region into which a cloud of neutral gas is released. A hydrogen plasma is used and collides with neutral helium gas ($v_c \doteq 34.3$ km/s). The plasma velocity (~ 400 km/s) is much greater than the critical velocity. Typical plasma and neutral gas densities are $10^{18} m^{-3}$ and $10^{20} m^{-3}$ respectively and the initial electron energy is small (5-10 eV). A strong interaction is found leading to ionization of the neutral gas and braking of the plasma. After the initial transient response electric field measurements indicate that the plasma velocity is reduced to a value close to the critical velocity for helium. The initial plasma conditions are such that only a weak interaction would be expected. However measurements indicate a rapid increase of the electron energy to values which can account for the observed ionization (>100 eV). The polarization of the emitted spectral lines indicate that the electrons gain energy predominantly along the magnetic field. Thus there is clear evidence for the active role of electrons in the critical velocity mechanism and the non-isotropic velocity distribution suggests that collective interactions are responsible for their energization.

Recent experiments with a homopolar device have given further evidence of collective processes (Himmel and Piel, 1973; Himmel et al., 1976; Himmel et al., 1977; Möbius et al., 1978; Piel et al., 1978; Möbius et al., 1979a). An ionization front in the form of a rotating plasma spoke is found. There is an axial magnetic field and the rotational motion is limited to the critical velocity of the neutral gas filling the apparatus. At higher densities detailed measurements of the structure of spectral lines indicate the presence of electrostatic plasma oscillations (Möbius et al., 1978, 1979a). These fluctuating fields may be associated with the energization of electrons leading to ionization of the neutral gas.

4. Theories for the Critical Ionization Velocity

A number of early theories (Lin, 1961; Drobyshevskii, 1964; Sockol, 1968) were developed to explain the results of particular critical velocity experiments mainly those of Fahleson (1961) and Angerth et al. (1962). Such theories have been discussed by Sherman (1972, 1973). However as critical ionization velocity effects have now been found for a variety of different experiments it is perhaps of more interest to consider general theories, particularly if one has in mind applications to space plasmas. Such general theories have also been reviewed by Sherman (1972, 1973).

Lehnert (1967) considered the space charge structure set up in a magnetised plasma due to the production of non-thermal ions by ionization of a moving non-uniform gas. He found structures on the length scale of an ion gyroradius and potential differences comparable to the ionization energy when the relative motion between neutral gas and plasma equaled the critical velocity. If such transverse potentials could be used to accelerate electrons, ionization would then be produced by electron impact ionization. This would provide an explanation of the critical velocity phenomenon. However the electron heating mechanism is not completely described in this theory. One basic approximation used in the calculations is that the phases of the particle gyration motions in the magnetic field are completely random. This assumption essentially removes the possibility of electrostatic instabilities.

Sherman (1969, 1972) has proposed that electrons can in fact be energized through the modified two-stream instability. The energization forms part of a feedback process of the general type indicated by Figure 1. As plasma with velocity u_o transverse to a magnetic field $\underset{\sim}{B}$ penetrates a region of neutral gas it can interact collectively through plasma instabilities (e.g. modified two-stream instability) with newly formed ions produced by ionization. This interaction leads to acceleration of the new ions (their initial velocity u_n is equal to that of the neutral gas) and a deceleration of the plasma (to a velocity, u_1). The energy released goes into plasma heating and wave energy. For the modified two-stream instability electrons can as a result reach high energies ($\approx \frac{1}{2} m_n (u_1 - u_n)^2$) before the instability is saturated. These energies are then just sufficient to produce ionization of the neutral gas by electron impact when the relative velocity ($u_1 - u_n$) is equal to the critical ionization velocity v_c for the neutral gas (Sherman, 1969). The modified two-stream instability which was first discussed by Buneman (1962) energizes both electrons and ions. From the experimental evidence and the requirements of the theory the electrons must be energized rather than the ions. This is the case for those modes of the modified two-stream instability which saturate at the high energies required by the critical ionization velocity mechanism (Raadu, 1975, 1978b). A further property of this instability is that it produces electron energization parallel to the magnetic field as observed in the impact experiments (Danielsson, 1970; Danielsson and Brenning, 1975). Thus there are good arguments that electrons are energized through the modified two-stream instability in some critical velocity situations. In general one may expect the particular energization mechanism to depend on the plasma parameters, but to form part of a feedback process as shown in Figure 1.

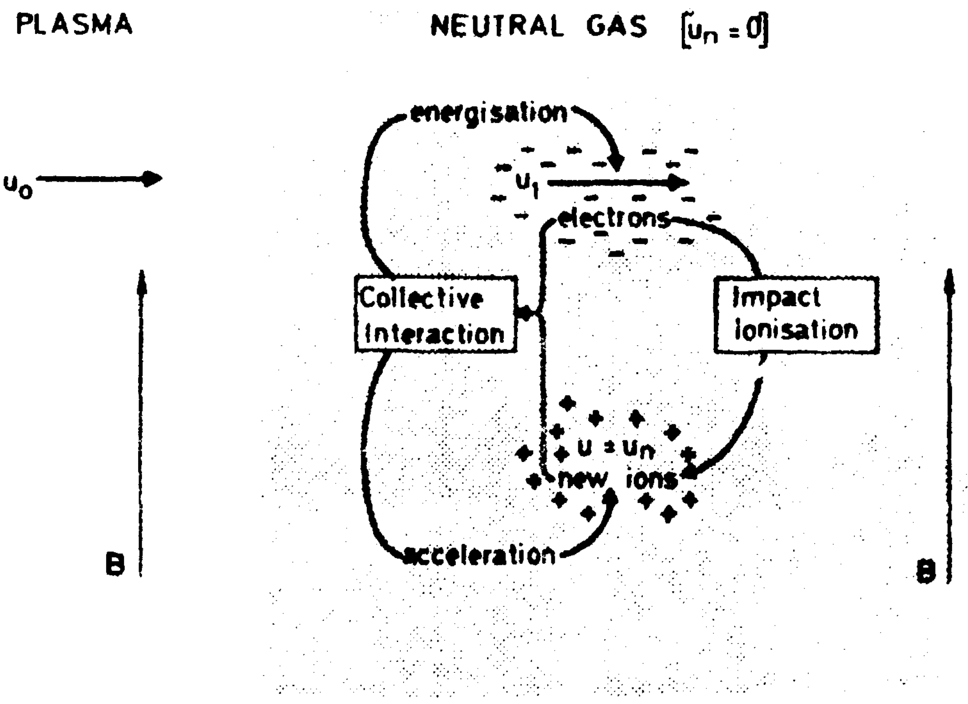

Figure 1. The critical ionization velocity mechanism. Plasma with velocity u_0 across a magnetic field B penetrates a region of neutral gas (velocity u_n). Newly formed ions drive instabilities leading to electron heating and further ionization. The plasma velocity is reduced to u_1 and new ions are accelerated.

Energization of electrons within space charge structures similar to that proposed by Lehnert (1967) has been discussed recently (Varma, 1978; Piel et al., 1978, 1980). Varma (1978) argues that for a streaming plasma of finite diameter the three-dimensional structure of a charge separation sheath is important for the energization of electrons. Piel et al. (1978, 1980) consider the transverse relative drifts between ions and electrons set up within a space charge sheath. For sheaths with dimensions comparable to an ion gyroradius these drifts can drive the modified two-stream instability and produce sufficient electron energization to account for the critical ionization velocity effect by a feedback mechanism of the type originally considered by Sherman (1969).

5. Applications to Space Plasmas

As mentioned above the concept of the critical ionization velocity was originally conceived of in the context of space plasmas (Alfvén, 1954). Following the prediction of the critical velocity effect most of the early work was concerned with its experimental confirmation and the development of theoretical interpretations both specific to particular experiments and general theories of the basic mechanism as outlined above.

Recently several applications to space plasmas have been discussed. Critical velocity effects have been proposed to explain the interaction between neutral gas, produced at the lunar surface due to the impact of a lunar module, and the solar wind (Freeman et al., 1972; Manka et al., 1972; Lindeman et al., 1974). A flux of hot electrons and an unexpectedly large flux of heavy ions originating from the released neutral gas was observed. Srnka (1977) proposed that naturally released gas from lunar transient phenomena would lead to a critical velocity reaction with the solar wind. The energetic electrons produced could then produce light emission through excitation of the neutral gas.

The magnetisation of the moon by cometary impact was investigated by Gold and Soter (1976). During such an impact the solar wind magnetic field should be increased as the cometary atmosphere is compressed. The authors proposed that an increased ionization due to the critical ionization velocity effect would enhance this process of magnetic field amplification.

The plasma associated with Jupiter's satellite Io has been accounted for by an interaction with the Jovian magnetosphere. Cloutier et al. (1977) who have proposed this interaction suggest that ionization is initiated by the critical velocity effect and that further ionization is then produced by energetic magnetospheric electrons.

The dominant ionization mechanism within comets has not yet been identified. In a discussion of cometary ionization processes, Mendis and Ip (1977) suggest that critical velocity effects can be important. Ionization has been found to be more rapid than would be expected from solar photoionization. From a comparison of characteristic laboratory parameters with those for the solar wind, Petelski et al. (1979) conclude that the critical ionization velocity must be operating in the interaction region between the solar wind and the interstellar medium. The authors solve the coupled system of governing equations including the effects of hot electrons produced by critical velocity effects. As a result the electrons in the outer solar wind are maintained at ionizing energies leading to a stronger deceleration of the solar wind as compared to a situation where photoionization and charge exchange alone operate.

Proposals have been made to perform a critical ionization velocity experiment from Spacelab (Chappel et al., 1975; Möbius et al., 1979). Such an experiment could be made by expelling a neutral gas with a critical velocity which is less than the orbital velocity (≈ 7 km s^{-1}) relative to the ambient magnetized plasma. Möbius et al.(1979) have suggested that Xenon should be used and point out the advantages of avoiding the effects of current carrying walls which are a feature of most laboratory experiments. By assuming an effective process of energy transfer to electrons, Axnäs (1979) has evaluated some necessary parameters for an experiment with Xenon as proposed by Möbius et al. (1979). An important process is charge transfer between ambient ions and cloud atoms and for Xenon the situation is particularly favourable.

6. Discussion

The purpose of this review has been to show how the original proposal of the critical ionization velocity effect has been confirmed by a variety of experiments and to indicate theoretical work which has led to an understanding of the underlying mechanisms. It is useful to contrast the macroscopic aspects with the microscopic aspects of the phenomenon. From a macroscopic point of view the critical ionization velocity effect is a consequence of the conservation of energy and momentum. This is the point of view of Alfvén's (1954) description. The kinetic energy of the neutral atoms on ionization balances the energy lost in producing the ionization and momentum is taken up by the magnetized plasma as a whole. Varma (1978) uses moments of the Vlasov equation with source terms to derive a system of macroscopic (fluid) equations from which it is possible to derive the critical velocity. Petelski et al. (1980) also use what is essentially a macroscopic point of view. In principle the critical ionization velocity effects follow directly as a consequence of a correctly formulated set of macroscopic equations. However it is implicitly assumed in such treatments that some effective energy transfer mechanism exists by which the available kinetic energy of newly formed ions is used for further ionization. This energy transfer mechanism is essentially a microscopic process relying on plasma collective interactions such as the growth of the modified two-stream instability to transfer energy to the electrons (Sherman, 1969 and 1972 ; Raadu, 1978b; Piel et al., 1980).

Following such work as that of Varma (1978) and Petelski et al. (1980) it is possible to see how the large scale properties of critical ionization velocity interactions in space may be theoretically analysed and useful conclusions drawn as to their significance. Similarly experimental studies of the ionization and braking effects accompanying the critical velocity are of considerable interest. However the microscopic aspects are essential in determining whether or not there is a suitable energy transfer mechanism in any particular situation. In view of the great experimental parameter range over which critical velocity effects are found it seems likely that different transfer mechanisms may be operating depending on the particular experiment. Much experimental work remains to be done on this aspect of the critical velocity phenomenon. In space experiments of the type proposed by Möbius et al. (1979) the identification of collective interactions would be a good indication of the presence of a critical velocity interaction.

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Key words: Critical ionization velocity, Critical velocity, Ionization, Plasma-neutral gas interaction, Electron energization, Collective effects, Space plasmas