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In 1942 the Swedish astrophysicist Hannes Alfvén postulated the existence of a new kind of wave motion in an attempt to explain certain sunspot phenomena.[1] Interest in these Alfvén waves has greatly increased and they are now of considerable importance in both astrophysical and laboratory plasma observations. A particularly impressive demonstration of Alfvén waves was produced in 1958 by the explosion of a nuclear device in the earth's ionosphere.[2] From this high-altitude experiment called Argus we can understand the nature of the Alfvén waves, which depend upon the interaction of an electrically conducting fluid with a magnetic field.

Thus to begin we must establish an important relationship between an electrically conducting fluid and a magnetic field. The basis of the relationship is the observation that magnetic field lines are "frozen into" a highly conducting fluid. That is, if an element of the fluid is moved, the magnetic field lines passing through that element are dragged along by the moving fluid. We see that this situation is plausible, for if there were relative motion between the magnetic lines and the conducting fluid, an electric field would be induced in the fluid just as an electric field is induced in a generator's armature conductors as they move through the generator magnetic field. Now, in a perfect conductor an electric field cannot exist, and therefore the magnetic flux in a given cross section is constant.

Another way of arriving at the same conclusion is to note that if a conducting fluid moves with respect to a magnetic field, currents are induced in the fluid. If the fluid is a perfect conductor these induced currents will themselves produce a magnetic field which will in combination with the original field leave constant the magnetic lines through any fluid element. In less than perfect conductors, limited relative motion of the magnetic field with respect to the fluid can slowly occur. As a corollary to this discussion we see that if an expanding sphere of conducting fluid is introduced into a magnetic field, the field lines will be excluded from the expanding volume.

This relationship between conducting fluids and magnetic fields has proved so important that a new field of study called magnetohydrodynamics--or, more simply, hydromagnetics--has developed. The areas of application of this new field range from the stars to the physics laboratory engaged in work on controlled thermonuclear fusion. In the stars the highly conducting stellar material continually interacts with both steady and transient stellar magnetic fields, while in the laboratory conducting fluids in the form of ionized gases are confined and manipulated by their interaction with magnetic fields.

Let us begin our discussion of Alfvén waves by considering the earth together with its magnetic field and ionosphere, as shown in Fig. 1. The ionosphere begins at an altitude of 80 km above the surface of the earth and contains, in addition to neutral atoms and molecules, many charged particles. The charged particles are electrons and atoms which have lost one or more of their orbital electrons. In the ionosphere the positively charged ions and the negatively charged electrons are of approximately equal density. The ionized gas of the ionosphere is an example of what is called a plasma. Since the ionosphere has free electric charges we would expect it to be a good conductor, and this is indeed true, particularly at the higher altitudes. Then we can picture the earth's magnetic field lines as being frozen into the plasma of the ionosphere.

Suppose a high-altitude nuclear burst occurs at the point A in Fig. 1. The tremendous energy liberated ionizes the atoms of the atmosphere adjacent to the burst and there exists an expanding fireball of very highly electrically conducting material. Magnetic field lines are excluded from this expanding conducting region in the manner discussed earlier, therefore the magnetic lines and the ionospheric plasma adjacent to the fireball are displaced as shown in Figs. 1b and 1c. The expanding fireball will continue to displace magnetic lines for about half a second. As shown in Fig. 1c, the earth's magnetic field lines are now considerably stretched. From elementary theory one can show that for a magnetic field of intensity B the magnetic lines have an effective tension of $B^2/4\pi$. Under the influence of this tension the lines will contract toward their original position, as shown in Fig. 1d, pulling the adjacent ionosphere along with them. At the later time shown in Fig. 1e the magnetic lines in the region of the burst have returned to their original positions. But north and south of this region the original deformation of the magnetic field produced by the explosion has caused images of that deformation to move along the magnetic field lines. This movement of a magnetic field deformation along a field line which is frozen into a plasma is called an Alfvén wave or a hydromagnetic wave, and is similar to a wave traveling along an ordinary string under tension. The magnetic field provides the necessary tension, and the inertia is provided by the mass of the ionosphere that is attached to the moving field lines. The velocity of propagation of the waves shown in Fig. 1e can be obtained by analogy with the velocity V of wave propagation in a string with mass density ρ under a tension T: $V = \sqrt{T/\rho}$.

If we substitute for T the magnetic field tensions $B^2/4\pi$ and for ρ the mass density of the matter that moves with the magnetic lines, we have

$$V = B/\sqrt{4\pi\rho}.$$

This velocity was obtained by Alfvén, using Maxwell's equations of electrodynamics in combination with the equations describing fluid motion.

For values of B and ρ typical of the ionosphere, Alfvén waves propagate with a velocity of about 1000 km/sec north and south along the magnetic lines that pass through the region of the high-altitude nuclear burst. At the locations on the surface of the earth marked C and C' in Fig. 1a, where these magnetic lines pass into the earth, it should be possible to detect the waves even though an Alfvén wave is not possible in the nonconducting levels of the earth's atmosphere below the ionosphere. The transmission through these lower levels to the surface of the earth is by ordinary electromagnetic propagation. For the Argus experiment the magnetic lines that passed through the fireball entered the earth at the Azores in the northern hemisphere and off the west coast of Africa in the southern hemisphere. A wire loop with a diameter of about 10 km was set up at the Azores location to detect the wave. It was necessary to use a very large detecting loop so that the disturbing effects of automobile ignition systems and other local equipment would be averaged out. A signal was observed at the Azores 10.8 seconds after the burst, whereas the calculated time for the Alfvén wave to travel this distance along magnetic field lines was 12.0 seconds.

In addition to the Alfvén waves described above which travel along magnetic field lines, there are also more complicated modes of propagation that involves a coupling between Alfvén waves and sound waves. These modes can propagate at arbitrary angles to the magnetic lines and can display propagation times different from that expected for pure Alfvén waves. A signal from the nuclear burst was detected not only at the points C and C' in Fig. 1a but also with weaker intensity at many locations on the surface of the earth.

We have described the generation of Alfvén waves in the ionosphere by high-altitude nuclear bursts. These waves are also generated by irregular blobs of plasma from the sun which impinge on the earth's magnetic field and displace magnetic lines.[3] Wire loops at the surface of the earth are also used to detect these disturbances of the earth's field by solar material. However, the area of such loops can be only about one-hundredth or one-thousandth of those used in connection with the Argus experiment because of the comparitively large magnitude of the solar-induced phenomena.

The influence of Alfvén waves induced by impinging solar material on phenomena such as aurorae borealis and magnetic storms is being investigated by many researchers. It has been suggested that these waves influence the rate of loss of particles from the earth-girding Van Allen belts, thus causing substantial variations in the auroral activity which results from the interactions of these particles with the atmosphere.

Alfvén waves have also been generated and observed in laboratory plasma experiments. Some experiments by the authors and co-workers at the Lawrence Radiation Laboratory of the University of California at Berkeley are outlined here and described more fully elsewhere.[4] Similar observations of Alfvén waves have been reported by workers at Harwell and in Japan. Several other laboratories have such experiments in progress.

The waves are generated in a cylindrical copper tube 1 meter long and 15 cm in diameter that is placed in a magnetic field of 15,000 gauss as shown in Fig. 2. A small coaxial electrode is mounted in a vacuumtight seal in a glass plate at each end of the copper tube. The tube is evacuated and then filled with hydrogen gas to 10^{-4} atmospheric pressure. An electric discharge ionizes the gas and produces a highly ionized plasma with a density of 5×10^{15} protons per cubic cm. The density of the plasma is measured by observing the width and shape of the Balmer lines radiated by the hydrogen plasma.[5] The spectroscopic method is similar to the analysis used by astronomers to determine the properties of stars.

The Alfvén wave is generated by discharging a small capacitor between a central electrode and the copper tube. A radial current flows through the plasma and exerts a force on the plasma that tends to rotate it about the axis of the tube. The voltage appearing between the electrode and the copper cylinder as the capacitor discharges is shown in Fig. 3a. As the plasma is twisted the magnetic lines are stretched and a torsional Alfvén wave propagates along the magnetic field lines. The motion of the plasma is at right angles to the direction of wave propagation, hence we have a transverse wave. Since the magnetic lines are being stretched and moved as the wave propagates, there is a time-varying magnetic field associated with the Alfvén wave. Very small coils of wire capable of detecting these time-varying magnetic fields are inserted into the plasma at each end of the copper cylinder. Figures 3b and 3c show the magnetic field detected by each of these coils as an Alfvén wave is propagated down the cylinder. The Alfvén wave velocity can be obtained from the observed transit time and the distance between the two coils. The measured velocity has been compared with that obtained from the formula

$$V = B/\sqrt{4\pi\rho}$$

by use of the known magnetic field B and the spectroscopically measured plasma density ρ.

This experiment and the theory agree within the experimental uncertainty of a few percent. For fields of about 14,000 gauss these waves travel at a velocity of about 4×10^7 cm/sec, and therefore take about 2.5 μsec to travel through the tube. The formula above predicts that the wave velocity will be a linear function of magnetic field, and this is observed experimentally as shown in Fig. 4. The attenuation of the Alfvén wave can be obtained by comparing the amplitudes of the wave at the two different coil positions. The tube is essentially a coaxial waveguide in which the plasma is the dielectric. In a solid dielectric energy is stored by displacing atomic or molecular bonds, whereas this plasma dielectric stores energy in the form of kinetic energy of rotation of the plasma itself. The characteristic impedance of this hydromagnetic wave guide can be predicted, and is in close agreement with the experimental ratio of the voltage and current at the driving electrode. The wave-guide aspect of the experiments may find engineering applications such as a hydromagnetic resonator.

At the far end of the tube the plasma density goes to zero in a distance short compared with the wavelength. Therefore waves should reflect from this abrupt discontinuity. This behavior is observed experimentally, and the reflected waves have the theoretically predicted phase changes. It is also possible to fill the tube half full of plasma, as shown in Fig. 5. An Alfvén wave propagating in the plasma should reflect off this boundary, and a reflected wave is indeed observed experimentally. This laboratory situation is somewhat similar to the conditions at the lower boundary of the ionosphere. The density of the ionosphere goes to zero in a distance short compared with the wavelength, so that much of the wave should be reflected back into the ionosphere. As mentioned above, however, some of the energy is propagated past the boundary by ordinary electromagnetic radiation.

We have described a set of laboratory experiments which establish the primary properties of Alfvén waves and have discussed several natural phenomena in which these waves exert a strong influence. To date few technological applications of Alfvén waves have been made, although they are being considered for use in hydromagnetic amplifiers and in connection with plasma heating techniques associated with controlled thermonuclear fusion devices. As with any new findings, detailed predictions of future applications are impossible.

Footnotes and References

[*] Work done under the auspices of the U. S. Atomic Energy Commission.

[†] On leave at the Royal Institute of Technology, Stockholm.

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Figure Captions

Fig. 1. The generation and propagation of a hydromagnetic disturbance by the explosion of a nuclear device at A in the earth's magnetic field. The progress of the Alfvén wave is shown in c, d, and e.

Fig. 2. A device for generating Alfvén waves in laboratory plasmas.

Fig. 3. Wave forms associated with experimentally generated Alfvén waves. The time dependence of the applied voltage, the associated magnetic wave field, and the corresponding received wave field are shown in a, b, and c, respectively.

Fig. 4. Experimentally determined variation of wave velocity as a function of magnetic field.

Fig. 5. The laboratory device half filled with plasma.

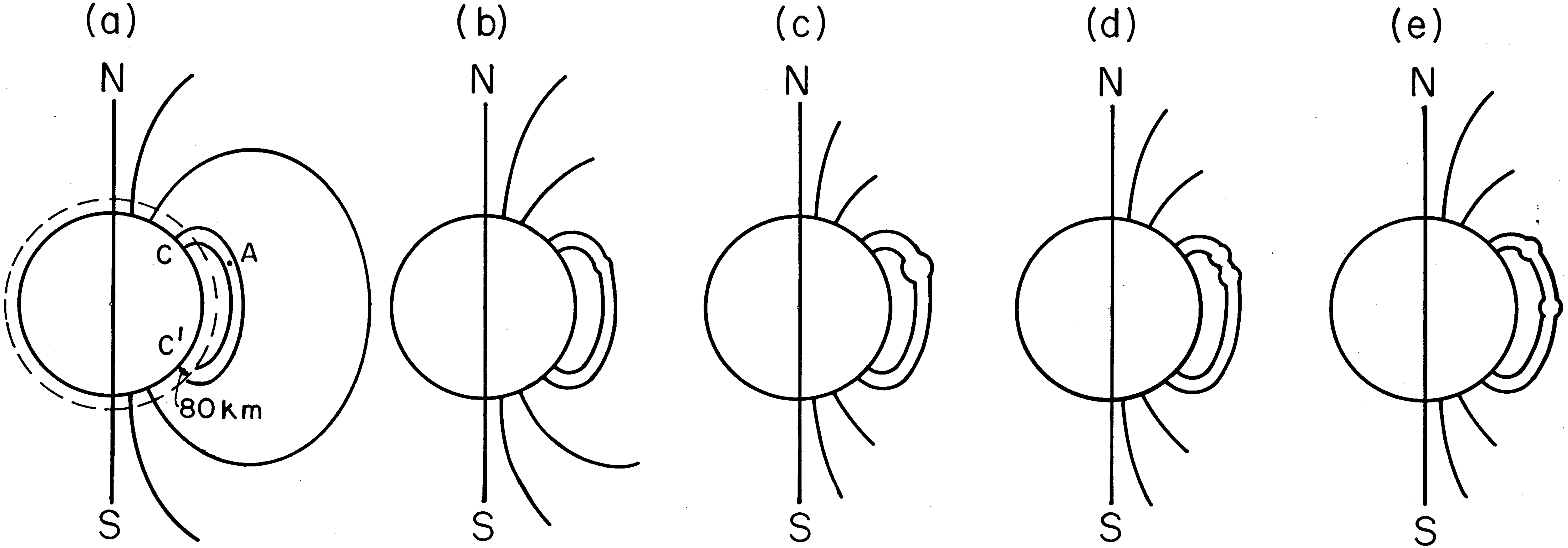

Fig. 1

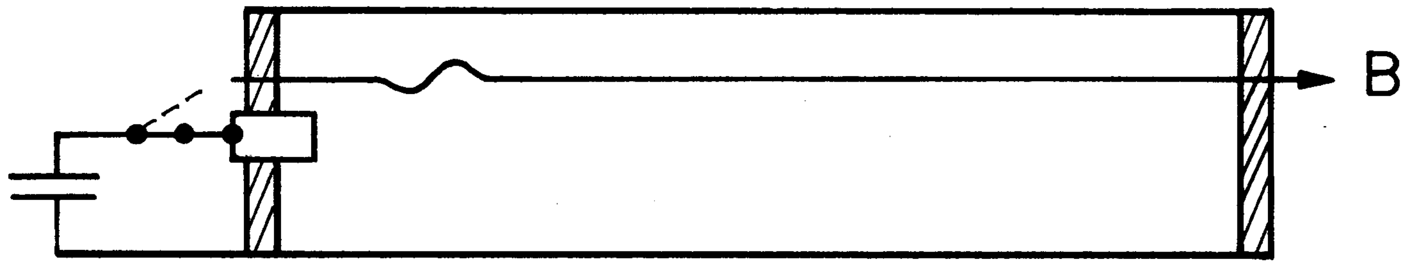

Fig 2

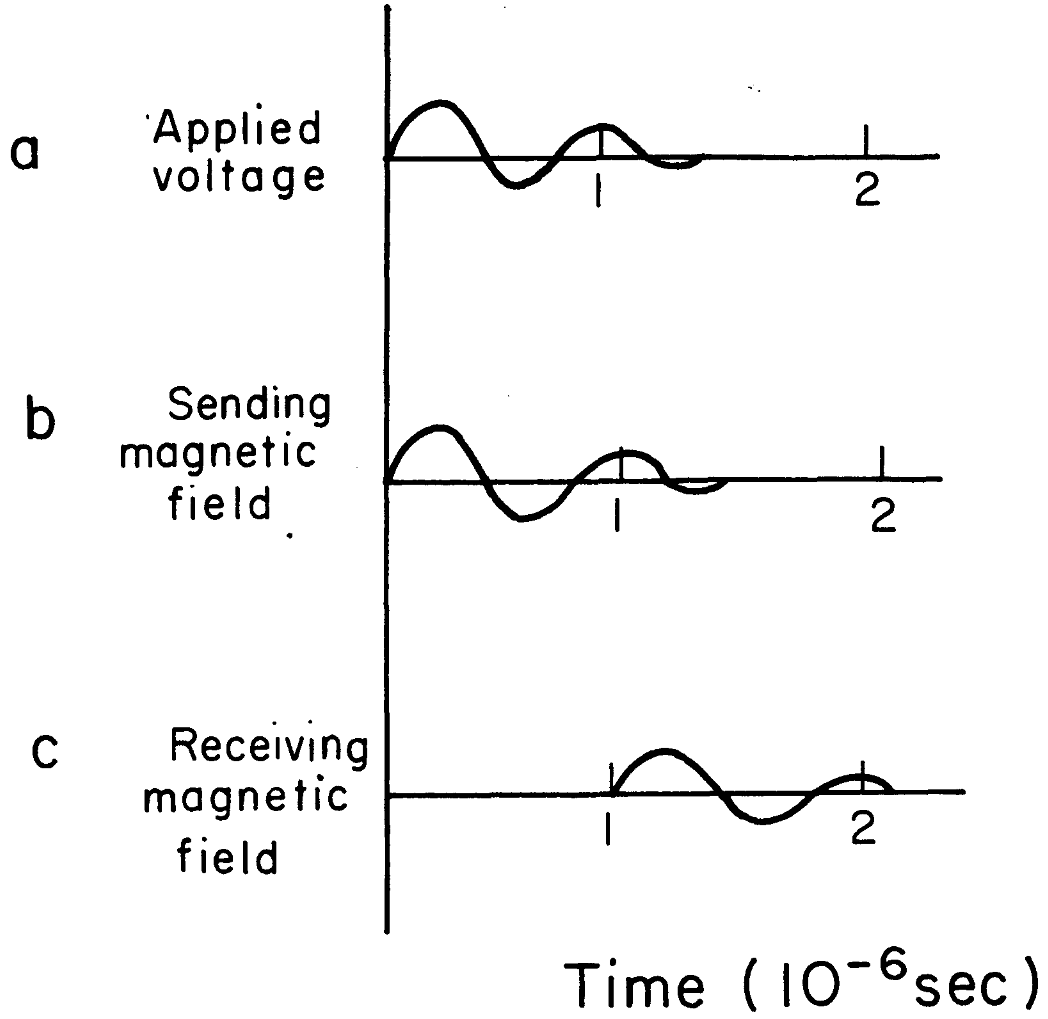
a
Applied voltage
1
2
b
Sending magnetic field
1
2
c
Receiving magnetic field
1
2
Time (10⁻⁶sec)

Fig 3

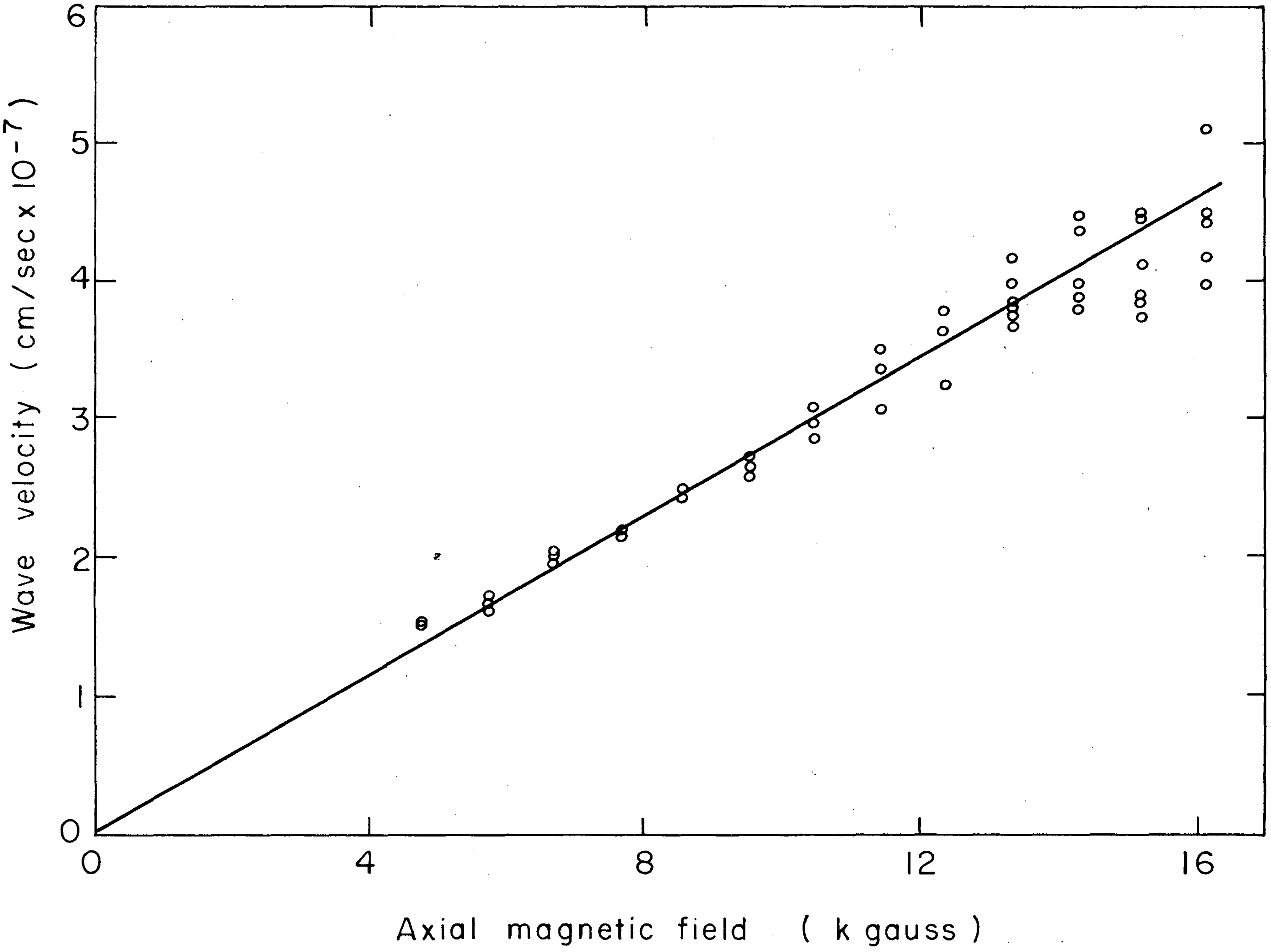

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Fig 4
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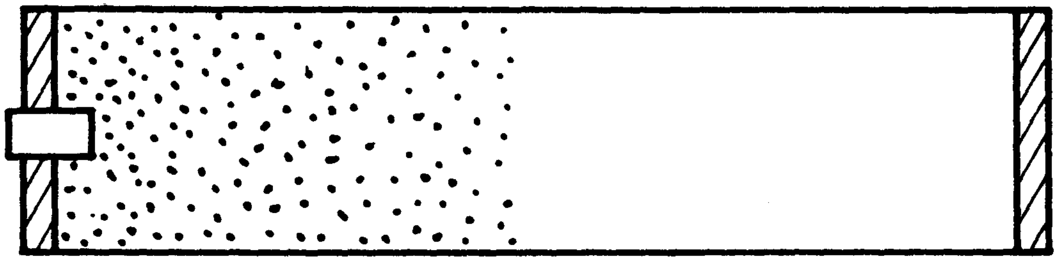

Fig 5

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