INVESTIGATION OF THE PLASMA PRODUCED BY A NORMAL IONIZING SHOCK WAVE USING POLYCHROMATOR TECHNIQUES

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Summary

Measurements of the electron density of a transient hydrogen plasma have been made by a study of the Stark broadening of the emitted Hβ radiation. The plasma is formed by the passage of a strong ionizing shock wave through a neutral gas in the pressure range $100 \leqslant p \leqslant 400$ mtorr. The instantaneous Stark-broadened line profiles have been constructed by simultaneously sampling the light intensities at a number of wavelengths within the Hβ line by the use of an eight-channel polychromator.

It is shown that this approach yields information about the density and homogeneity of the plasma which is not available from laser interferometer measurements. Evidence is also presented which suggests that the ionizing shock waves presently obtained may have marked snow-plough characteristics.

I. Introduction

Measurements of the electron density and temperature of a transient high density low temperature plasma formed by the passage of a normal ionizing shock wave through a neutral gas immersed in a strong magnetic field may be investigated conveniently by spectroscopic means.

The preparation of a hydrogen plasma in this manner was first carried out by Wilcox, Boley, and DeSilva (1962), and plasmas prepared in this way have since been investigated by Brennan *et al.* (1963), Irons and Millar (1965), and Gross, Levine, and Geldon (1966). The electron density, when it has been considered (Irons and Millar 1965), has been determined from measurements of the shape of the Stark-broadened Hβ line emitted by the plasma. The profile was compared with the theoretical profiles calculated by Griem (1964) for different electron densities. The experimental profile was obtained by successively measuring the radiated intensity at various wavelengths isolated by a monochromator. At least eight firings of the shock tube were required to obtain a profile. In fact, because of the inevitable shot-to-shot variations, many more firings were required to obtain a reliable profile.

Profiles of the Hβ line can be obtained more efficiently and reliably by simultaneously sampling the intensities at eight different wavelengths within the Hβ line by the use of an eight-channel polychromator (Stirling and Westwood 1968). The variation of electron density with time can, therefore, be determined for any one firing of the shock tube. This facility has been used to determine the electron density as a function of both time and position in the shock tube in order to determine the most favourable conditions for the propagation of waves in the plasma, and in a

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preliminary study of the density profile following the passage of the normal ionizing shock wave used to produce the plasma.

II. Description of Shock Tube

The cylindrical shock tube used in these experiments is 90 cm long with an internal diameter of 10 cm and is constructed from two Pyrex pipe sections. At one end of the tube, hereafter called the firing end, is a concentric electrode assembly made of non-magnetic stainless steel. For the experiments described in the present paper, a 2 cm diameter electrode and an 8 cm internal diameter outer electrode were used. These electrodes extend only 2 cm along the z axis of the tube, this being one of three electrode configurations currently being investigated, namely short outer

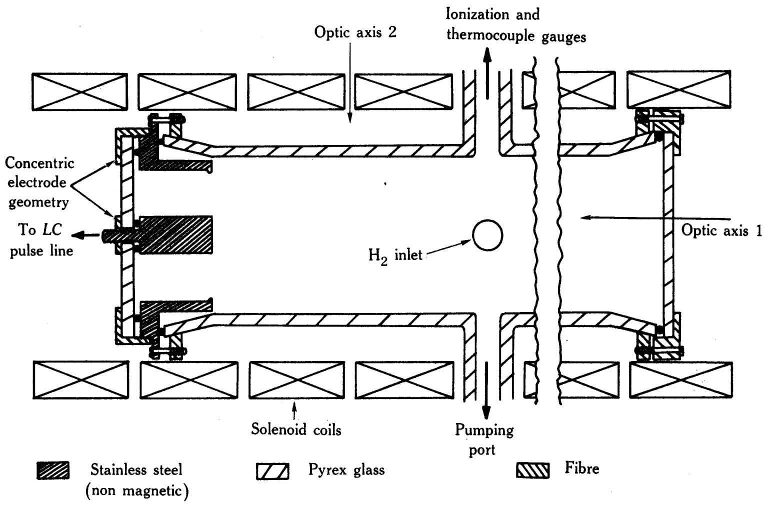

Fig. 1.—Schematic diagram of shock tube.

and inner electrodes, a short inner electrode with the outer electrode extended along the length of the tube, and a coaxial geometry with both electrodes extended along the tube. The other end of the tube is usually sealed off with a Pyrex plate, although for some applications axial probes may be inserted through this end plate. Four side arms, 25 cm from the firing end, allow for pumping the tube and for vacuum gauges and also for the introduction of diagnostic radial probes.

A residual gas pressure of 10^{-6} torr is achieved by means of a two-stage rotary pump backing a 2 in. oil-diffusion pump. Palladium-purified hydrogen gas is circulated continuously through the machine at pressures within the range 10–800 mtorr. No cold traps were incorporated in the vacuum system. A schematic diagram of the shock tube is shown in Figure 1.

The plasma is produced by an ionizing shock wave, propagating along the cylindrical tube in the presence of an axial magnetic field of 0·8 tesla, driven by a square current pulse of duration approximately equal to the transit time of the shock down the tube. This method of plasma production is similar to that used by Brennan *et al.* (1963) and Gross, Levine, and Geldon (1966) except that, in the present experiments, neither the central anode nor the outer ring-shaped cathode extend the length of the tube.

All times quoted in the present paper are measured from the start of the current pulse.

III. Diagnostics

The profile of the Stark-broadened Hβ line depends on the electron temperature as well as the electron density. Thus, the electron temperature must be determined before the experimental and theoretical profiles can be compared to determine the electron density. The temperature was determined from a comparison of the measured and calculated values of the ratio of the total intensity in the Hγ line to the intensity

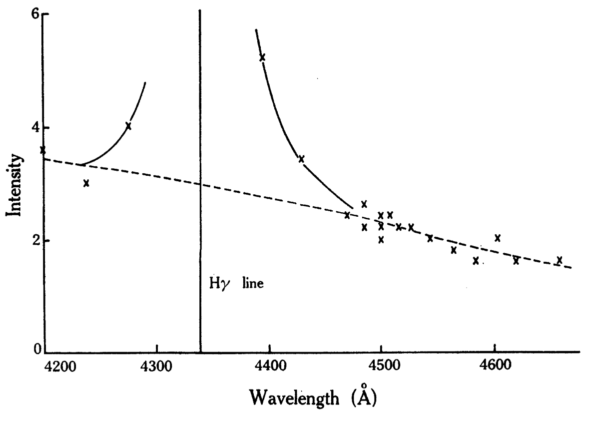

Fig. 2.—Typical curve showing the variation of light intensity (arbitrary units) with wavelength for wavelengths near to the Hγ line used in determination of the electron temperature. This particular curve was constructed from data obtained at 100 μsec and 400 mtorr:
x, experimental points
——, Hγ line wings
– – –, continuum

due to continuum radiation in a 100 Å wide band centred on the Hγ line. The theoretical ratios have been calculated by Griem (1964) for temperatures up to 4×10^4 °K. A Techtron monochromator selected a spectral band that had a triangular response with a half-width of 9·37 Å, measured using a hydrogen Geissler tube. The ganged slits were opened wide, and the triangular response was due to the entrance and exit slits having the same width. The intensity was monitored by a photomultiplier (R.C.A. 1P28) mounted behind the exit slit. The signal from the photomultiplier was passed through an emitter follower (to maintain high frequency response) and an amplifier, and was then displayed on an oscilloscope. With the monochromator successively centred on wavelengths between 4200 and 4600 Å, the intensity was measured on repeated firings of the shock tube (Fig. 2). From this the total intensity in the Hγ line (which lies at 4340·46 Å) was determined, and the continuum intensity in the 100 Å wide region centred on the Hγ line was obtained by interpolation from the values near 4200 and 4600 Å.

At wavelengths closer to the Hγ line than these values, there was still an appreciable contribution to the intensity from the Hγ line, and at wavelengths outside this range contributions from the Hδ and Hβ lines at 4101·74 and 4861·33 Å became appreciable. Thus, from plots (of which Fig. 2 is an example) made for different times after the shock tube was fired, the variation of the electron temperature with time was determined.

Stark-broadened Hβ line profiles were measured using an eight-channel polychromator designed and built in these laboratories* (Stirling and Westwood 1968). This polychromator simultaneously measures, as a function of time, the intensity of the broadened spectral line at eight wavelengths 1·1 Å apart. Two Tektronix 551 oscilloscopes fitted with four 1A1 plug-in units, operated in the chopped mode, were used to display eight signals simultaneously. One channel was recorded on both oscilloscopes as a monitor so that, in practice, only seven channels of the polychromator were used. The theoretical profiles used were computed by folding Griem's (1964) calculated profiles for the appropriate electron temperature with the measured spectral profile of the polychromator (Stirling and Westwood 1968). A comparison of the experimental line profile with the theoretical profile then gave the electron density. In Figure 3 the experimental intensities obtained at the same time from

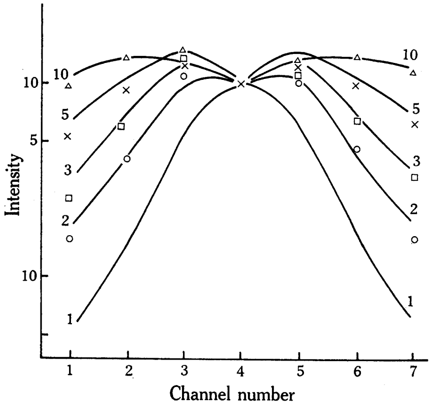

Fig. 3.—Comparison of the experimental intensities (arbitrary units) simultaneously obtained from seven channels of the polychromator with the calculated profiles at an electron temperature of 10^4 °K, showing computed profiles for the following densities:
1, 1×10^{15} cm^{-3}
2, $(2\pm0\cdot2)\times10^{15}$ cm^{-3}
3, $(2\cdot9\pm0\cdot3)\times10^{15}$ cm^{-3}
5, $(4\cdot2\pm0\cdot4)\times10^{15}$ cm^{-3}
10, $(10\pm1)\times10^{15}$ cm^{-3}

the seven channels on one firing of the shock tube and the calculated profiles are shown. It is evident that the experimental points are in excellent agreement with the calculated profiles. It should be noted that, in these experiments, the central dip in the Hβ profile was regularly observed whereas many investigations (Irons and Millar 1965) have failed to observe this dip. The only imperfection in the experimental profiles was a systematic asymmetry in the line peak, which appeared to be moved towards longer wavelengths, whilst the wings remained symmetrical. Exhaustive tests, including centering the line on different channels, have failed to show any fault in the polychromator. A similar asymmetry in the Hβ line has been reported by Birkeland, Oss, and Brown (1967).

IV. Results

Before the detailed measurements of intensity versus wavelength were made using the Techtron monochromator, a Hilger D187 constant deviation spectrograph, modified to accept a polaroid film back, was used to make extensive observations of the plasma spectrum. Such observations along optic axis 1, which included the electrode region in the line of sight (see Fig. 1), showed the presence of numerous impurity lines, the wavelengths of which indicated iron as the main contaminant.

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A comparison of the observed spectral lines with the spectral lines of iron gave the following values for the strongest lines observed versus the Fe^{+}/Fe lines respectively:

5035	5020	4630	4620	4545	4530	4410	4310	4109	4105	4100
5030	5018	4625	4619	4547	4528	4404	4307	4109	4104	4100

Similar observations along optic axis 2 (Fig. 1) did not show any iron impurity lines. Hence, the electron temperature was always determined from spectroscopic measurements along optic axis 2.

(*a*) *Temperature Measurements*

Measurements of electron temperature have been made at neutral gas pressures of 100 and 400 mtorr, and at 100, 120, and 160 μsec. Since currents are still flowing in the plasma and there is marked turbulence before 100 μsec, no measurements of either temperature or density were initially made prior to this time. The results of these temperature measurements are summarized as follows.

Time (μsec)	Electron Temperature (°K) at 100 mtorr	400 mtorr
100	—	$(18\pm2)\times10^3$
120	$(22\pm5)\times10^3$	$(13\pm2)\times10^3$
160	$(13\pm2)\times10^3$	$\sim 10\times10^3$

It can be seen that an error of up to 20% is associated with these measured temperatures. However, since the shape of the Stark-broadened Hβ line profile is only weakly dependent upon electron temperature, a correspondingly large error is not introduced into the electron density measurements, and these temperature measurements are adequate to determine which of the calculated profiles should be used to obtain the density.

(*b*) *Density Measurements*

Measurements of the electron density were made at 100, 140, and 180 μsec at neutral gas pressures of 100 and 400 mtorr. Observations were made both longitudinally along the plasma column, optic axis 1, and across the plasma column, optic axis 2 (Fig. 1). The variation of density across the radius of the plasma column was thus investigated by moving optic axis 1 across the horizontal radius, and the density variation along the length of the plasma was studied by moving optic axis 2 along the plasma from the firing end of the tube. In the latter case, observations can be made only at intervals of approximately 10 cm in the spaces between the coils.

The spatial resolutions of the optical system were 0·5 and 1·0 cm along optic axes 1 and 2 respectively.

In this way it was anticipated that a three-dimensional picture of the plasma density would be established for any given time. The results of these observations are summarized in Figure 4. The most obvious feature of these results is the good agreement between the radial and the axial observations. In general, the plasma is of substantially uniform density along the length and, at 400 mtorr, also across the radius. At 100 mtorr, however, the electron density has a maximum in the radial direction at approximately half the radius. This maximum is most evident at early time and tends to diminish as the plasma decays.

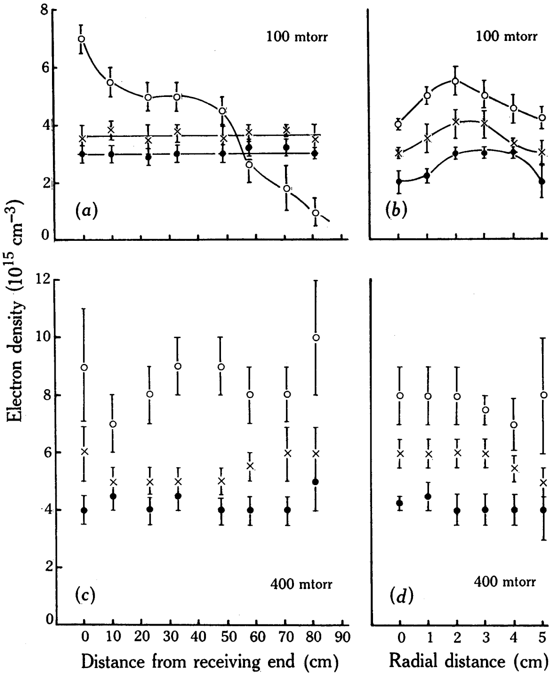


Fig. 4.—Experimental electron density variations within the plasma at various times: o, 100 μsec; x, 140 μsec; ●, 180 μsec. (*a*) and (*c*) are the variations along the plasma columns (measured from the receiving end of the shock tube) and (*b*) and (*d*) are the variations across a radius of the plasma column. The measurements were made at gas pressures of 100 and 400 mtorr as shown.

An obvious exception to the general uniformity of the electron density is the situation at 100 mtorr and at 100 μsec (shown in Fig. 4(*a*)). Although the radial distribution is not significantly different from the situation at 400 mtorr above,

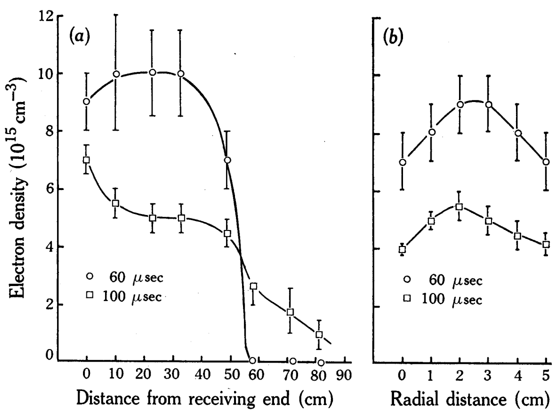


Fig. 5.—Electron density variations within the plasma at earlier times, with neutral gas pressure of 100 mtorr:
(*a*) longitudinal variation;
(*b*) radial variation.
The points shown as zero density indicate densities below the lower limit of the polychromator, that is, $n < 5\times10^{14}$ cm^{-1}.

the axial distribution shows a marked asymmetry, the electron density being much higher in the half of the vessel remote from the electrodes than in the half containing the electrodes. Although not conclusive, axial displacement of the plasma in this manner suggests the possibility of snow-plough behaviour of the shock wave. In order to investigate this effect, further density measurements were made at 100 mtorr and 60 μsec. These results are compared in Figure 5 with the previous results at 100 mtorr and 100 μsec. It is evident that the effect is even more marked at earlier times. Furthermore, the electron density of 10^{16} cm^{-3} at 60 μsec observed at the receiving end of the tube is significantly higher than the initial neutral density of 7×10^{15} cm^{-3}. This effect is currently being studied in detail at even earlier times and the results will be published elsewhere.

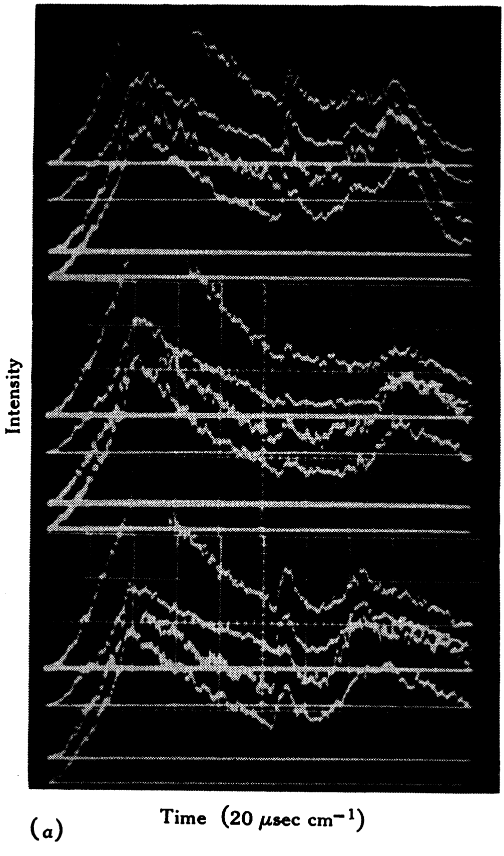
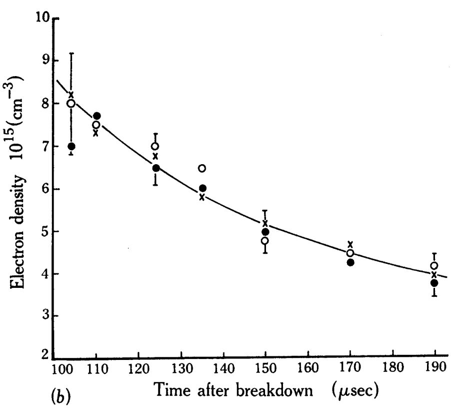


Fig. 6(a).—Oscillograms of the output of four of the eight channels of the polychromator on three consecutive shots of the shock tube showing the difference in light intensity output from shot to shot.

Fig. 6(b).—Electron density as a function of time obtained from the three oscillograms shown in (a):
×, from the top traces
○, from the centre traces
●, from the bottom traces



The advantage of using the polychromator to determine the Hβ profile from one firing of the shock tube instead of building up the profile by the shot-to-shot method is clearly demonstrated by the oscillograms in Figure 6(a). These show the variation of intensity with time recorded for four adjacent channels of the polychromator on three successive firings of the shock tube at a gas pressure of 400 mtorr. For a given channel, the intensity at a given time shows large variations from shot to shot. Variations of up to 100% in intensity have been observed. Thus, if these measurements were used to build up a profile by the shot-to-shot method, the profile would be very poorly defined. However, the polychromator gives good profiles on each shot and the electron density can be accurately determined. The variation of the density with time measured from each shot is shown in Figure 6(b).

Two rather surprising conclusions may be drawn from Figures 6(*a*) and 6(*b*). Firstly, despite the large variations from shot to shot in the intensity, the electron density (as a function of time) measured from each shot is the same within the experimental error. Secondly, although for a given shot the intensity at a given wavelength shows large and irregular variations with time, the measured density decreases slowly and smoothly with increasing time.

Thus, although the measured electron density is the same for the three shots, the total amount of plasma in the line of sight varies from shot to shot. And, for a given shot, as the measured density decreases smoothly, the total amount of plasma in the line of sight changes rapidly and irregularly. Thus it appears that the shock tube contains clouds of plasma, within which the electron density is constant but outside of which the electron density is extremely low. If this were not so, the emitted Hβ radiation from the plasma outside the plasma cloud would be much narrower than the profile emitted by the plasma cloud, and the observed profiles would not fit the calculated profiles for any density as closely as is observed.

Thus, it would be correct to talk about an average density throughout the tube only if the emitted intensity were constant from shot to shot. If a laser interferometer alone were used to determine the electron density, a misleading picture of the plasma would be obtained, since the laser interferometer measures an average density.

Such intensity variations are not observed at low pressures ($\simeq$ 100 mtorr), the intensity of the Hβ light output being highly reproducible from shot to shot and decaying smoothly during each shot. More extensive measurements will be needed to determine the nature and origin of the plasma irregularities.

V. Conclusions

From the results described above, the use of an eight-channel polychromator to determine electron density measurements is to be preferred to the single-shot method. While the large variations in intensity from shot to shot cause a large uncertainty in the profile in the latter case, they do not affect the density measured by the polychromator, and the intensity variations actually provide additional information about the nature of the plasma.

Because the plasma exists only in regions of the tube at high gas pressures ($\gtrsim$ 400 mtorr) the polychromator gives data concerning the electron density within the plasma clouds and the degree of inhomogeneity which a laser interferometer would not give. For some applications, however, where the phenomenon investigated is large compared with the dimensions of the turbulence, an average density may be required. In this case laser interferometer data are applicable, although care must be taken in the interpretation of the data.

From the data obtained in these experiments it is evident that future wave propagation studies in this type of plasma should be restricted to times of at least 150 μsec after the start of the plasma preparation, and to neutral gas pressures of $<$ 200 mtorr. At earlier times the electron density has not become uniform after the passage of the ionizing shock wave, whilst at higher gas pressures the plasma is not homogeneous.

The presence of snow-plough characteristics in the ionizing shock wave is disturbing because not only does it limit wave studies but such properties are not allowed for in present ionizing shock wave theory (Woods 1965; Taussig 1966). Hence, any experimental investigation of ionizing shock wave parameters may not be expected to show good agreement with theoretical predictions. It should be noted, however, that the results presented here are applicable only to the present electrode geometry. It is hoped that experiments currently in progress, with the coaxial geometry used by Gross, Levine, and Geldon (1966) and the electrode configuration used by the Sydney group (Brennan *et al.* 1963), will reveal the extent to which snow-plough characteristics are present in the various configurations.

VI. Acknowledgments

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VII. References

Birkeland, J. W., Oss, J. P., and Brown, W. B. (1967).—Proc. 8th Int. Conf. on Ioniz. Phenom. Gases, Vienna.

Brennan, M. H., Brown, I. G., Millar, D. D., and Watson-Munro, C. N. (1963).—*J. nucl. Energy* **5C**, 229.

Griem, H. R. (1964).—"Plasma Spectroscopy." (McGraw-Hill: New York.)

Gross, R. A., Levine, L., and Geldon, F. (1966).—*Physics Fluids* **9**, 1033.

Irons, F. E., and Millar, D. D. (1965).—*Aust. J. Phys.* **18**, 23.

Stirling, A. J., and Westwood, W. D. (1968).—*Rev. scient. Instrum.* **39**, 1575.

Taussig, R. T. (1966).—*Physics Fluids* **9**, 421.

Wilcox, J. M., Boley, F. I., and DeSilva, A. W. (1962).—*J. nucl. Energy* **4C**, 587.

Woods, L. C. (1965).—*J. Fluid Mech.* **22**, 689.