Investigation of Laboratory Plasma Instabilities in a Dipole Magnetic Field

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The properties of a steady-state plasma belt confined in a dipole magnetic field and the properties of instabilities arising from this configuration have been measured using electric probes and photographic techniques. The spatial variations of the steady-state plasma density and temperature have been determined. It is found that in the steady case the electrons are gyrating, mirroring, and drifting for appreciable lengths of time. The character of the instabilities and the conditions under which they arise have been measured. The results can be interpreted in terms of a theory originally proposed in 1965 by Swift as a possible mechanism for energizing electrons in the magnetosphere. On this basis speculation concerning comparisons of laboratory and auroral phenomena are made. An alternative theoretical description of the experimental results that uses the basic postulate of Alfvén's 1954 theory on the origin of planetary systems is also discussed.

INTRODUCTION

In an earlier publication [*Quinn and Chang*, 1966], a technique for maintaining a steady-state plasma discharge, trapped in the field of a permanent dipole magnet, was described. One of the experimental difficulties encountered was the fact that the size of the dipole sphere was too small to permit adequate spatial resolution of measurements of plasma properties. Results of preliminary investigations indicated that new phenomena are observable when one uses a larger sphere under the same conditions [*Quinn*, 1965]. In addition to the steady-state plasma belt found in the smaller scale experiments, intense arc instabilities that follow magnetic field lines and precipitate on the sphere are observed.

By careful control, it has been possible to separately determine the properties of the instabilities and the stable plasma belt. The characteristics of these configurations will be described and analyzed. The experimental results seem to have some geophysical significance inasmuch as they are consistent with at least one theoretical argument concerning a mechanism for energizing auroral electrons. The results may also be interpreted in terms of the assumptions of a theory relating to the origin of planetary systems. These correlations and applications will be analyzed and discussed.

EXPERIMENTAL APPARATUS

A uniformly magnetized 15.3-cm diameter cylinder of Alnico V was machined to a spherical shape by a cathode deterioration technique. The sphere was suspended inside a stainless steel vacuum chamber by means of a supporting rod to a removable flange. The supporting rod was constructed with an insulator fitting to allow electrical isolation of the sphere. The chamber itself is cylindrical in shape (60-cm diameter × 109 cm) and equipped with three viewports (two side 90° apart, one bottom) to enable visual observation of the sphere and the discharge. The vacuum was attained by a series of four molecular sieve pumps and a fine control mechanical pump-leak system. A diagram of the system appears in Figure 1. After repeated pump down operations, the pressure could be maintained during the experiment to within 5 microns of the desired operating pressure.

The discharge circuit schematic also appears in Figure 1. A regulated dc high voltage was applied between the vacuum chamber walls that served as a grounded anode and the sphere that was allowed to float as an isolated cathode. Since the anode circumvented the sphere-cathode, asymmetric field effects were minimized. The discharge voltage was maintained by the power

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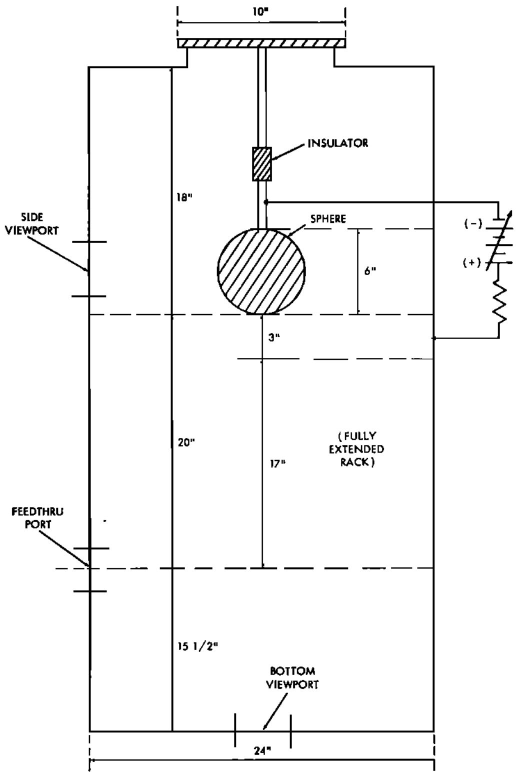

Fig. 1. Schematic diagram of experimental apparatus.

supply, and the discharge current was varied by adjusting a load resistor.

The principle tool used to investigate the plasma configuration was the Langmuir probe. A standard mechanical rod feed through was employed together with a guidance support and a rack and pinion device that allowed vertical and horizontal movement. Probe characteristics were obtained for the steady-state belt by manually varying the biasing voltage.

The time variation of the floating potential during an instability was measured in the equatorial plane and below the south pole in the following manner. The voltage signal with respect to ground was fed from a probe to the vertical amplifier of an oscilloscope. The horizontal sweep was set to trigger on any incoming dc pulse a few volts greater than the equilibrium or static voltage value, which the probe measured due to its spatial orientation with respect to the sphere. The potential variation in time with distance as a parameter was also obtained by this method.

The magnetic field was measured with a F. W. Bell No. 120 Hall Probe Gaussmeter. An electrically shielded axial type probe was mounted on the rack and pinion device previously mentioned so that the probe could be moved in a vertical plane perpendicular to the equatorial plane. To note any change in magnetic field with the plasma present, a Bell No. 240 incremental Gaussmeter was used to balance out the permanent dipole field. The maximum meter sensitivity was 0.001 gauss.

Experimental Results

When a dc voltage is applied as shown in Figure 1, a number of different phenomena occur depending on the gas pressure, the magnitude of the applied voltage, and the limiting resistance. Figure 2 is a photograph taken over an extended period of time that shows the main features. The first feature is a luminous plasma belt, confined to low-latitude regions; the second feature is the presence of intense white arcs that last the order of milliseconds and occur in regions near the equatorial plane; the third feature is the occurrence of blue streamers less intense than the white arcs, which follow magnetic field lines and terminate at higher latitudes. One or all of these features may occur at a given time, depending on the particular pressure, voltage, and resistance. Visual observations indicate that arcing seriously disrupts the plasma belt formed during the discharge. Frequently, the arcing is so violent and rapid that the belt is in a state of fluctuation. It often flickers on and off continuously, accompanied each time by a drop in the discharge voltage.

To systematically study each of these phenomena, it was necessary to determine the conditions under which one can sustain a continuous plasma belt unaccompanied by arcs and streamers for a time sufficiently long to make measurements. The technique employed for determining these conditions was as follows. The system was pumped down to a starting pressure of about 10 microns, and a voltage was applied to break the gas down with a few kilohms in the discharge circuit. After the formation of the plasma, the conditions at breakdown were noted. The applied voltage was then increased to note additional features. The load resistance was progressively increased and the whole proce-

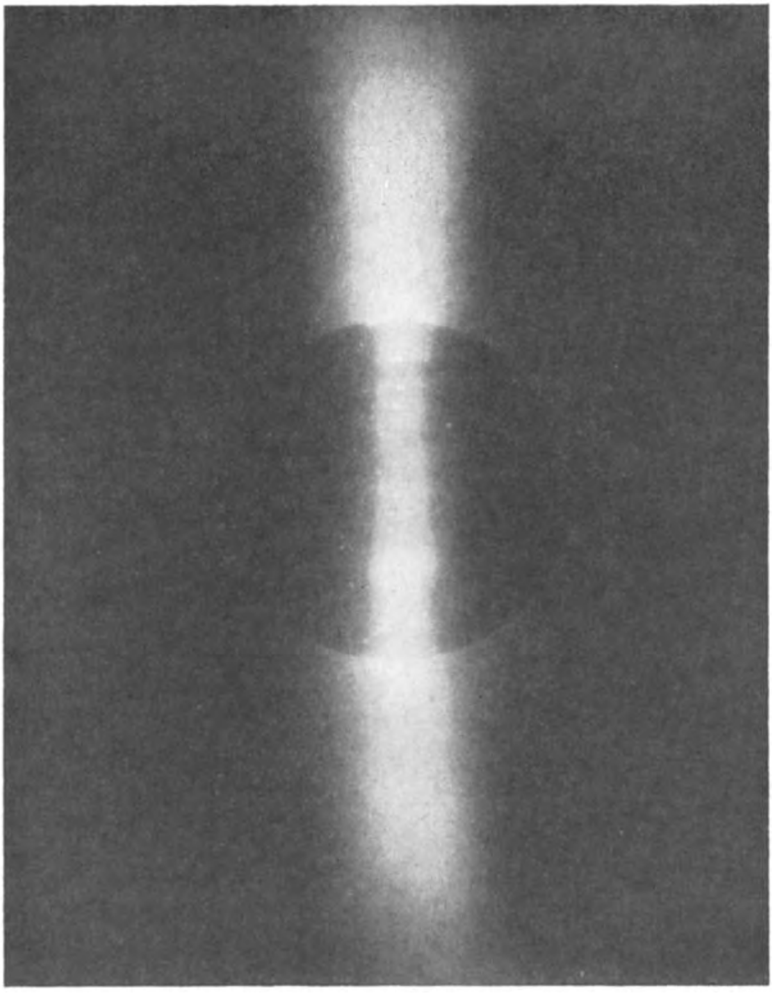

Fig. 2. Extended exposure photograph of discharge showing stable belt, arcs, and streamers.

dure repeated. In each step the discharge was quenched by bringing the applied voltage to zero before new initial conditions were imposed. Finally, the pressure was increased and the above technique repeated.

Both air and nitrogen were used as the residual gas with no essential differences in the discharge observable. A brief description of the phenomena observed with air as the residual gas will be given. At 11 microns the color of the initial discharge is a definite blue. The breakdown voltage is approximately 550 volts. At breakdown a diffuse belt is formed, accompanied by very rapidly sparkling arcs near the equator. As the resistance is increased from 500 ohms to 100 kilohms, a slight modification in the behavior of the belt appears. A steady oscillation of the belt in the latitudinal direction occurs before an arc arises and dissipates the belt. The belt appears to oscillate about 30° from the equator quite rapidly. At 20 microns this oscillatory behavior continues, increasing in frequency but decreasing in amplitude. At 30 microns, the oscillation visually disappears, and a faint but well-defined belt is formed when the resistance is increased to 3 Megohms. The arc rate is about one arc per minute. It is found that a limiting resistance of 1–3 Megohms, with a potential of

450–550 volts dc at a pressure range of 30–40 microns gives the most reproducible configuration. In fact, the discharge stability can be maintained for several hours, provided that the pressure change is less than 10 microns.

In this range, the discharge current can be changed from about 0.2 to 0.5 ma by increasing the applied voltage, without changing the discharge voltage more than 5 volts or producing instability. The number of arcs for extended periods (3–4 hours) could be restricted to a few per hour at best and at worst to 1 or 2 per minute. This range of stability is thus suitable for static probe measurements that will be described below. Observation of the discharge at higher pressure indicates that no stability can be achieved in this range.

We will separate the discussion of experimental results into two parts, one concerning the stable luminous belt, and the other concerning the arcs and streamers.

Stable Configuration

a. Visual observation. Once stability is attained, the features of the steady-state discharge are readily observable. From a side view of the sphere a bright blue-red ring is observed surrounding the sphere within $\pm 30°$ latitude of the equatorial plane. Photographs of the static condition taken from the side and bottom viewports

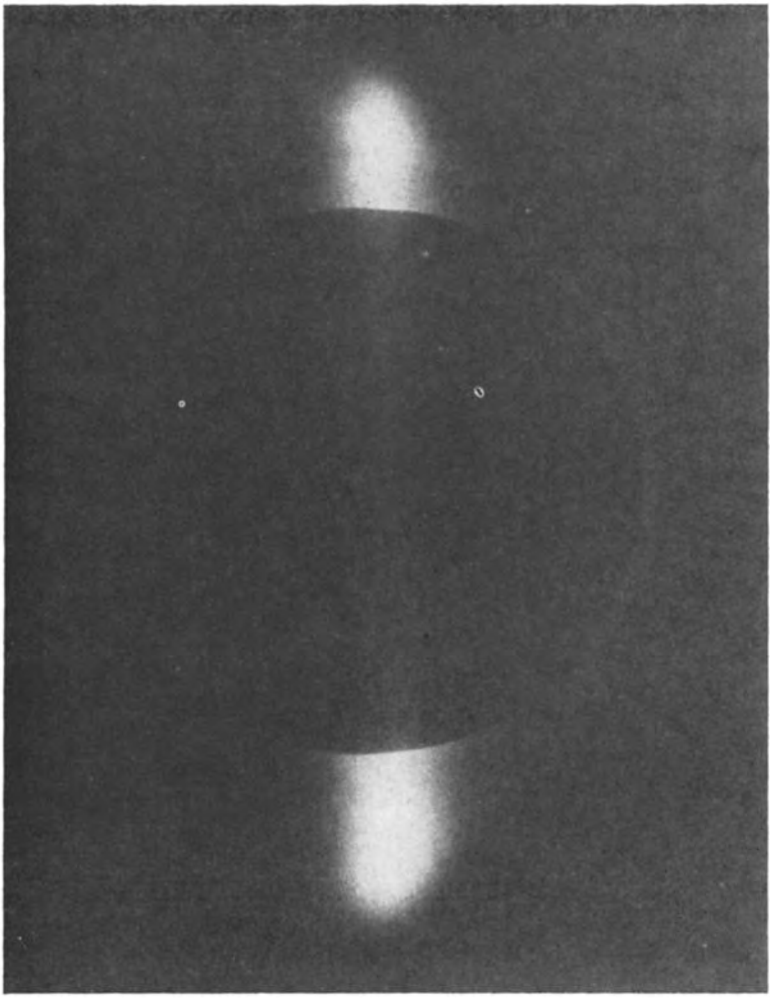

Fig. 3. Equatorial view of stable plasma belt.

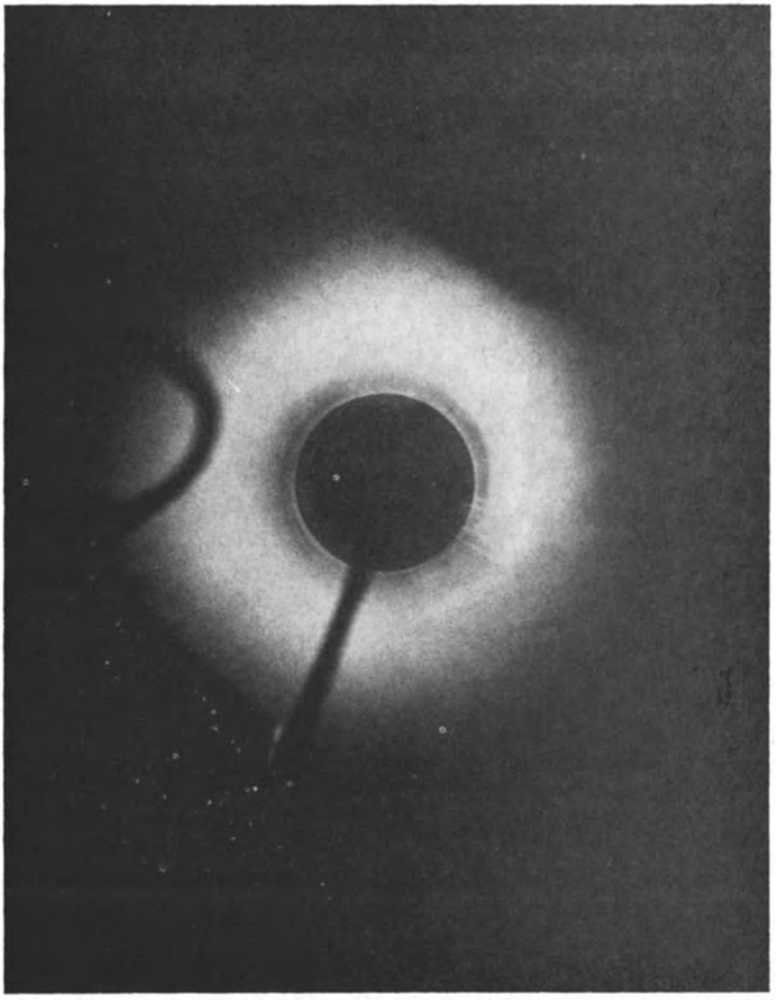

Fig. 4. Polar view of stable plasma belt.

of the chamber are shown in Figures 3 and 4. When the discharge current is decreased below 0.2 ma, the belt dims and eventually disappears as the applied voltage is decreased to the extinction potential.

If the applied voltage is increased, the belt reforms at the equator and becomes brighter and more defined. At this point, from the bottom viewport, a dark region about 3–4 cm long between the belt and the sphere's surface is apparent. The most intense part of the belt appears at the end of this dark space. At larger distances the belt gradually becomes more faint and diffuse as seen in Figure 4. There is an apparent fanning of the belt in the latitudinal direction near the chamber wall. Increasing the voltage has the effect of compressing the inner dark region and increasing the luminosity. In all cases, there was no glowing plasma near the polar regions of the sphere.

When the voltage is increased beyond a value of 1250 volts, the configuration becomes unstable. The belt slowly expands out and upward beyond the equatorial plane accompanied by increasing brightness until an arc or several arcs appear. The arcs are formed between the belt and the surface of the sphere. They will be described below.

b. Electric probe measurements. The analysis of Langmuir probe data in this experiment is complicated by two factors, the presence of the magnetic field and the presence of a radial drift velocity.

A magnetic field will usually decrease the ratio of the electron saturation current to the ion saturation current. If the cyclotron radius and the Debye length are comparable to the probe dimension, the diffusion rate will be reduced. Thus, in weak fields, the ion collection may be unaffected, while the electron collection is greatly changed. The presence of the field may also destroy electron saturation since the effective length of the flux tube into which electrons can diffuse to reach the probe increases with voltage. The temperature measured by the probe is not, however, greatly affected. The presence of a drift velocity superimposed on an assumed Maxwellian distribution will also affect the temperature measured.

The application of theories proposed for accounting for these effects is quite difficult and questionable, in that numerical methods are necessary and that idealized assumptions have been made. (See, for example, *Huddlestone and Leonard* [1965].) Fortunately, in this experiment, in regions more than 8 cm from the sphere, the effects of drift velocity and the magnetic field are negligible, and one may apply the usual simple probe theory. We have applied the simple theory to data obtained in all regions. Thus, the values of temperature quoted for the inner regions are probably higher than actually exist, while the electron number densities may be lower. However, the relative measurements in this region should be quite reliable.

It is estimated that the densities quoted herein are accurate to within an order of mag-

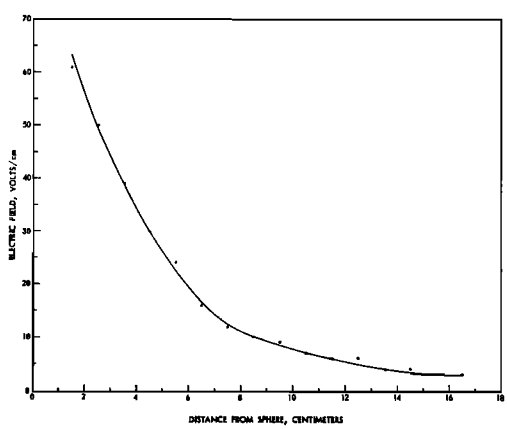

Fig. 5. Electric field variation in the radial direction, equatorial plane.

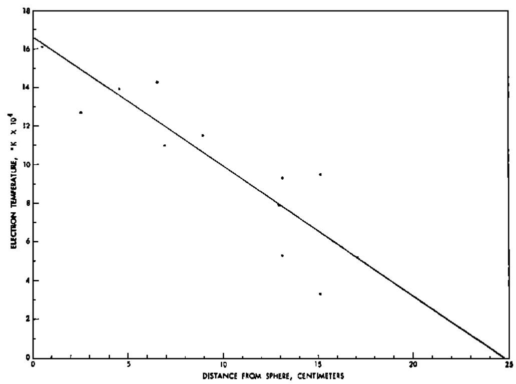

Fig. 6. Electron temperature variation in the radial direction equatorial plane (equidistant points indicate upper and lower limits).

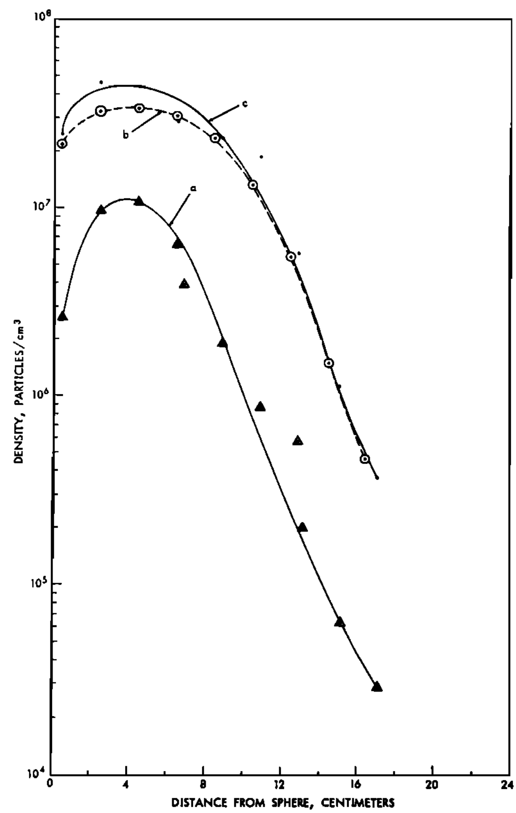

Fig. 7. Charge particle density variation in the radial direction equatorial plane. *a*, Electron number density; *b*, net charge density; *c*, positive ion density.

nitude, while the relative values are accurate to within 20%. The temperatures quoted are accurate to within a factor of 2.

The variation of the electric field in the equatorial plane is presented in Figure 5. It is seen that the field is large near the cathode and gradually decreases to zero as the anode is approached. The variation of the electron temperature in the equatorial plane is presented in Figure 6. It should be noted, as mentioned earlier, that the values near the sphere are high and indicative of the fact that the plasma in this region is under the influence of an accelerating electric field, and that no attempt has been made to separate the drift from the thermal motion.

The variations of electrons, ion, and total charge density are given in Figure 7. All three curves have a maximum in the region 2–5 cm, which is the visual position of the intense glow region described above.

Quinn and Chang [1966] have noted that the measure of a transverse potential difference between two probes separated in the longitudinal direction and placed in the equatorial plane of a smaller sphere was a qualitative measure of drift current in this plane. This current was thought to be produced by action of the magnetic field

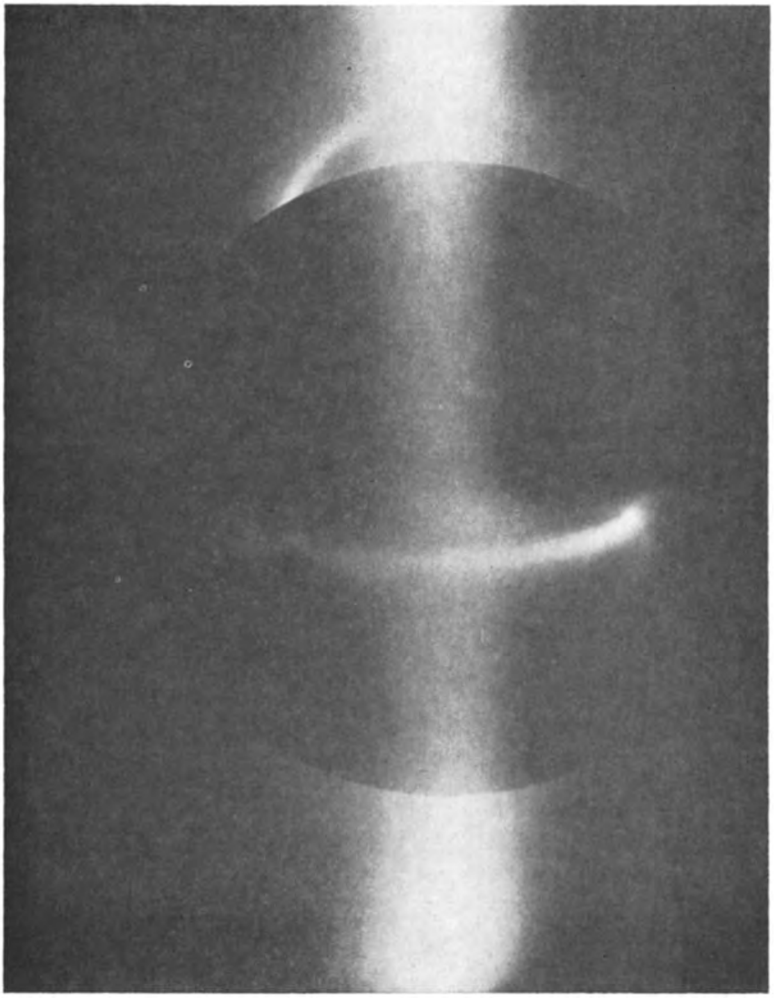

Fig. 8*a*.

Figures 8*a* and *b* show equatorial view of arc instabilities.

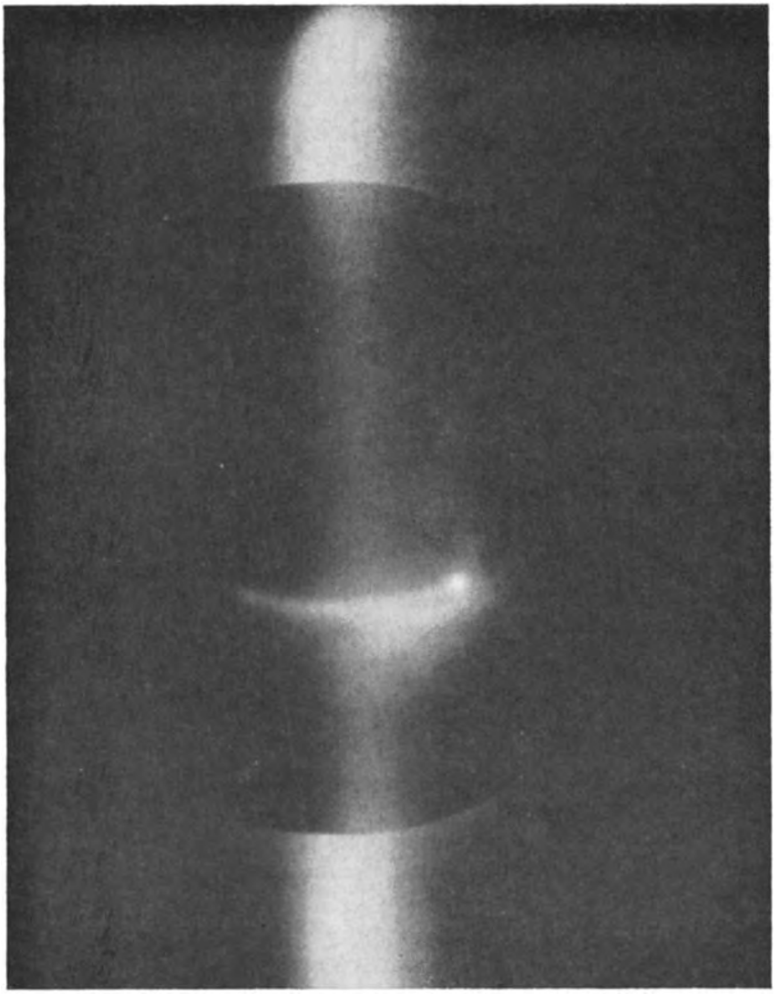

Fig. 8b.

radial gradient and the electric field on the non-neutral plasma configuration. A similar experiment was performed for the 15.3-cm sphere. The dimensions of the probes used here were much smaller and no potential difference was detected, although a visible wake was observed.

c. Magnetic field measurements. The component of the magnetic field parallel to the surface of the sphere was measured as a function of distance in the equatorial plane. The field is dipolar to within 2% having a dipole moment of 1.0×10^5 gauss cm.[3] A differential gauss meter was used in an attempt to measure the field generated by an equatorial ring current, should it exist. No change in the field due to the plasma was detectable, indicating that the field perturbations are less than a milligauss.

Unstable Configuration

Experimentally, the production of an arc from a stable system can be accomplished in several ways. One method is to increase the applied voltage sufficiently above the stable operation condition. Stimulation of arcing can also be accomplished by increasing the neutral gas pressure.

The arcs themselves fall into two categories. The first type, which appeared to be the most violent and rapid, is a bright white arc usually found between ± 70° latitude, lasting the order of hundreds of milliseconds and following a magnetic field line. The point of precipitation may be in either hemisphere or both for any given arc. During a bright arc the plasma belt dims and sometimes disappears altogether, returning immediately after the extinction of the arc. Normally, the belt merely flickers during such an arc. Photographs of such events are shown in Figures 8 and 9, giving a side and polar view. The second type of arc observed is a blue or blue-red streamer that travels a wide trajectory that follows a magnetic field line and appears only in regions close to the poles. The streamers usually last for several seconds, are much less intense than the white arcs, and have only one precipitation point in either hemisphere. They are also more evident at higher pressures and/or lower voltages. Photographs of these streamers alone and accompanied by arcs are shown in Figures 10 and 11. Both phenomena, of course, are evident in Figure 2 as well.

The two types of arcs appear simultaneously or separately, depending on the experimental conditions. At 0.64 ma with 2.2 Megohms resistance and 1250 volts, for example, the arcing was predominately the intense type with a frequency of one or two every few seconds. As

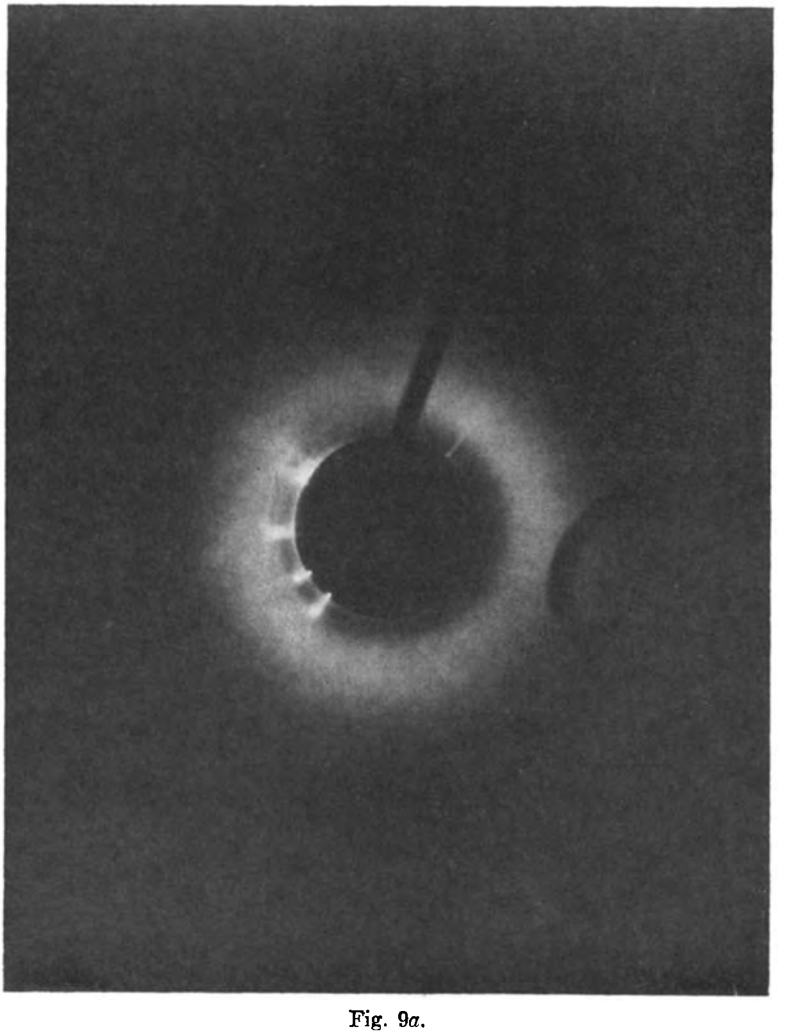

Fig. 9*a*.

Figures 9*a* and *b* show polar view of arc instabilities.

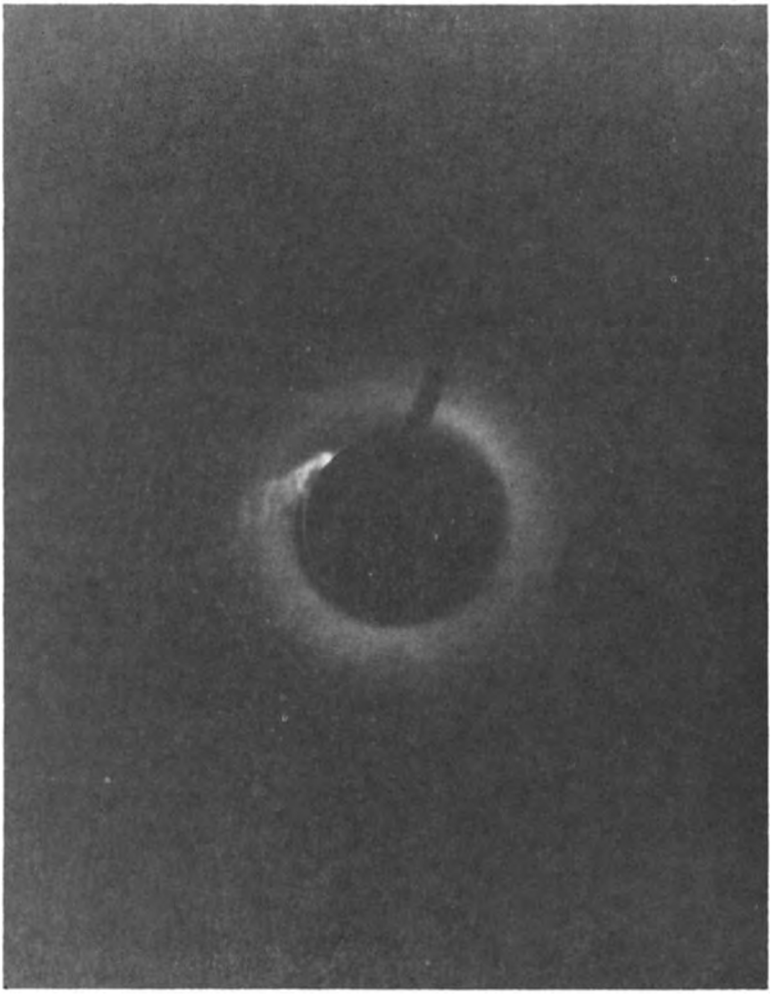

Fig. 9b.

the voltage is further increased, the frequency of occurrence also increases. Similar behavior is observed at all other pressures.

Views from the bottom of the chamber, or south polar view, are given in Figures 9 and 11. These indicate that during a bright arc, the belt configuration is greatly disturbed in the vicinity of an arc as the plasma there is in a turbulent state. Streamers, on the other hand, have little effect on the plasma at all. In fact, it appears that the plasma belt alters the streamer that is swept back about the sphere in a counterclockwise direction with respect to the south pole. The azimuthal position of the streamer is not apparent from Figure 11 since one is observing the streamer along its path. Visual observations, however, indicate that the streamer follows the path seen in Figure 10.

The temporal variation of the space potential during these arcs was also measured. The bright arcs are especially suited to this study in that they are a major source of energy dissipation and give a strong reproducible signal. No reproducible signal was obtainable for the streamers.

The photograph in Figure 12 is a voltage-versus-time trace of a typical arc event. The trace indicates that the initial disturbance causes a rapid rise in voltage from equilibrium in approximately 50 msec to a zero value where it remains constant for approximately 50 msec and then rapidly returns to a value near the negative potential associated with the quiet belt.

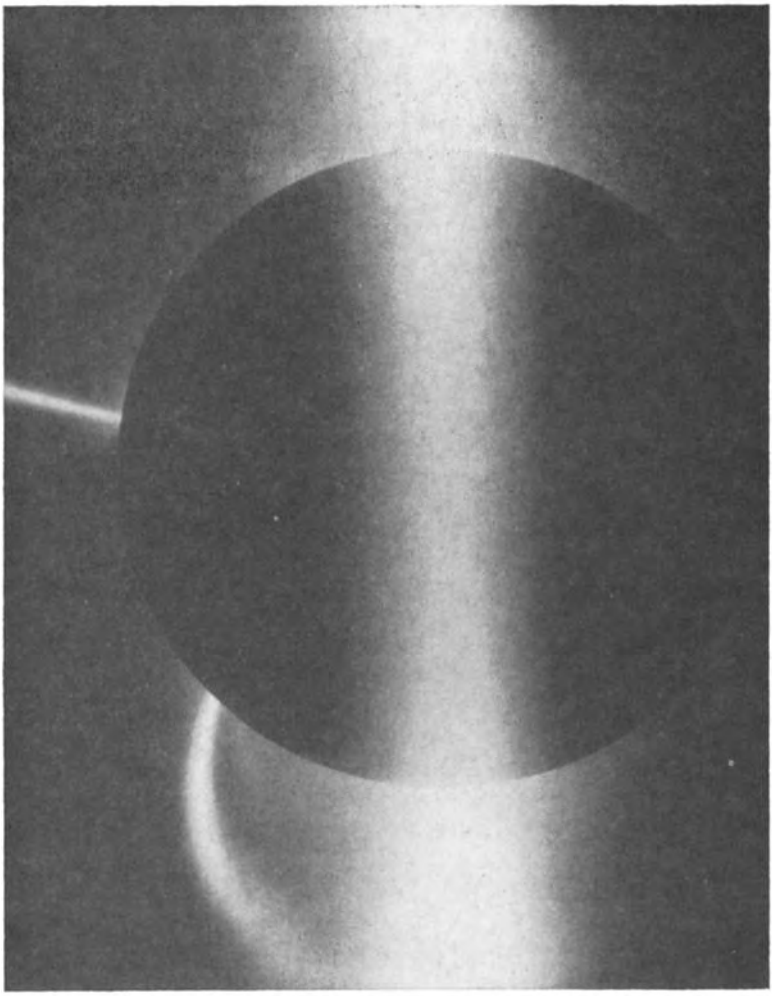

Fig. 10*a*.

Figures 10*a* and *b* show equatorial view of streamers and arcs.

The slight sinusoidal variation of the signal after the return to equilibrium is due to 60-cycle leakage and is not a characteristic of the plasma.

The photographs of Figure 13 display a series of arcs occurring during one sweep. These photographs again show that the voltage, after each discharge, usually returns to an equilibrium value. When the potential is equal to this value or exceeds it, an arc might occur, but no arcs occur when the voltage is below the equilibrium value.

The traces also indicate that all arcs have essentially the same time history. The photographs in Figure 14 constitute an equatorial mapping of voltage-versus-time events under typical operating conditions.

An examination of Figure 14 at large distances from the sphere indicates that the variation of voltage with time is negligible except at the very beginning of the arc. Closer to the sphere, the variation becomes more and more pronounced with the greatest variation appearing in the region from approximately 2.5 to 4.5 cm. This is the region of maximum plasma density, and, from visual observation, the region where arcing occurs most frequently.

The photographs in Figure 15 show the superposition of three separate arcs to compare the

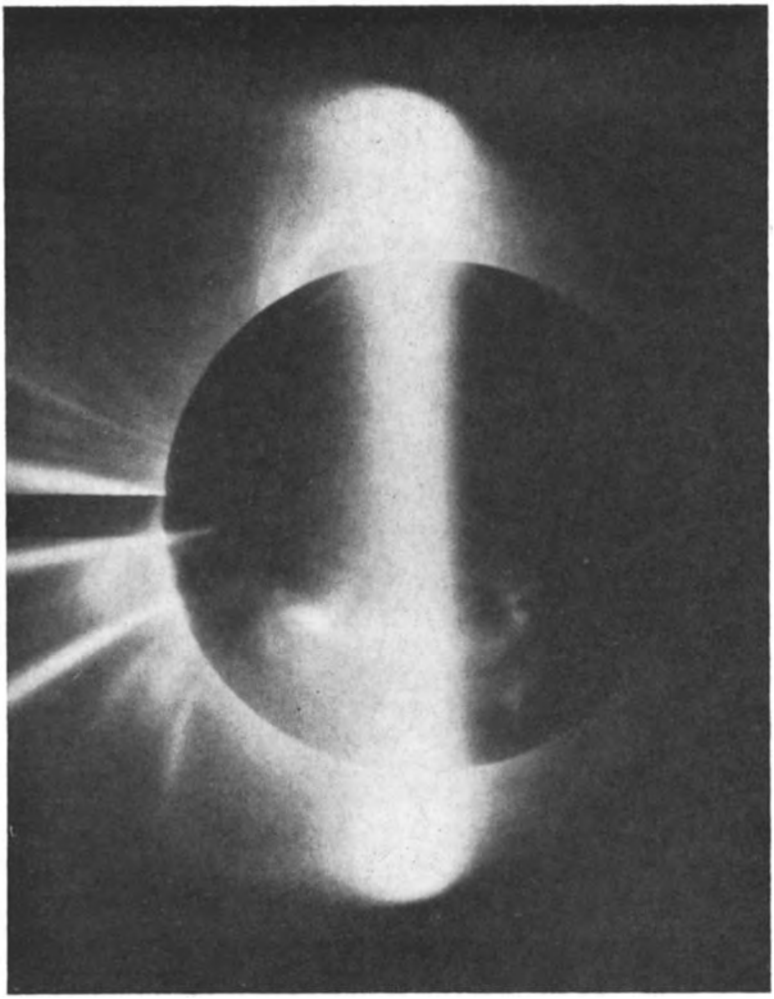

Fig. 10b.

time history of different arcs. The arcs have essentially the same time history with the exception of regions very near the sphere. Here the only difference that occurs is the manner in which the voltage returns to the equilibrium value. It can be seen that the rate of return to equilibrium is different and that it is possible for the voltage to overshoot the equilibrium value. These differences are, however, only slight. The extended time traces indicate that the voltage always returns to equilibrium after a sufficient length of time, regardless of the type of arc.

Figure 16 presents a plot of voltage versus time, with distance as a parameter taken in the radial direction from the south pole of the sphere. The photographs indicate that the signal remains essentially zero except for a deviation of perhaps 5–6 volts at the initiation of each arc. It is apparent, then, that the arcs cause little disturbance in the region of the poles as indicated by visual observation. In fact, the south pole signals did not differ greatly from the signals taken in the equatorial plane at large distances from the sphere.

In summary, measurements of the potential variation in space during an arc indicate the following: during arcing there is little variation in the potential at the poles for all distances; the disturbance in the equatorial plane for distances greater than 10 cm is also small; finally, the only appreciable fluctuations occur in an

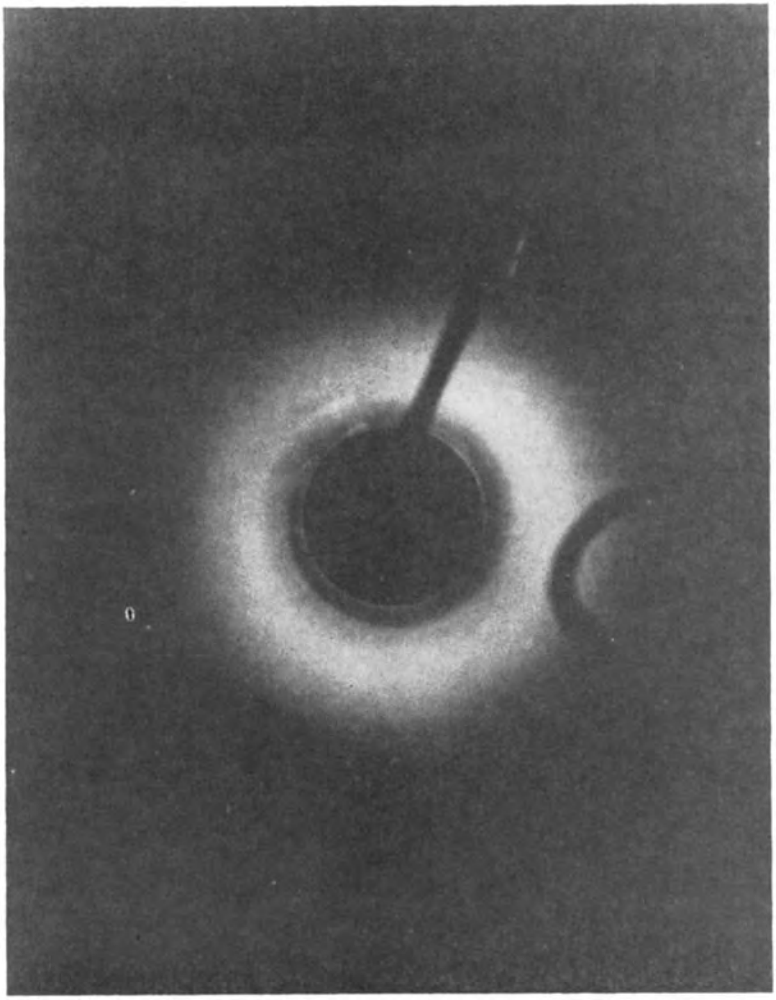

Fig. 11*a*.

Figures 11*a* and *b* show polar view of streamers and arcs.

equatorial region near the sphere where the steady-state plasma density and electric fields are large.

Discussion

a. Stable configuration. Observations indicate that the general features of the steady state are those of a glow discharge. The dark space near the sphere, the intense glow region, and the less intense glow extending to large distances are normal visible features of a glow discharge. The radial variations of the temperature, electron and ion densities, and the electric field are also typically characteristic of a glow discharge.

However, visual observations indicate that the magnetic field causes additional phenomena. First, the visible plasma is confined to lower latitude regions and strongly suggests that a significant portion of the plasma is trapped in the dipole magnetic field and undergoing motions characteristic of such plasma, namely, gyrating, mirroring, and drifting.

The experimental results can be examined to establish to what degree these motions occur. Of prime importance in analyzing the motion of the

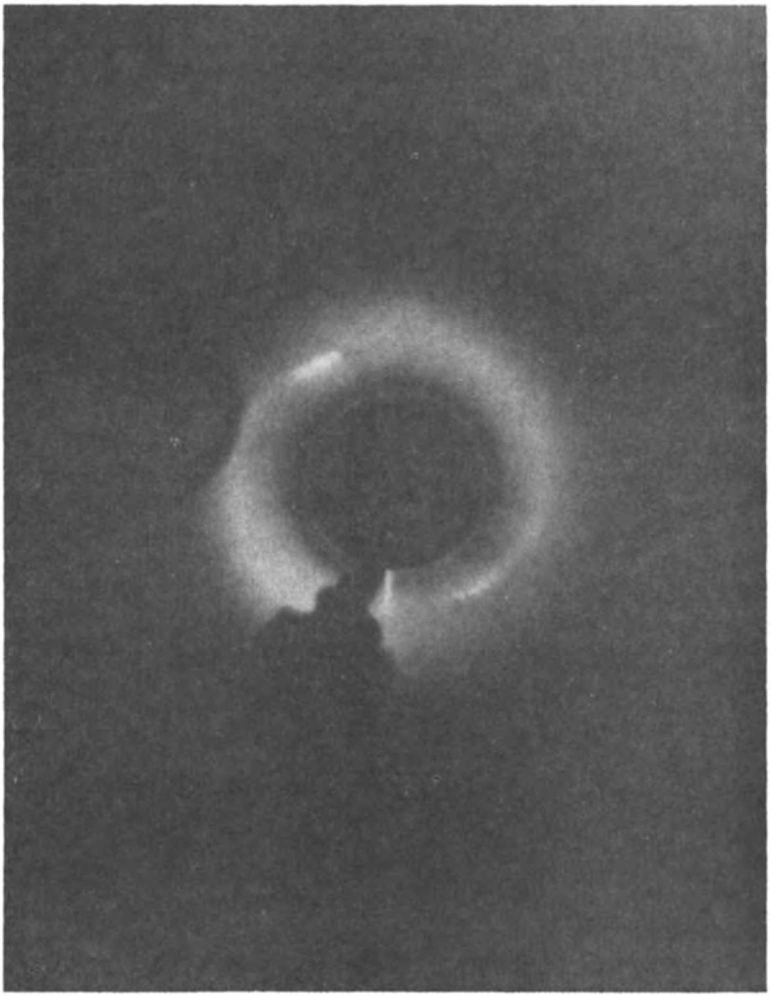

Fig. 11*b*.

plasma is a consideration of the mean free paths for various particle collisions. The electron-electron collision mean free path is of the order of 10^6 cm, and thus electron-electron collisions can be ignored. In addition, electron-ion collisions may also be ignored because of their low densities. The electron neutral mean free path is dependent upon energy, and in the pressure range under study it will vary between 5 and 15 cm. Thus the controlling collision for the electrons is the electron-neutral collision as expected. The ion-neutral and neutral-neutral collision mean free paths are of the order of 10^{-3}–10^{-4} cm.

The cyclotron radius for electrons, assuming that the energy is totally transverse to the magnetic field lines, thus giving the largest possible value, ranges from 0.06 to 0.45 cm. in the equatorial plane. Thus the cyclotron radius for electrons is much less than the electron-neutral mean free path. Also, the cyclotron frequency is a factor of 100 larger than the collision frequency. We may thus conclude that the electrons are on the average gyrating for at least 100 cyclotron periods. In addition, the magnetic moment may be considered an adiabatic invariant during the motion since the magnetic field is time independent and characteristically

$$\left\{\rho \left|\frac{\nabla B}{B}\right| \approx 0.02 \ll 1\right\}$$

where ρ is the cyclotron radius.

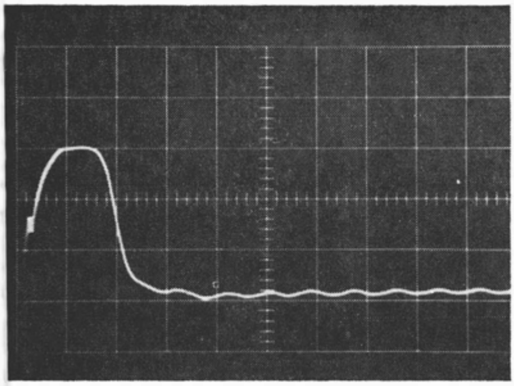

Fig. 12. Equatorial probe potential versus time, during single arc distance from the sphere = 6.9 cm. Vertical scale, 10 v/cm; horizontal scale, 50 msec/cm. Ground is second graticule from top.

The mirroring time for a free particle is approximately a factor of 5 larger than the collision time and is a relatively insensitive function of energy varying as the square root and a function only of the component of the particle velocity parallel to the field line. Thus one would expect that any electron initially moving from the equator toward the poles would travel approximately half way to the mirror point before recombining, and essentially all such electrons would recombine in this manner regardless of the initial component of velocity parallel to the field. This explains the relatively flat plasma disc that extends to approximately ±30° of the equator, provided that the major portion of electrons are produced in the equatorial plane. This is a reasonable assumption since the regions of highest electric fields occur in the equatorial plane.

Occasionally, one would expect some electrons to have a component of velocity parallel to a field line large enough to permit it to cause ionization extending to the surface of the sphere. It is believed that such a phenomenon gives rise to the weak streamers observed that cause only small perturbations in the discharge configuration and current.

The maximum free particle longitudinal drift velocity due to the radial electric field or the radial gradient in the magnetic field for the experimental conditions is of the order of 10^7 cm/sec with a corresponding drift frequency of 10^5 cps. The mean free path for such an equatorial drift motion is of the order of 3 to 8 cm. Visual evidence for such drift motion occurring is seen in Figures 9 and 11. The wakes caused by an arc in the equatorial plane are approximately 6 cm long. In addition, when a probe is placed in the equatorial plane, one observes a visible wake. As mentioned earlier, an attempt was made to measure the drift velocity using a double probe technique, but this method yielded no definite results because of lack of sensitivity. The attempt to measure an equatorial ring current by detecting its associated magnetic field was also inconclusive since the sensitivity of the instrument was too low to measure the expected fields. We may conclude, however, on the basis of visual observations and calculations from

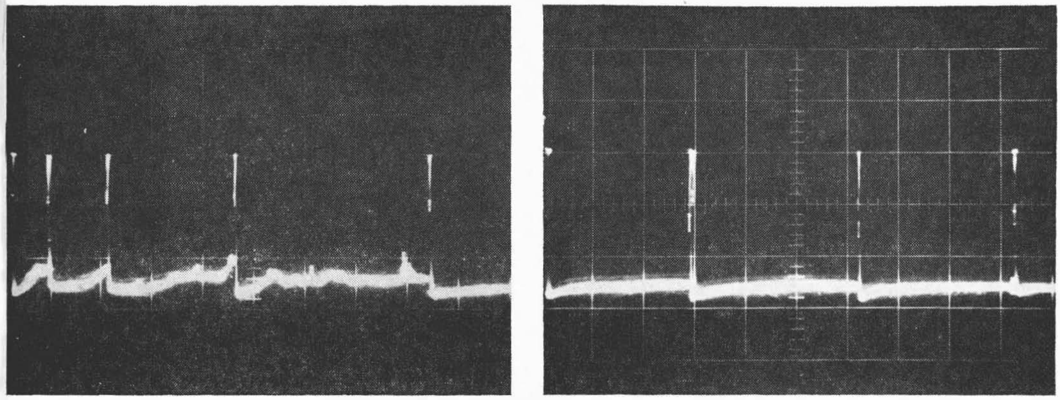

Fig. 13. Probe potential versus time for a succession of arcs. Distance from sphere = 6.9. Vertical scale, 10 v/cm; horizontal scale, 1.0 sec/cm. Ground is second graticule from top.

experimental data that drift motion occurs inasmuch as a particle drifts at least for 40° of longitude before suffering one collision on the average.

The cyclotron radius for ions is much larger than the mean free path for collisions with neutrals, and thus significant gyration of ions does not occur. The ion motion is essentially a

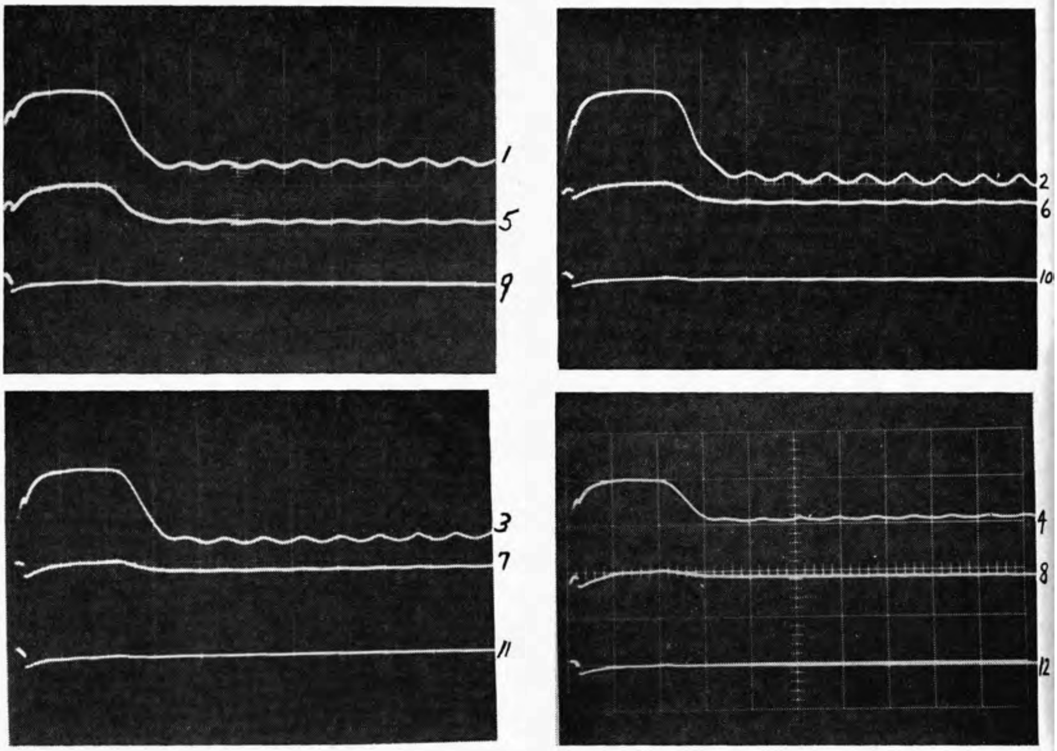

Fig. 14. Probe potential versus time at various distances from sphere in equatorial plane; vertical scale, 20 v/cm; horizontal scale, 20 msec/cm; distance from sphere in cm for each trace as follows: 1 = 0.5, 2 = 2.5, 3 = 4.5, 4 = 6.5, 5 = 6.9, 6 = 8.9, 7 = 10.9, 8 = 12.9, 9 = 13.1, 10 = 15.1, 11 = 17.1, 12 = 19.1.

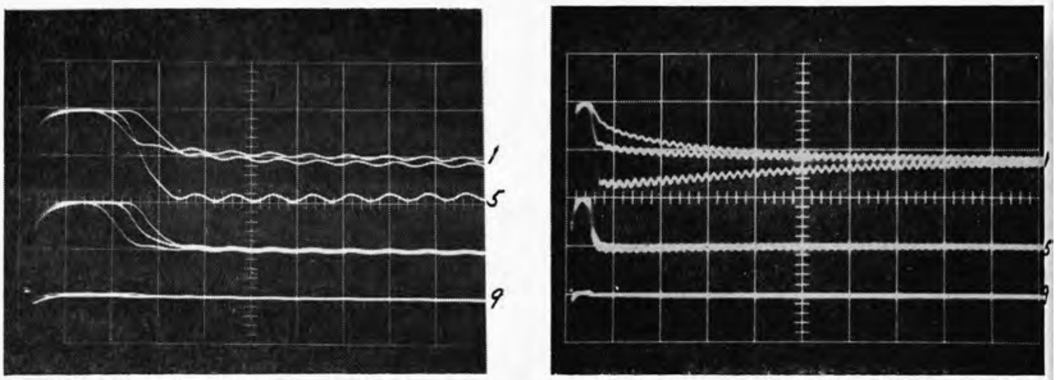

Fig. 15. Probe potential versus time at various distances from sphere in equatorial plane, showing superposition of three arcs with conditions same as those in Figure 14, except sweep on right photograph is 0.1 sec/cm.

drift in the radial electric field relatively unaffected by the magnetic field.

b. Unstable configuration. Let us now turn our discussion to the instabilities that occur. Our interest is directed to the bright arcs that cause large fluctuations in the stable configuration. Visual evidence indicates that the arcs arise in the equatorial plane, traverse a field line, and strike the sphere. The frequency of occurrence of the arcs increases with applied voltage. The region of precipitation of the arcs is normally between 55 and 75°. Little or no precipitation occurs near the poles. The precipitation points are shifted to lower latitudes as the applied voltage is increased.

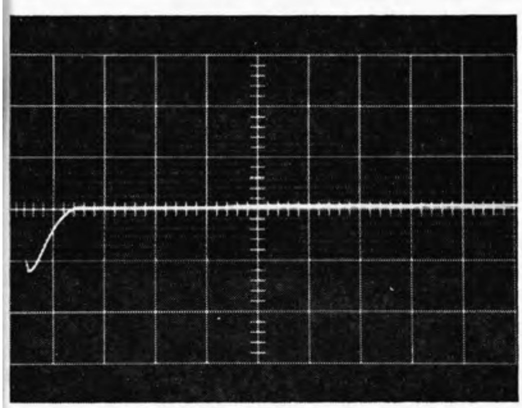

Fig. 16*a*.

Figures 16*a–f* show probe potential versus time at various distances from the pole of the sphere. Ground is center graticule. *a*, 10 msec/cm, 2 v/cm, 0.5 cm from pole.

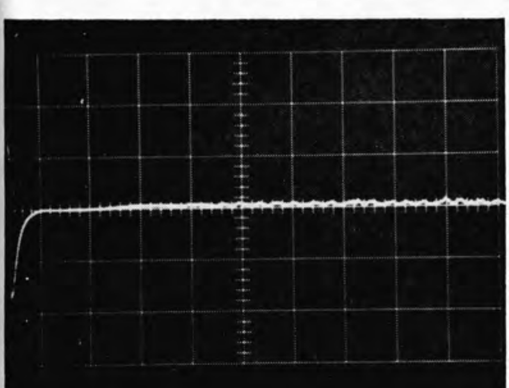

Fig. 16*b*. 20 msec/cm, 2 v/cm, 2.5 cm from pole.

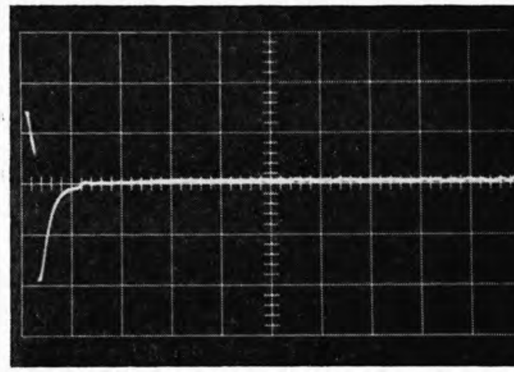

Fig. 16*c*. 20 msec/cm, 2 v/cm, 4.5 cm from pole.

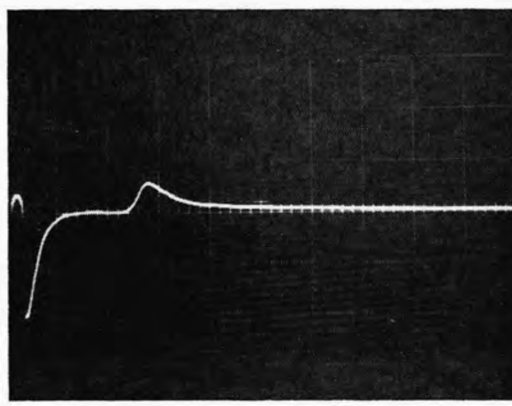

Fig. 16*d*. 20 msec/cm, 2 v/cm, 7.5 cm from pole.

An individual arc is very intense and short in duration. If the stable belt is very faint, an arc can totally quench the discharge. Once this occurs, the belt reappears and grows in intensity until another arc occurs. It has been seen from the dynamic probe measurements that the regions in the equatorial plane are short-circuited to the sphere, indicating that the plasma becomes highly ionized. It is also observed that most of the arc instabilities arise in the equatorial region where the radial electric field, the plasma density, and drift velocity are the greatest. These observations suggest that the kinetic energy of the plasma in the equatorial plane is transferred to the neutral gas by a rapid ionization process that initiates and then sustains the arc.

Two possible explanations of these phenomena will be presented herein. Both have been found to be consistent with experimental results and each is based on theories or assumptions that have astrophysical or geophysical applications.

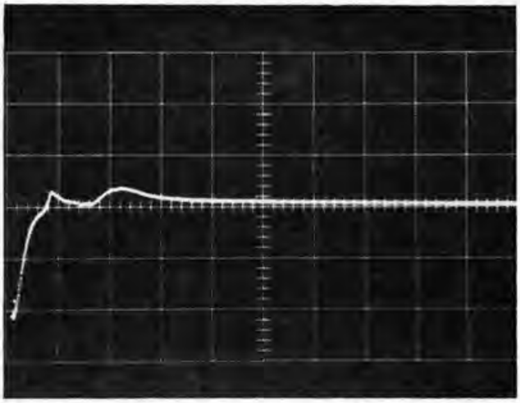

Fig. 16*e*. 20 msec/cm, 2 v/cm, 12.5 cm from pole.

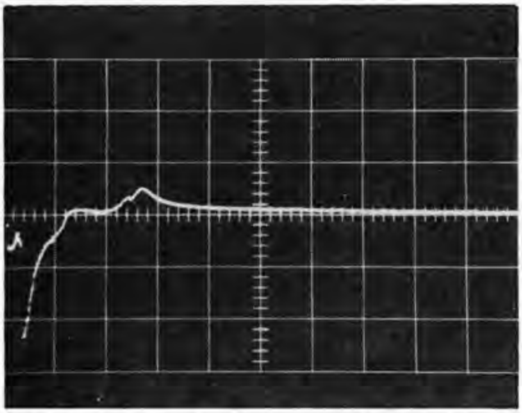

Fig. 16*f*. 20 msec/cm, 2 v/cm, 17.5 cm from pole.

On the basis of present evidence, it is not clear which of the two is applicable, or if, in fact, a third explanation is possible.

The first explanation is based on the existence of a phenomenon postulated by *Alfvén* [1960] and *Alfvén and Wilcox* [1962]. In a theory concerning the origin of satellites and planets, Alfvén proposed the following assumption that is essential to his entire theory: a neutral gas that is moving with a velocity relative to a plasma will become ionized when the velocity increases to a value such that the kinetic energy is equal to the ionization energy. Now energetically, such a phenomenon is possible, but when one considers the various cross sections involved for ionization, it is found that only electrons can cause significant ionization at this energy, and thus some mechanism that transfers energy rapidly from the heavy particles to the electrons is necessary. This assumption of critical limiting velocity for neutral gas moving with respect to a plasma has been given experimental support by *Fahleson* [1961]. Experimental results obtained by *Baker et al.* [1961] and *Baker and Himmel* [1961] on Ixion III, a rotating plasma device, have obtained similar results although no quantitative agreement has been obtained. *Lin* [1961] has obtained a quasi-steady-state description for a homogeneous plasma undergoing a simultaneous ionization and rotation in a crossed electric and magnetic field, which is the configuration of both the rotating plasma device and this experiment in the equatorial plane. He has found that the ordinary electron impact ionization process can be greatly enhanced when supported by energy transfer from the ions to the electrons via Coloumb collisions. This transfer can be sufficiently rapid to provide a close coupling between the kinetic energy of the ions and the ionization energy of the neutrals under a very wide range of conditions. This is consistent with the experimental results of *Fahleson* [1961], which were obtained over a wide range of electric field, magnetic field, discharge current, and ambient neutral pressure.

The magnitude of the critical velocity is, of course, dependent upon the ionization energy of the neutral gas. Once this velocity has been obtained, all energy that is supplied or is available goes into ionizing the neutral gas. The values for the critical velocity that have been measured are typically of the order of 10^6–10^7 cm/sec in rough agreement with the theory.

If this postulate is accepted and applied to the plasma drifting in the equatorial plane, it is observed that should the velocity of the plasma with respect to the neutral gas in a given region approach the critical value, a rapid ionization in this region would occur. This enhanced ionization would then most probably cause the precipitation of an arc along the magnetic field line, the path of least resistance to the sphere. The theory is consistent with the experimental results. Most arcs are generated in the regions where the electric fields are largest and the critical velocity is most likely to be attained. Also, more arcs occur as the electric field is increased. Finally, it is observed that under proper conditions an arc can totally quench the discharge, indicating almost complete transfer of the plasma kinetic energy to ionization energy.

One method of verifying the applicability of this theory would be to observe the discharge and arc instabilities using various neutral gas constituents. As mentioned earlier, both air and nitrogen were used with no noticeable difference. However, the ionization energies in these cases are relatively close. In any event, a truly quantitative verification requires a detailed sensitive analysis of the energy balance within the system, before, during, and after the instability and cannot as yet be performed. However, it may be stated that all the experimental evidence presently obtained is qualitatively consistent with Alfvén's assumption.

An alternative explanation of the existence of the instabilities can be based on a theory proposed by *Swift* [1965]. In a mechanism proposed for energizing auroral electrons in the magnetosphere, Swift considers a longitudinal ring current in a dipole field that is subjected to a local fluctuating electric field due to charge separation. This field is assumed to be transverse to the magnetic field. It is then shown that under proper conditions, this longitudinal current can be of sufficient intensity to become unstable, resulting in growing ion acoustic waves. These waves tend to inhibit current flows in the plasma and transform the ordered flow energy of the longitudinal current into turbulent energy, causing rapid and extreme heating of the electrons as they are accelerated down the field line. An alternative simplified explanation of the process is that the regions of positive and negative space charge may exist temporarily within the magnetosphere, which has essentially zero conductivity transverse to the magnetic field. Current then flows from the region of positive charge down a field line to the ionosphere, which has a finite conductivity and from there up the field line to the region of negative space charge. Now if there is a high resistance along the field line with respect to the ionospheric path caused by the collective interaction, energy will be dissipated in the magnetosphere causing heating of the electrons.

Swift has shown that the conditions for the onset of the instability can be expressed in terms of the relative velocity of the electrons with respect to the ions, the electron thermal velocity, and the ratio of the electron to ion temperature. The range of experimental values obtained for these parameters indicate that the proper conditions for instability can exist in the laboratory experiment. Calculations show that the conditions can be met as one approaches the sphere in the equatorial plane. In addition, the number of instabilities increases with the applied field in agreement with the theory. One again, a quantitative verification is not possible due mainly to the fact that the magnitude of the longitudinal current has not been obtained. Nevertheless, all of the essential assumptions of the theory are satisfied, and there is a striking similarity between the laboratory phenomena and the phenomena predicted by the theory.

On this basis, it is interesting to pursue an analysis of the experimental results as they relate to auroral phenomena. First, the time scale of an arc instability is approximately 150 msec, which scales satisfactorily to the time scale of auroral disturbances. Second, precipitation of the arcs occurs most frequently in those latitudes that correspond to terrestrial auroral zones. Virtually no arcs occur near the polar zones. If one increases the applied voltage, the arcs precipitate with higher frequency and at lower latitudes. These phenomena are analogous to terrestrial auroras in that auroras occur infrequently near the poles and occur at lower latitudes during large disturbances.

Conclusions

On the basis of the experimental evidence obtained, it is not clear which of the two possible explanations presented is applicable. The present opinion of the authors is that the theory proposed by Swift more adequately describes the laboratory experiment in that essentially all of the assumptions and conditions of the theory are fulfilled, whereas the mechanism for energy transfer in the alternate description is extremely obscure and the validity of its main postulates has not been established. It should be noted that the obvious differences between the assumption of a local electric field perturbation of short duration in the Swift's treatment and the constant electric field perturbation in the experiment are not critical [*Buneman*, 1959]. We thus presently view the results as experimental evidence that the instabilities described in the theory can occur. Whether the theory is applicable to the terrestrial case for which it was formulated is still unknown. However, the nature of the instabilities, their frequency of occurrence, region of precipitation, and time duration indicate some correlations with terrestrial auroras. These correlations tend to support the applicability of the theory to both cases. The measurement of the magnetic field perturbation, spectroscopic analysis, and noise radiation may provide additional correlations that will determine the applicability of the theory and the possibility of scaling the experimental phenomena to terrestrial phenomena.

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