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1970 J. Phys. A: Gen. Phys. 3 559

(http://iopscience.iop.org/0022-3689/3/5/013)

J. Phys. A: Gen. Phys., 1970, Vol. 3. Printed in Great Britain

Ionization-diffusion waves in the helium positive column

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MS. received 10*th April* 1970

Abstract. An investigation of the simultaneous occurrence of moving striations and backward disturbance waves in the helium positive column at low to medium pressure is described. The interaction between these nonlinear wave motions is discussed and an instability of the positive column for electrode separations greater than 14 cm is reported.

1. Introduction

The main properties of ionization–diffusion waves in positive columns at low to medium pressure, both when self-excited ('moving striations') and where artificially stimulated ('waves of stratification'), are now fairly well understood (Oleson and Cooper 1968, Pekarek 1968, Nedospasov 1968, Garscadden *et al.* 1969). Certain features of moving striations, which are associated with their large amplitude, are, however, still not clear. In particular, there is some lack of information about their behaviour in helium, compared, for example, with neon and argon.

The present paper is mainly concerned with two aspects of moving striations observed in the course of an investigation of the helium positive column, namely:

(i) The simultaneous appearance of the commonly found waves moving towards the cathode and of 'disturbance waves' (Stewart *et al.* 1965) moving towards the anode.

(ii) An effect of the length of the positive column on the stability of moving striations.

2. Experimental arrangements

The glass discharge tube was mounted horizontally, and was 120 cm long and 2·6 cm in diameter. The cathode was a zirconium disk, 1·3 cm in diameter and 1 mm thick: a pointed rod of platinum, 4 cm long and 3 mm in diameter served as anode. Both electrodes were movable, allowing a maximum separation of 50 cm. The gas used was supplied as 'spectrally pure' by the British Oxygen Company.

Time-resolved images of the moving striations were obtained by reflection from a flat mirror, rotating about an axis parallel to the tube, on to fast film (speed 800 ASA) through an f 1·4 lens. They were also monitored using photomultiplier tubes.

3. Experimental results

The current and pressure ranges covered in the investigation were 1–100 mA and 1–50 torr respectively. The present paper is specifically concerned with data obtained at 23 torr.

The general appearance of the time-unresolved helium glow discharge is similar to that of the usual cold cathode glows through the other rare gases. With time resolution, moving striations were observed in the positive column of all the discharges studied. Their behaviour was again similar to that of striations in the other

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rare gases. The waves travelled away from the anode with speeds of the order of 100–200 ms^{-1}. The frequency of the waves was about 1000–2000 s^{-1} and the wavelength varied between 5 and 20 cm. No striations were detected in either the Faraday dark space or the cathode region of the discharge.

Figures 1(*a*), (*b*) and (*c*) (plates—see Appendix) show typical time-resolved photographs of the column at 23 torr pressure and 33 mA current. The anode is at the right in each case and the negative glow appears as the broad streak at the left. Time increases from top to bottom, so that a horizontal line in a photograph gives the appearance of the discharge at a particular instant. Figures 1(*a*), (*b*) and (*c*) were obtained at electrode separations of 8·6, 10 and 12·7 cm respectively. The sequence illustrates the onset and development of backward-moving (negative) 'disturbance waves' as the distance between the electrodes is increased. The negative waves move towards the anode with roughly the same speed and frequency as the moving striations, but appear to have smaller amplitude.

The movement of striations in the anode–cathode direction is impeded by the backward motion of the negative disturbances, the effect increasing as the electrode separation is made larger. Maximum interference between the two wave motions occurs when the distance between the electrodes is 12–13 cm.

When a positive striation meets a negative disturbance, an interaction or 'collision' occurs, as a result of which the positive striation is brought to rest for a short time (a few microseconds). A plasma of greater than average charge concentration is formed by this interaction which is visible as a region of increased light intensity. After some microseconds the positive striation continues its motion towards the head of the column with roughly its original speed. The regions of increased light intensity (standing striae) occur at fixed points in the column which are determined by the electrode separation (i.e. the oscillation mode of the column).

In the case of the helium column, a rather peculiar connection between electrode separation and discharge stability was observed. When the anode-cathode distance was increased beyond about 14 cm the positive column became unstable, and remained so up to the maximum separation obtainable (about 50 cm). This instability, which was not observed in neon or argon (Coulter 1959), persisted even when care was taken to localize the anode spot on the pointed tip of the electrode.

Figure 1(*d*) (plate—see Appendix) was obtained at a current of 48·5 mA, when the electrode separation was 11 cm. Under these conditions it is observed that a backward wave moves through the positive column and (in contrast with (*a*), (*b*) and (*c*)) reaches the anode region with little attenuation. In doing so, it meets and interferes with more than one moving striation providing a rather unusual time-resolved 'criss-cross' pattern.

On close examination of the photographs anode spot oscillations can be observed. It has been pointed out (Takamine *et al.* 1933, Coulter *et al.* 1961) that, in the rare gases, moving striations are often coupled with oscillations of increasing amplitude in a high-intensity spot localized on the anode or at an equivalent gas-anode (Coulter *et al.* 1958). This aspect of moving striations is not discussed in the present communication, but it is worth noting that the same mechanism can be associated with the generation of moving striations in helium, although it is now generally believed that moving striations can also occur without anode spots being present.

4. Discussion

In overall nature and appearance, the helium positive column is very similar to the other rare gas columns, but the behaviour of moving striations in the former is different in several respects.

(i) In helium the presence of backward 'disturbance waves' and their effect upon moving striations is more marked than in the other rare gases. The interaction results in a kind of standing wave pattern being set up for stable modes of oscillation. (The relation $1 = \lambda n$, where 1 is the length of the positive column, λ the striation wavelength and n an integer, proposed elsewhere for neon columns (Stewart *et al.* 1965), is valid for the helium column.)

There is now abundant evidence from theory (Garscadden *et al.* 1969) and from other experimental work, both with self-excited moving striations and induced waves of stratification, that either the wave or group velocity or both can be in either direction (anode–cathode or cathode–anode). We have in figures 1(*a*)–(*d*) some clear examples of their simultaneous existence and mutual interactions. Dispersion data are, however, not available for detailed analysis of the complex patterns obtained which are almost certainly complicated by the disturbances being of large amplitude and nonlinear.

The interaction pattern in figure 1(*d*), although similar in many respects to (*a*), (*b*) and (*c*), is probably only obtained for limiting values of certain of the tube parameters. Conditions in the tube then permit a negative disturbance to travel into the vicinity of the anode without appreciable decrease in amplitude. This results in the disturbance wave meeting and interacting with more than one striation, resulting in a much more symmetrical perturbation pattern.

It is unlikely that the backward-travelling waves described here are the negative striations first observed by Donahue and Dieke (1951): the latter have velocity an order of magnitude greater than that of normal positive striations whereas the velocity of the 'disturbance waves' is roughly the same as that of positive striations. (The negative striations described by Donahue and Dieke may be negative space charges (e.g. electron bunches) moving in the normal electric field of the column, while the 'disturbance waves', which it is thought can be included in dispersion and growth theories of moving striations, may be associated with the movement towards the anode of low-energy positive ions.)

(ii) In the present investigation, constriction of the positive column was not observed over the current and pressure ranges investigated. We have found, in agreement with Kenty (1963), that the tendency of a positive column towards constriction decreases with decreasing atomic weight. Although the phenomenon of constriction is a complex one, involving the interdependence of many of the discharge parameters, the above behaviour might, to some extent, result from the thermal conductivity of the plasma becoming greater with decreasing atomic weight, thereby decreasing the tendency of the core to become hot and contract radially.

(iii) Perhaps the most striking difference between the helium and other rare gas columns was that it was not possible within the current and pressure ranges investigated, to obtain a stable positive column when the distance between anode and cathode was greater than about 14 cm. This rather unexpected behaviour (which was not found in other inert gases), may be the result of regenerative interaction between the positive column and its end boundaries, causing overmodulation of striations in the anode region with consequent instability (Nedospasov 1968).

In any event, the perturbations giving rise to the disturbance waves described in this paper probably have their origin in the anode and cathode regions of the discharge, coupling between these regions being affected at least in part via the external circuit. It is demonstrated that the character of moving striations (e.g. frequency and velocity) is strongly influenced by the presence of disturbance waves—which observation would almost certainly be supported by analysis of dispersion data. The disturbance waves may, in addition, cause variations in the current and pressure ranges over which moving striations are observed.

Acknowledgments

The authors wish to thank Professor K. G. Emeleus for his advice and helpful comments.

Appendix. Key to photographs

In all of the photographs the cathode is at the left and the anode at the right. Time increases from top to bottom so that a horizontal line gives the appearance of the discharge at a particular instant. Relevant parameters are summarized below.

Figure	p	i	f	d	λ	t
(*a*)	23	33	2536	8·6	4·3	2·0
(*b*)	23	33	2469	10·0	7·3	2·2
(*c*)	23	33	2112	12·7	10·8	2·2
(*d*)	23	48·5	3096	11·0	11·1	1·1

where p is the gas pressure in torr, i is the tube current in mA, f the striation frequency in s^{-1}, d the anode–cathode distance in cm, λ the striation wavelength in cm and t the time included from top to bottom in ms.

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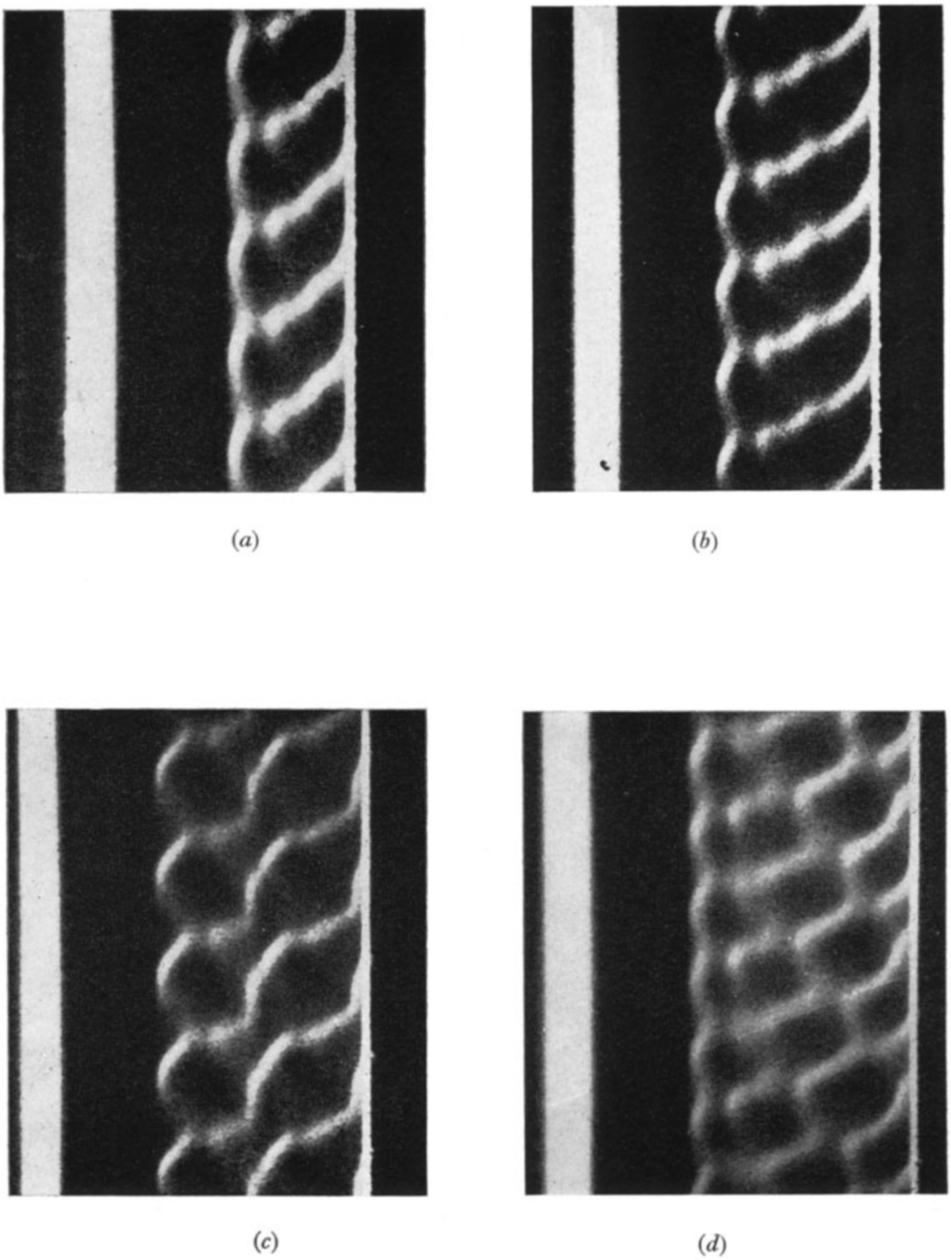

(*a*) (*b*)

(*c*) (*d*)

Figure 1.