SPECTRAL AND MICROWAVE STUDIES OF THE DECAY OF A HIGHLY IONIZED HYDROGEN PLASMA

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Summary

The decay of an almost fully ionized hydrogen plasma immersed in a magnetic field of 1 tesla has been investigated spectroscopically and with microwave interferometers at 35 and 120 GHz. It has been found that the plasma decays approximately exponentially in time and that the density–temperature relations in the contracting central column are adequately described in terms of the theoretical predictions of Bates, Kingston, and McWhirter down to densities of about $1\times10^{19}\,\mathrm{m}^{-3}$ and temperatures of 2000°K. Competing processes of axial and transverse diffusion have been shown to play no significant part in the decay of this plasma.

I. Introduction

The ways by which ionized plasmas decay are of considerable interest not only to those working in the field of gaseous discharge physics, but also to astrophysicists and upper atmosphere physicists. Some early experimental observations were reported by Kenty (1928) and theoretical calculations by Cillié (1932). The decay of laboratory hydrogenous plasmas has been studied by Lord Rayleigh (1944), Craggs and Meek (1945), Fowler and Atkinson (1959), Hinnov and Hirshberg (1962), Cooper and Kunkel (1965), and Irons and Millar (1965). The first calculations that recognized the importance of three-body recombination were performed by D'Angelo (1961). Later calculations by Bates, Kingston, and McWhirter (1962*a*, 1962*b*; subsequently referred to as BKM) included other decay processes besides three-body recombination. The experimental observations of Hinnov and Hirshberg (1962) have confirmed the calculations of D'Angelo for low density plasmas ($n<5\times10^{19}$ m^{-3}). The denser plasma work (5×10^{21} to $1\times10^{21}\,\mathrm{m}^{-3}$) of Irons and Millar and of Cooper and Kunkel yielded results that agreed well with the theoretical predictions of BKM for a hydrogen plasma opaque to Lyman line radiation.

In this paper we report recent studies of plasma decay, extending the work of Irons and Millar (1965) to low densities ($10^{18}\,\mathrm{m}^{-3}$) and low temperatures (2000°K), and finding the same good agreement with the theoretical predictions of BKM.

II. Theory

We make the following assumptions (experimentally justified in our plasma):

(1) Neglect of inertial forces. Studies of image converter framing camera pictures show that at about 100 μsec after plasma formation turbulence has virtually disappeared (Brennan *et al.* 1963).

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(2) Neglect of $\boldsymbol{J}\times\boldsymbol{B}$ forces. These are very small in our plasmas after the ionization current has been switched off.

Under these conditions the rate of loss of charged particles in a cylindrical plasma is given by the equation

$$\frac{\mathrm{d}n}{\mathrm{d}t} = D_{\perp}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial n}{\partial r}\right) + D_{\parallel}\frac{\partial^2 n}{\partial z^2} - \gamma n^2\,, \tag{1}$$

where $D_{\perp}$ and $D_{\parallel}$ are the diffusion coefficients perpendicular and parallel to the magnetic field respectively, γ is the collisional–radiative decay coefficient and is a function of density and temperature, and n is the ion or electron density (equal in our hydrogen plasma).

Times for equipartition of energy between the ions and electrons (Spitzer 1962) are of the order of 2×10^{-8} sec (at 100 μsec) and 4×10^{-7} sec (at 800 μsec). (Times for Maxwellization of protons amongst themselves and of electrons amongst themselves are approximately 1/43 and 1/1836 times smaller respectively.) Since these times are much less than the time constant for the plasma decay (180 μsec) our assumption of equal ion and electron temperature is justified.

Equation (1) contains three charged-particle loss terms on the right-hand side corresponding to transverse diffusion, ambipolar axial diffusion, and volume recombination. We shall consider each in turn.

(*a*) *Transverse Diffusion*

The first term in equation (1) represents the loss of charged particles by diffusion radially across the magnetic field (Golant 1963). The transverse diffusion coefficient is

$$D_{\perp} = \eta_{\perp}\, kTn/B^2\,, \tag{2}$$

where $\eta_{\perp}$ is the electrical resistivity perpendicular to the applied axial magnetic field, and is equal to $1\cdot29\times10^2 \ln\Lambda\, T^{-3/2}$ ohm m (Spitzer 1962) with $\ln\Lambda\approx6$ for our plasmas; T (°K) is the electron or ion temperature; and B is the applied axial magnetic field.

We have assumed that ion–electron collisions dominate. It can be shown that at our densities the frequency for collisions with neutrals is lower by a factor of at least 10.

A calculation based on a magnetic field B of 1 tesla and our plasma conditions before 100 μsec, when the transverse drift speed is greatest, yields a minimum time of about 50 msec for the particles to drift to the vessel walls. This is much longer than our observed decay time constant of 180 μsec and so this contribution can be neglected. The experimental decay rate remains independent of the axial magnetic field even at fields as low as $0\cdot2$ tesla.

(*b*) *Axial Diffusion*

The second term in equation (1) represents the loss of charged particles by axial diffusion. The axial diffusion coefficient is (Golant 1963)

$$D_{\parallel} = 2kT/m_{\mathrm{i}}\nu_{\mathrm{in}}\,, \tag{3}$$

where m_i is the ion mass, and ν_{in} the ion–neutral collision frequency, which is $\sim 4\times10^5$ sec^{-1} (calculated from charge exchange cross sections obtained by Brown and Watson-Munro (1966) under conditions similar to ours).

Initial axial density gradients resulting from the rarefaction behind the shock front (see Section III(a)) are smoothed out in an acoustic wave characteristic time of about 50 μsec. If the subsequent losses were due to axial diffusion, a cosine distribution would be approached in a characteristic time τ, where

$$\tau \sim l^2/\pi^2 D_{\parallel}\,, \tag{4}$$

l being a characteristic length in the plasma (Heading 1963). Under our conditions, this time can never be less than 10 msec, which is again much longer than our observed decay time constant. Therefore this contribution can also be neglected. We have indeed found no significant axial variation of density at different points along the vessel during the plasma decay. However, at low pressures (below 2 mtorr), where ν_{in} is smaller, axial diffusion gives rise to a cosine density distribution along the axis.

These considerations allow us to reduce equation (1) to

$$\mathrm{d}n/\mathrm{d}t = -\gamma n^2\,. \tag{5}$$

(c) *Collisional–Radiative Decay*

At first, two-body recombination

$$\mathrm{H}^+ + \mathrm{e}^- \rightarrow \mathrm{H}^* + h\nu \tag{6}$$

was assumed to be the dominant process responsible for plasma decay. However, theoretical calculations of the plasma decay rate based on this model by Zanastra (1946) were found to be considerably lower than the experimental observations of Craggs and Meek (1945) and Fowler and Atkinson (1959).

Decay dominated by three-body recombination, which is the inverse of collisional ionization,

$$\mathrm{H}^+ + \mathrm{e}^- + \mathrm{e}^- \rightarrow \mathrm{H}^0 + \mathrm{e}^-\,, \tag{7}$$

was suggested by Giovanelli (1948a, 1948b) in connection with stellar atmospheres and was calculated in detail for laboratory plasmas by D'Angelo (1961). D'Angelo considered only radiative transitions and electron collisional ionization. His values of decay coefficients were found to be reasonably applicable to the low density plasmas ($n_e < 5\times10^{19}$ m^{-3}, $T_e < 3000$°K) of Hinnov and Hirshberg (1962). However, D'Angelo's calculations gave coefficients much less than the observed values in dense plasmas (e.g. Cooper and Kunkel 1965; Irons and Millar 1965).

Various refinements to D'Angelo's studies were made by Byron, Stabler, and Bortz (1962) and Hinnov and Hirshberg (1962). A more general treatment of the decay has been given by BKM, who consider the rate equations for the population and depopulation of all the atomic energy levels due to collisional and radiative processes. In addition to three-body recombination and its inverse process of collisional ionization, BKM included inelastic and superelastic collisions, which were neglected by D'Angelo. Their calculations yielded, for both optically thick and optically thin plasmas, the decay coefficient and the distribution of electrons in the levels in the excited states.

III. Experiment and Results

(*a*) *Plasma Preparation*

Our plasmas were produced in the Supper I plasma source (see Fig. 1), which consists of a copper vessel (diameter 15·2 cm, length 86 cm) sealed with quartz end plates. The vessel is immersed in an axial magnetic field (maximum value 1 tesla) that is constant in space and time to within 4% over the region of interest.

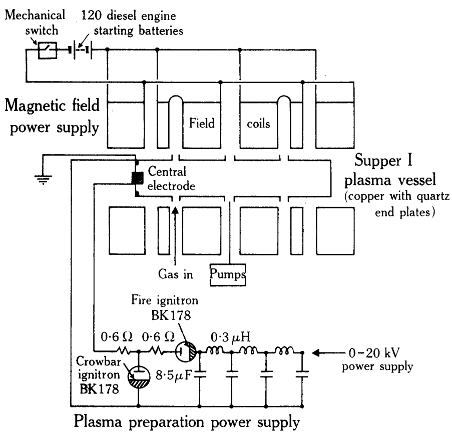

Fig. 1.—Schematic diagram of Supper I.

The plasmas were prepared by the so-called $\boldsymbol{J}\times\boldsymbol{B}$ process (Brennan *et al.* 1963) where a constant current energy source is discharged between a central electrode and the outer cylinder. The ensuing radial breakdown current of about 10 kA reacts with the axial magnetic field to produce a rotating plasma. In addition, an ionizing shock front travels up the vessel at a velocity of about 5×10^4 m sec^{-1}. The plasma rotational energy is removed by short-circuiting ("crowbarring") the energy source just before the ionizing shock front reaches the other end of the vessel. This process causes plasma turbulence, which within 100 μsec, has disappeared leaving a quiescent plasma whose decay during the next millisecond forms the subject of the present paper.

We chose an axial magnetic field of 1 tesla and a hydrogen gas pressure of 100 mtorr. Under these conditions the plasma is free from the "density hollow" at the inner electrode radius shown in the paper by Cooper and Kunkel (1965), who used a magnetic field of 1·6 tesla.

(*b*) *Electron Density and Temperature Measurements*

Electron Densities. These were measured by:

(1) The Stark broadened profiles of Hα, Hβ, and Hγ lines, measured with a monochromator and compared with the theoretical values of Griem, Kolb, and Shen (1959, 1962). This method was used for electron densities about 10^{21} m^{-3}. The results have been confirmed by one of us (C.N.W-M.) using interferometric measurements with a helium–neon gas laser (Brown *et al.* 1967).

(2) Microwave Interferometry. A double interferometer (Brand 1968) operating at 35 and 120 GHz gave the average electron density across a diameter of the plasma half way along the vessel as a function of time. The radial electron density distribution (Fig. 2(*b*)) was obtained from a second interferometer (35 GHz) using a

special antenna (Brand and Heckenberg 1969) consisting of a waveguide with a wall aperture so arranged as to provide radial directivity. It was mounted within the vessel at various radii inside an 8 mm ID quartz tube. The presence of the tube was found to have a negligible effect on the rate of plasma decay. Knowledge of the radial profile allowed the peak electron density to be obtained as a function of time (Fig. 3) from the average density as measured by the double interferometer.

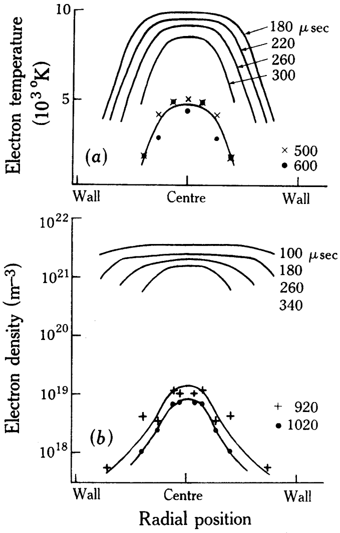

Fig. 2.—Electron temperature (*a*) and density (*b*) profiles across a diameter of the vessel at representative times. Profile measurements before 400 μsec are from Irons and Millar (1965).

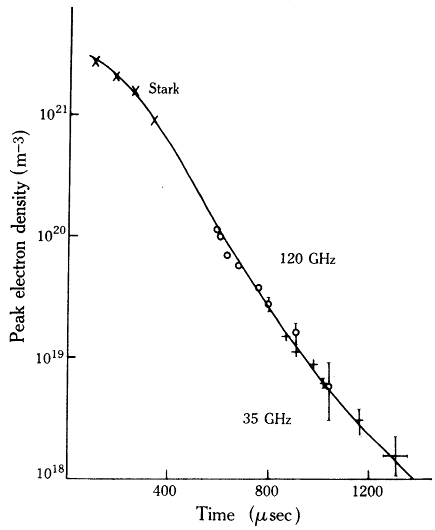

Fig. 3.—Decay of peak electron density with time as measured by Stark broadening and microwave interferometry at 120 and 35 GHz. Experimental points and curve of best fit are shown.

Electron Temperatures. The temperature decay of the central region (Fig. 4) and the radial temperature variation (Fig. 2(*a*)) were both measured. Temperatures that were:

(1) above 5000°K were measured by the relative intensities of the Hγ line and of two bands of the continuum, each of width 32 Å centred at 3440 and 5094 Å.

(2) below 5000°K were measured by the Balmer-decrement method, where the relative intensities of Hβ, Hγ, Hδ, Hϵ, and Hζ were compared.

The logarithm of the number of electrons in the upper level of each transition was plotted against the energy of the upper level. We found that above 5000°K all the points lay along a straight line, but as the temperature fell, first the point for Hβ and then, below 2000°K, the point for Hγ departed from the straight line. Those points that lay on the straight line indicated that the corresponding upper levels had populations consistent with local thermodynamic equilibrium, allowing a meaningful electron temperature measurement to be made.

The monochromator used had a focal length of 50 cm and a dispersion of 16 Å mm^{-1}. For temperature measurements the complete optical system was calibrated against a standard tungsten ribbon lamp, kindly standardized for us by the National Standards Laboratory, CSIRO.

Our plasmas have been prepared under the same conditions as those of Irons and Millar (1965). Several measurements that we made at early times confirmed their description of the decay. Their detailed measurements of density and temperature profiles have been included in Figure 2.

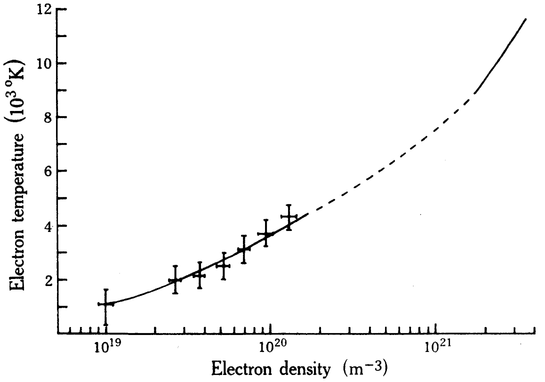

Fig. 4.—Electron temperature versus electron density of the central region of the plasma. The plotted points show Balmer decrement temperatures at densities measured by microwave interferometry. The curve of best fit is extended (dashed line) to high temperature and density results of Irons and Millar (1965).

(*c*) *Plasma Decay*

As the plasma decays, it rapidly contracts into a column of several centimetres radius which lasts for > 1 msec (Fig. 2). The plotted points in Figure 4 show the experimentally determined relationship between electron density and temperature during the later stages of the decay (> 500 μsec). A dashed line connects these measurements at low densities and temperatures to the high density and temperature measurements of Irons and Millar (1965), whose curve of best fit is shown by a solid line.

IV. Discussion

The collisional–radiative decay coefficient γ has been derived, using equation (5), from the measured electron density decay (Fig. 3). These experimental values are plotted as a function of electron temperature (and electron density) in Figure 5. The corresponding values of γ, predicted by BKM, are shown as a solid line.

Irons and Millar have demonstrated that, as expected from the theory, our plasmas are opaque to Lyman line radiation. Their results at high densities and temperatures confirm the theoretical curve B (the corresponding theoretical values of γ over their range of measurement for a plasma transparent to Lyman radiation are shown by curve A). In the range of our measurements, the two cases become indistinguishable. Further, ionization processes are unimportant and the decay coefficient γ becomes equal to the collisional–radiative recombination coefficient $\alpha^{(i)}$ (BKM).

Taken together, these results, for a plasma decaying over three orders of magnitude in density, show excellent agreement with the theoretical calculations of BKM and so give strong support to their theoretical model including the additional collisional processes (Section II(a)) as a fully adequate description of the physical processes taking place in a decaying hydrogen plasma.

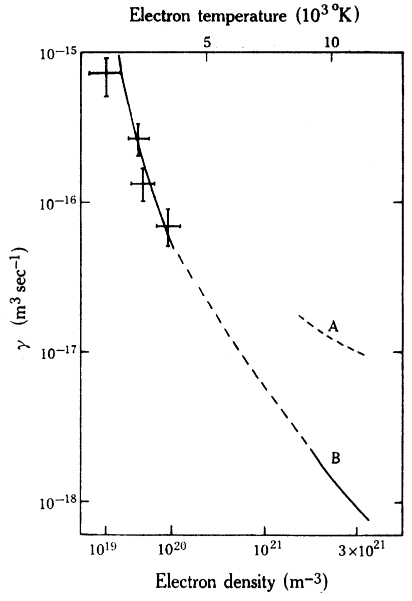

Fig. 5.—Decay coefficient γ versus electron temperature and density (related by Fig. 4). The plotted points show values derived from the electron density decay rate. The complete curve B gives the values of γ for a plasma opaque to Lyman line radiation computed by BKM for the conditions through which the plasma passes. The solid portion of curve B at high temperatures and densities has been confirmed by Irons and Millar (1965). For comparison are shown the values of γ (curve A) predicted for a plasma transparent to Lyman line radiation under the same conditions of temperature and electron density. Curve A, if continued, would become indistinguishable from curve B over the range of the low density and temperature measurements.

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