An approximate measurement of the ionization time behind shock waves in air

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Summary

A hydromagnetic shock tube has been used to obtain an approximate measurement of the time to reach equilibrium ionization behind shock waves of Mach number 11 to 17, moving into air at a pressure of about 1 mm of mercury. This ionization time decreases with increasing Mach number. Experimental results are presented as a graph of the ionization time *vs* Mach number. The principal source of error in the measurements is the attenuation of the shock and the results indicate a lower limit for the ionization time in air.

Introduction

In recent years there has been considerable interest in the rate at which equilibrium ionization is reached behind shock waves in gases. Petschek & Byron (1957) measured the ionization rate for argon at shock velocities from Mach number 10 to 18; their results indicate that the dominant ionization process is collisions between electrons and argon atoms, and that there is good agreement between experimental measurements and theoretical calculations of the ionization rate. Turner (1956) has made similar measurements in xenon gas. In a theoretical paper, Bond (1957) also concludes that the electron–atom process is the dominant one.

No measurement of the ionization time behind shocks in air have been reported so far despite the importance of this information in aerodynamic problems. Lamb & Lin (1957) measured the electrical conductivity of shock heated air, and concluded that, at the densities used, the time to reach equilibrium ionization is short compared with the time interval which can be resolved in their experiments. The present note reports a rough measurement of the ionization time in air behind shocks in the Mach number range 11 to 17 and at an initial pressure of about 1 mm of mercury.

Experimental method

Plane shocks in air were generated using a hydromagnetic shock tube. This apparatus has already been described by Blackman, Niblett & Schrank (1957). It consists of a one-inch diameter glass tube with a single-turn copper coil wrapped around it. A low-inductance capacitor (rated at

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1·6 microfarads and 0·025 microhenrys) is discharged through the coil and the rapidly varying magnetic field (70 kilogauss per microsecond) induces an electric field which breaks down the air and produces circular current loops. An analysis of the initial process has been described by Blackman & Niblett (1958). Shock waves, moving outward in both directions from the coil, are produced by the rapid expansion of the gas due to Joule heating and the interaction of the magnetic field with the current loops. The motion of the shock wave in the horizontal tube is photographed using a drum camera; photographs taken with a vertical slit show that the shock becomes plane within about three diameters of the coil, and photographs taken with a horizontal slit and drum camera yield the shock velocity. A typical streak photograph is shown as figure 1 (plate 1). With the capacitor initially charged to 20 kilovolts and the air at 1 mm pressure, the luminous front achieves its maximum velocity of about Mach 90 at 1 cm from the coil and decays, rapidly at first and then more slowly, to Mach 10 at about 30 cm from the coil. Over the range of Mach numbers 11 to 17 the rate of decay of the front is about 0·5 Mach numbers per cm.

The shock front itself is not visible on the photographs, but is followed at some distance by a region where the luminosity increases rapidly. It is assumed that the radiation is produced mainly by processes which involve free electrons. This assumption is reasonable since in the range of photographic sensitivity the radiation is produced principally by oxygen free–free and oxygen free–bound transitions together with nitrogen band spectra (see Keck *et al.* 1957) which are likely to be excited by free electrons. The luminous front is thus taken to be the point at which ionization equilibrium is attained. For strong shocks in which the ionization time is very short the luminous front and the shock front are coincident but as the wave decays the shock front draws progressively further ahead of the luminous front. The intermediate dark space is the region in which the gas ‘relaxes’ to its equilibrium condition.

The vertical distance on the film (i.e. parallel to the time axis) between the shock front and the luminous front is taken as the measure of the ionization time. The essential problem, therefore, is to determine on each film the locus of the shock front. The position of the shock front was determined by reflecting the wave from the plane face of a one-inch diameter metal slug placed in the tube at appropriate distances from the coil. When the shock wave is reflected from the face of the slug the enthalpy of the gas is approximately doubled and the ionization time decreased. Over the range of these experiments the ionization time is reduced by a factor of about five on reflection and hence an error of about 20% is incurred by assuming the reflected shock and luminous front to be coincident.

A series of shocks were fired into air at pressures between 1 and 2 mm of mercury with the reflecting slug placed at varying distances from the coil. Fresh air was used for each experiment since the discharge may change the composition of the gas in the tube. A typical photograph

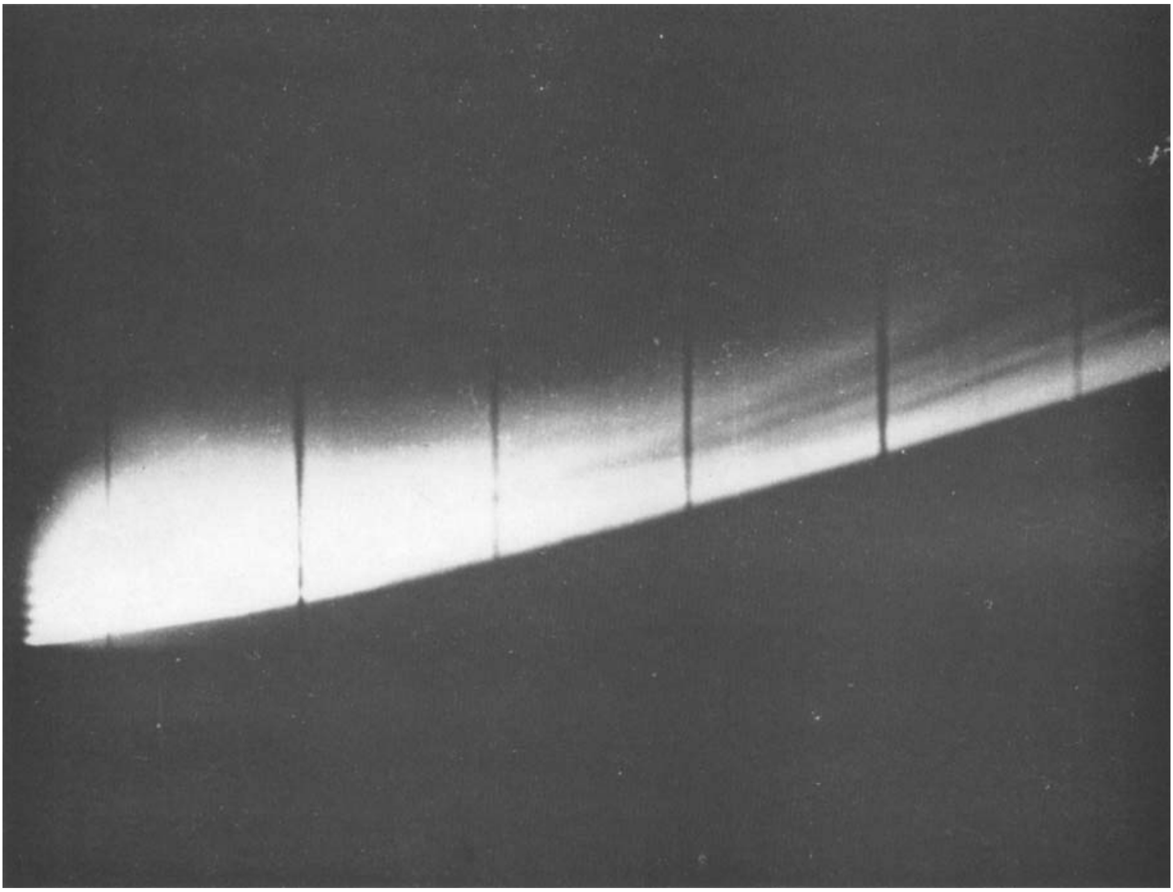

Figure 1. Typical streak photograph of a shock produced in the hydromagnetic shock tube. Distance is in the horizontal direction and time in the vertical direction. The coil is on the left and the vertical lines are markers 3 cm apart. Maximum Mach number is about 90 and occurs 1 cm from the coil.

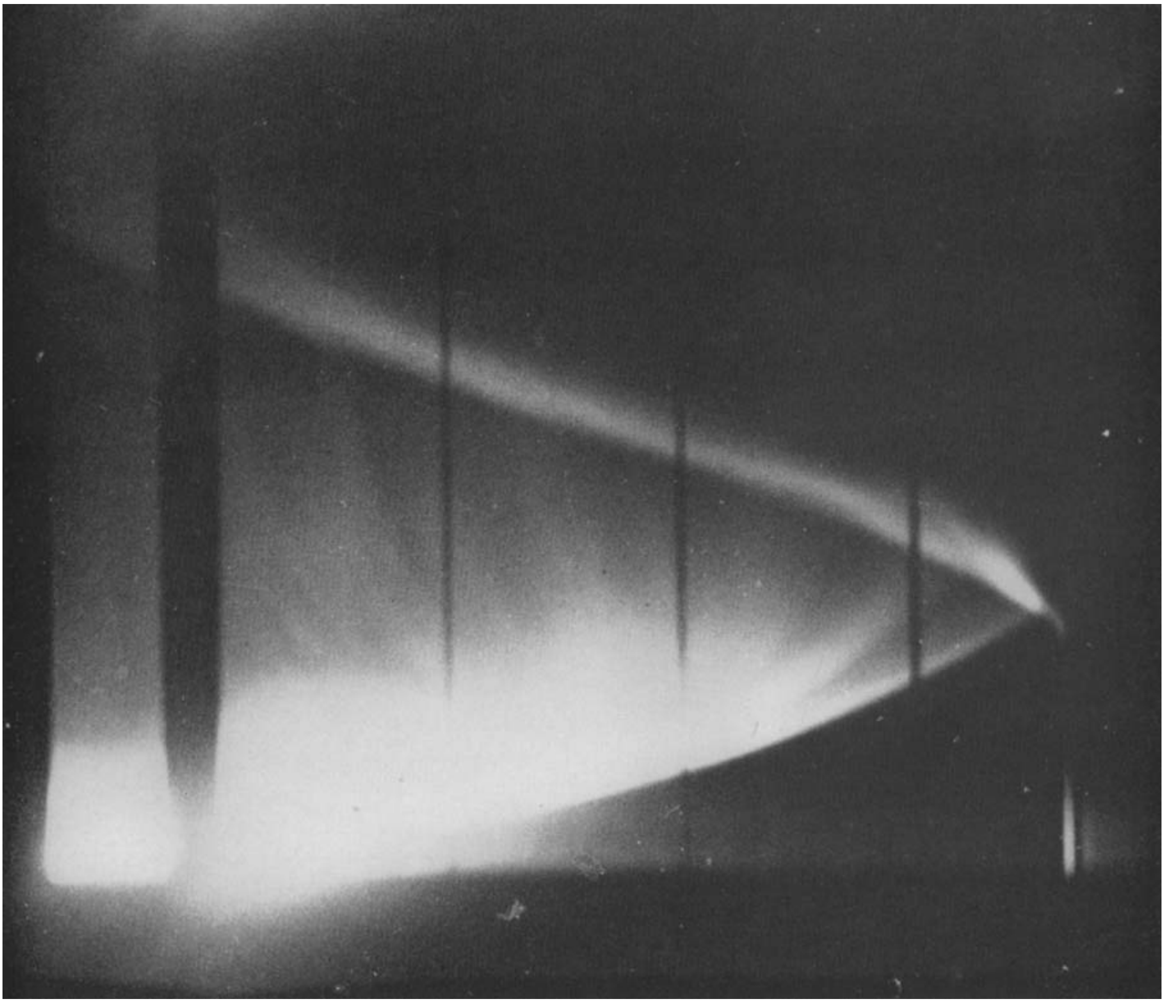

Figure 2. This photograph shows a shock reflected from a metal slug. At the reflecting surface the incident Mach number is 11·1, and $p_1 \tau = 0{\cdot}56$, in units of cm of mercury times microseconds.

is shown as figure 2 (plate 2); the reflected shock, appearing earlier in time than the incident luminous front, can be seen clearly. If a series of pictures is taken with the same gas pressure and the same capacitor voltage, the streak records can be accurately superimposed and a 'master' diagram constructed showing the locus of the luminous front and the shock front. Such a diagram is shown in figure 3. The Mach number of the shock can be obtained from the angle (as indicated in the figure) and the film speed;

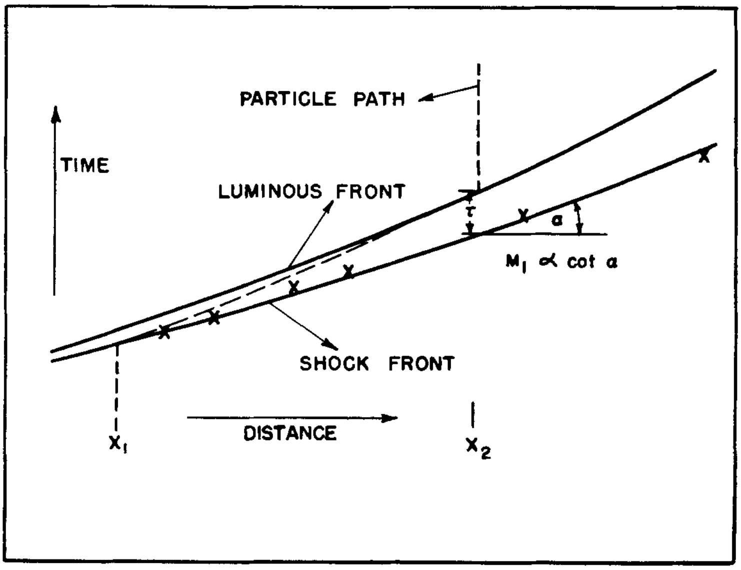

Figure 3. The position of the shock and luminous fronts as a function of time. The diagram is used to measure τ and the Mach numbers. The path that a gas particle follows is indicated by the dotted line. The scatter of the crosses, which represent the position of the shock front, gives a measure of the experimental precision.

and the distance along the time axis between the shock and luminous front is a measure of the ionization time. This measured time τ must be multiplied by the mean density ratio across the shock, which is about nine in these experiments, to give the true ionization time; i.e. the time for a given sample of gas to reach equilibrium ionization along a particle path.

Results

The results are plotted in figure 4 in terms of $\log(p_1 \tau)$ *vs* Mach number, where p_1 is pressure in cm of mercury and τ is in microseconds. The points fall roughly on a straight line when plotted in this way. Each point represents a value of τ and Mach number measured at the same distance from the coil.

The most serious source of error is the attenuation of the incident shock. The gas sample which reaches equilibrium ionization at a distance x_2 from the coil (see figure 3) has passed through the shock further upstream at a distance x_1 where the Mach number was greater. The Mach numbers plotted in figure 4 are therefore too low. The effect of this error has been avoided as much as possible in the following way. Measurements of the ionization time in argon have been made using the present technique and compared with the more accurate results of Petschek & Byron. Agreement was found to be reasonably good for short ionization time but increasingly poor for long times. Accordingly, results for air are included in figure 4 only for the range of ionization times over which there is reasonably good agreement between the two sets of argon measurements.

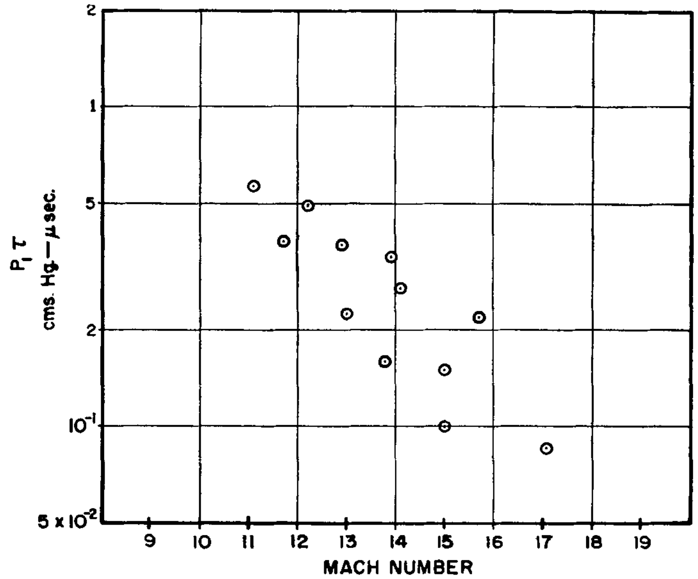

Figure 4. The experimental values of the ionization time in air plotted against Mach number. The ionization time is multiplied by p_1 since the ionization rate is closely proportional to the atom density.

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