Collision between a Nonionized Gas and a Magnetized Plasma

H. Alfvén

The Royal Institute of Technology, Stockholm, Sweden

1. PROBLEM

THE collision between a nonionized gas and a magnetized plasma can be expected to be of astrophysical importance. Of special interest is the case when a low-density plasma is hit by a continuous stream of nonionized gas of the same chemical composition. We assume that the position of the magnetized plasma is fixed by a magnetic field and that the electric field is zero. Further, let us suppose that the initial temperature of the plasma as well as of the gas is zero.

When the atoms of the stream collide with the ions and the electrons of the plasma, both gases are heated to a temperature which depends on the kinetic energy of the atoms. If this energy is small compared to the ionization energy, the nonionized gas diffuses through the plasma and only a certain change in velocity and density results. On the other hand, if the kinetic energy is much larger than the ionization energy, the gases may be heated so much that the incoming stream gets ionized. The result is that the invading gas is trapped in the magnetic field, and the density of the plasma increases. In an extreme case all the nonionized gas may be ionized and stopped by the magnetic field. The momentum is taken up by the magnetic field and its sources.

This means that a stream of nonionized gas, moving with sufficiently high velocity in relation to a coordinate system with a static magnetic field B_0 perpendicular to the motion, can suddenly be stopped by it. The coordinate system of the magnetic field must be defined by the condition $E=0$. Even if initially only a very thin plasma is present, its density increases when the nonionized gas collides with it and becomes ionized. Hence, moving gas represents an unstable condition, which naturally results in the ionization and stopping of the gas.

Seen from the coordinate system of the stream, the electromagnetic conditions are $B'=B_0$; $E'=v/c\cdot B_0$ (for nonrelativistic velocities) and the problem is equivalent to the question at which electric field E' a discharge is produced, which ionizes the gas.

A similar problem meets us when two nonionized clouds of gas collide with a high velocity in the presence of a magnetic field. If ionization is produced at the border between the colliding clouds, the essential problem is the collision between the plasma and a nonionized gas.

The first time the problem was discussed seems to have been in connection with a theory of the origin of the solar system.[1] In this theory, the basic process is that nonionized gas falls in towards a central body (the sun for the planetary system, planets for the satellite systems), and becomes ionized and stopped in the magnetic field of the central body. The process can be described as a collision between the falling gas cloud and a magnetized plasma in the magnetic field of the central body. Initially, the density of this plasma may be very low, but it increases due to accumulation of nonionized gas, which becomes ionized and is stopped.

From an energetic point of view, the process is possible when the energy, which the invading gas supplies, suffices for ionization. This is the case when the velocity exceeds a value v_c given by

$$\tfrac{1}{2}mv_c^2=eV_{\text{ion}} \tag{1}$$

(eV_{ion}=ionization energy, m=mass of an atom of the incoming gas).

It has been shown that the orbital distances of the groups of planets and satellites in the solar system can be explained if incoming gas becomes ionized when (1) is satisfied, and this seems to be an essential point for the understanding of how the solar system was formed.

However, a closer analysis of the process leads to some difficulties. When an atom collides with an ion, the atom is not ionized with reasonable probability unless the velocity exceeds the value given by (1) by more than a factor of 10. In contrast to this, an electron can ionize an atom with appreciable probability as soon as the kinetic energy exceeds the ionization energy. Hence, if the gas should be ionized rapidly enough as soon as (1) is satisfied, the process must be

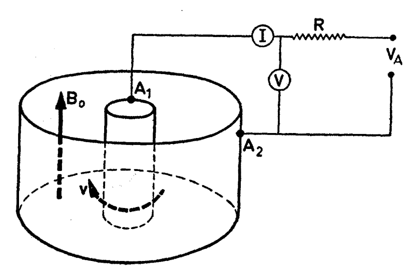

Fig. 1. Experimental arrangement. The plasma between the cylinders A_1 and A_2 rotates under the influence of the magnetic field B_0 and a discharge current.

[1] H. Alfvén, Stockholms Observatoriums Annaler (Stockholm, 1942, 1943, 1946); *On the Origin of the Solar System* (Oxford University Press, New York, 1954).

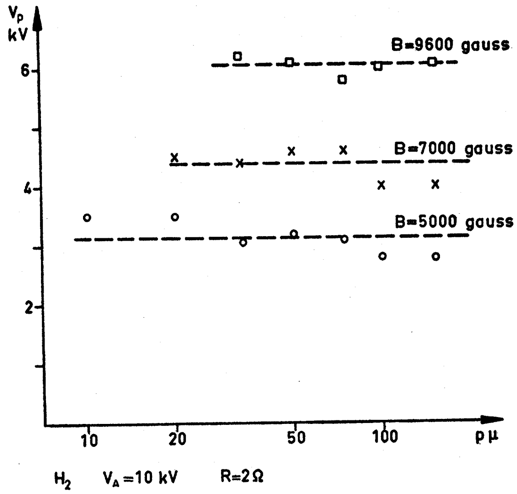

FIG. 2. Voltage between the electrodes as a function of the gas pressure (hydrogen).

more complicated than a direct collision: the incoming atoms must first transfer their kinetic energy to the electrons of the plasma and the electrons can then ionize the incoming atoms. A detailed analysis of this process has, so far, not been possible and the lack in this respect may have been one of the reasons why this theory of the origin of the solar system has not attracted more interest than other theories.

The so-called thermonuclear research has led to great experimental advances in the study of plasmas, and it is now possible to study experimentally the interaction between a magnetized plasma and a nonionized gas. This has recently been done by Fahleson,[2] using a technique developed by Block. Fahleson's experiments demonstrate that as long as the relative velocity is smaller than given by (1) the atoms pass the plasma with a relatively small interaction, but as soon as the velocity exceeds the value of (1), a very strong interaction occurs at the same time as the gas is ionized.

2. SUMMARY OF BLOCK'S AND FAHLESON'S EXPERIMENTAL RESULTS

Block has constructed an apparatus which is similar to the "homopolar" device reported by Anderson *et al.*[3] Its principle can be seen from Fig. 1. A voltage V is applied between the cylindrical electrodes A_1 and A_2 (with radii R_1 and R_2) and the space between them is permeated by a homogeneous magnetic field B_0. The vessel is filled with a gas at low pressure. When a high voltage is applied, a discharge takes place and a plasma is produced. The radial discharge current interacts with the magnetic field so that the plasma is put into rotation. After a few microseconds a stationary state is reached. The plasma rotates with a certain velocity v_θ and the voltage between A_1 and A_2 has a constant value (during 30 μsec or more). The voltage can be expected to be given by the polarization of the plasma, so that

$$V=\frac{1}{c}\int_{R_1}^{R_2} v_\theta B_0 dR. \tag{2}$$

Fahleson has obtained the remarkable result that in hydrogen, V is constant even if the pressure p or the current i between the electrodes is varied within very wide limits. In fact, a variation in pressure from 10 to 150 μ, and in current from 30 to 3000 amp, did not change the value of V appreciably. Further, if the magnetic field B_0 is varied from 2000 to 10 000 gauss, the voltage V is directly proportional to B_0. The experimental results are shown in Figs. 2-5.

These results can be interpreted in the following way. The nonionized gas is in so good contact with the walls of the vessel that at least at low degrees of ionization it does not rotate very rapidly. Hence, the velocity v_θ is essentially the relative velocity between the plasma and the nonionized gas. Even a rather small discharge current brings up the velocity to a certain critical value v_c, but this value is not surpassed when the current increases. Instead, the density of the plasma increases with increasing current. Not until a very large current is reached does the velocity surpass v_c, and this is probably connected with a total ionization of the gas.

Fig. 6 shows in a simplified way the behavior of the discharge when the input voltage V_A (see Fig. 1) is increased. Starting with a certain small degree of ionization, the velocity of the plasma increases but no increase in ionization takes place, until the critical velocity v_c is reached. A further increase in the input leads to no increase in velocity but an increase in the

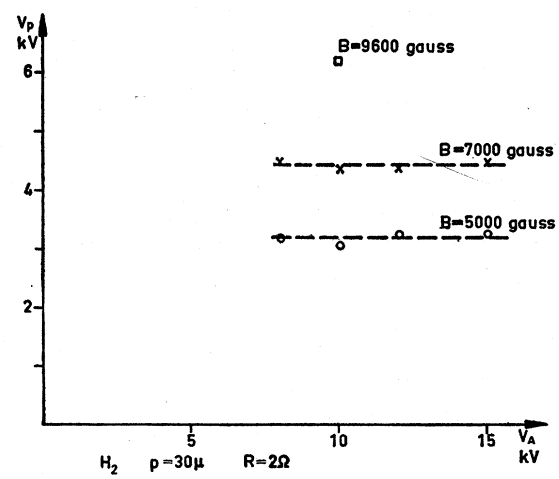

FIG. 3. Voltage between the electrodes as a function of the applied voltage V_A.

[2] U. V. Fahleson, Phys. Fluids (to be published).

[3] O. Anderson, W. R. Baker, A. Bratenahl, H. P. Furth, and W. B. Kunkel, J. Appl. Phys. 30, 188 (1959).

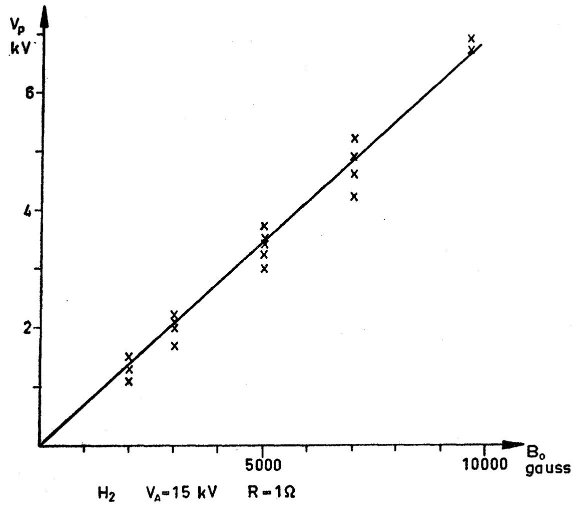

FIG. 4. Voltage between the electrodes as a function of the applied magnetic field B_0.

degree of ionization. Not until the whole gas is ionized is a velocity in excess of v_c possible.

For hydrogen, Fahleson obtains as average

$$v_c^H \approx 5.5 \times 10^6 \text{ cm sec}^{-1}.$$

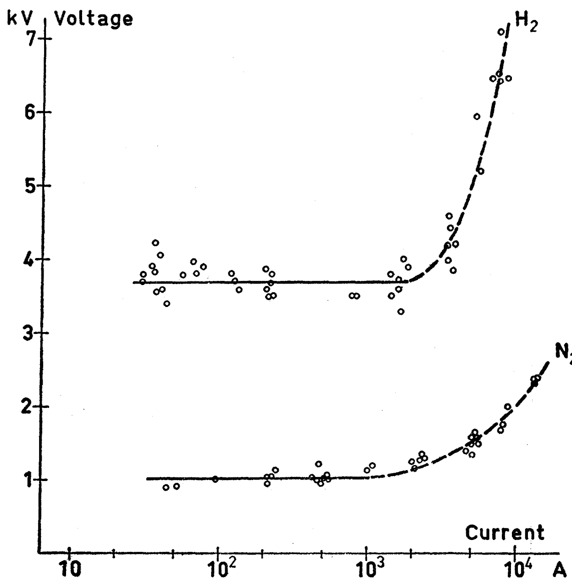

FIG. 5. Voltage between the electrodes as a function of the discharge current for hydrogen and nitrogen.

This corresponds to an energy of the protons [compare (1)] of 15 ev, which should be compared with the ionization energy of hydrogen atom, which is 13.5 ev, and of a hydrogen molecule, which is 15.4.

For nitrogen, the critical velocity was found to be

$$v_c^N = 1.4 \times 10^6 \text{ cm sec}^{-1},$$

which corresponds to a kinetic energy of a nitrogen atom of 14 ev. The ionization energy of a nitrogen atom is 14.5 ev and of a molecule 15.8.

3. THEORY

A theory of this phenomenon cannot be based on binary collisions, as an atom colliding with an ion has little chance of being ionized unless the velocity surpasses v_c by about a factor 10. The kinetic energy of the atoms must be transferred to the electrons of the plasma, but a direct transfer by elastic collisions is a much too slow process.

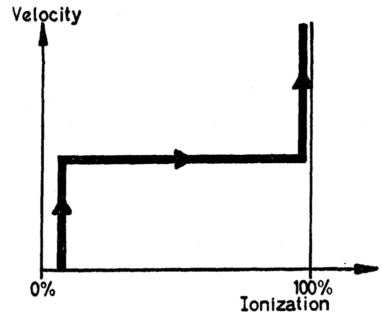

FIG. 6. Simplified picture of the change in ionization and velocity when the input voltage is increased.

A theory must involve some specific plasma phenomena and the following mechanism might be considered. Seen from the coordinate system of the plasma, atoms with an energy eV_1 knock out ions from certain regions of the plasma, creating irregularities in the charge distribution within the plasma. The magnetic field prevents the electrons from neutralizing the charge differences immediately. The process can continue until voltage differences V_1 are produced which are large enough to prevent further ions from leaving the region. In this way voltage differences up to V_1 are produced in the plasma and electrons can be accelerated by these. Hence, electron velocities corresponding to V_1 are produced and these velocities just suffice for the ionization of the atoms.

DISCUSSION

Session Reporter: W. B. RIESENFELD

H. E. Petschek, *Avco-Everett Research Laboratory, Everett, Massachusetts:* I think that it is possible to explain on general grounds why one gets such a definite, sharp critical velocity, when one makes the assumption that some mechanism exists which is rapid enough to produce the ionization. If the energy which goes into the plasma is entirely effective in ionizing it, then

$$\mathbf{v}\cdot(\mathbf{j}\times\mathbf{B}) = (W_{\text{ion}} + \tfrac{1}{2}Mv^2)\,dN_i/dt.$$

From the momentum equation for a plasma rotating with constant velocity, we obtain

$$jB = Mv\,dN_i/dt.$$

On combining these equations, we obtain

$$\tfrac{1}{2}Mv^2=W_{\text{ion}};$$

therefore, one obtains the critical velocity independently of the detailed ionization mechanism.

H. Alfvén: The energy does not go entirely into ionization, it also goes into heating the ion gas.

H. E. Petschek: This would tend to change the result by a factor of two.

L. Spitzer, Jr., *Matterhorn Project, Princeton University, Princeton, New Jersey:* Normally, when one produces ionization by energetic electrons, the cross section for excitation followed by radiation is considerably greater than that for ionization. One gets four to five times more energy going into light than into ionization. This changes the preceding results.

H. Alfvén: We have many atoms coming in and we need not ionize all of them. We have all the energy we need at our disposal.

L. Spitzer, Jr.: This consideration would then not affect your argument, but it would affect Dr. Petschek's equations.

H. Alfvén: That is correct.

A. C. Kolb, *U. S. Naval Research Laboratory, Washington, D. C.:* A large fraction of the radiation energy mentioned by Dr. Spitzer appears in the resonance line. The mean free path is extremely small compared to the dimensions of the system, so that the diffusion time for this radiation could be many microseconds.

S. A. Colgate, *Lawrence Radiation Laboratory, University of California, Livermore, California:* But that depends on the densities involved.

A. C. Kolb: For the resonance line, at an ambient pressure of 0.1 mm, the mean free path is of order 10^{-4} mm; therefore, this energy can be stored in the system.

S. A. Colgate: The resonance radiation diffuses in the "phase space" of the line. The photons make only enough collisions to get to the edge of the line, where the system is only a few mean free paths thick. This diffusion time goes only as the square root of the cross section, rather than the square, as Holstein[a] calculated some time ago. The resonance radiation gets out very fast.

A. C. Kolb: The diffusion time also depends on the atomic lifetime (10^{-10} sec for the resonance line), and the diffusion velocity can be very slow, of order 10^5 cm sec^{-1}, because of the short mean free path. Depending on the time scale of the experiment, the effect of radiation trapping may or may not be important. One should also consider whether or not an incoherent process, i.e., collisions, determines the line width since this has a strong influence on the radiative diffusion.

L. Spitzer, Jr.: I wonder whether Dr. Alfvén has considered how his space charge mechanism can operate in his device where the ions and neutrals are intermixed. It is hard to see how he would get an electrostatic field going all the way around the circumference of the homopolar device. Do you assume that there are blobs or clouds, i.e., that the plasma bunches up?

H. Alfvén: Yes, or possibly statistical fluctuations are enough.

S. A. Colgate: W. Baker has seen that the discharge in his homopolar devices goes to the wall in discrete sheets. There seem indeed to be local clouds going around.

R. Lüst, *Max-Planck-Institut für Physik und Astrophysik, Munich, Germany:* How are the mean free paths for ions and neutrals related to the dimensions of the system?

H. Alfvén: The mean free paths can be of the same order as the dimensions of the apparatus, but also considerably smaller. Collisions between charged particles are in some cases very rare, because at the lowest currents the degree of ionization is a fraction of a percent. The Larmor radii are always less than 1% of the radius of the apparatus.

M. B. Gottlieb, *Matterhorn Project, Princeton University, Princeton, New Jersey:* Could you estimate the electron temperatures in the system?

H. Alfvén: No, that has not been done. All we know is that there are electrons which ionize. It is not at all certain that there should be a meaningful electron temperature.

H. E. Petschek: I do not think that one can show directly that there are electrons present which can ionize, because there exist rapid processes involving molecules which lead to ionization. These might be of importance. In particular, two atoms can recombine to form a molecular ion. This is the most rapid mechanism in the ionization of air at somewhat lower temperatures.

H. Alfvén: I do not think that a process of this type is likely because the same phenomena are observed both in hydrogen and nitrogen.

A. C. Kolb: You remarked that the effect observed may have application to shock waves. Do you view this mechanism as limiting in some way the shock velocities obtainable by magnetic acceleration?

H. Alfvén: If the critical velocity is exceeded, the ionization process may be very rapid. It is possible that this phenomenon should enter, but I am not at all sure how. It is remarkable how often velocities very close to this critical velocity are reported in different experiments.

P. S. Lykoudis, *Purdue University, Lafayette, Indiana:* I would like to mention that in his book on hydrodynamics[b] Lamb examines what he calls "electromagnetic rotations" dealing with the same geometry as in your paper. His problem nevertheless starts where yours ends, since he assumes that he has a perfect conductor and discusses how the velocity increases with time.

R. A. Alpher, *General Electric Research Laboratory, Schenectady, New York:* It seems to me that your plasma makes about one revolution during your entire experiment.

H. Alfvén: No, the radius is between 10 and 20 cm, the velocity 6 cm/μsec, and the experiment is over in between 50 and 100 μsec.

M. Mitchner, *Lockheed Aircraft Corporation, Sunnyvale, California:* You mentioned the remarkable constancy in the velocity of shocks that have been produced experimentally. But in many of these shocks there is no transverse magnetic field, and the shock propagates into a stationary gas.

R. V. Hess, *Langley Research Center, National Aeronautics and Space Administration, Langley, Virginia:* The previous discussion brought out that in the homopolar device nonhomogeneities would lead to the formation of plasma clouds. For the astrophysical case where a stream of nonionized gas impinges on a plasma trapped in the magnetic field, do you expect nonhomogeneities to cause instabilities similar to those occurring when, for example, a water jet impinges on a water surface? Such instabilities could create a kind of turbulence and would be beneficial to the ionization process you described.

H. Alfvén: That is quite possible.

[a] T. Holstein, Phys. Rev. 72, 1212 (1947).

[b] Sir Horace Lamb, *Hydrodynamics* (Dover Publications, New York, 1945), 6th ed., p. 30.