Primer on "Gas Discharges"
(Plasmas)

Introduction

In the early and middle years of the twentieth century, electrical engineers were interested in using the nonlinear properties of electric plasma in circuits containing "gas tubes" to regulate currents and voltages in often quite clever ways[1]. After the advent of solid-state devices, however, the importance of gas tube technology dropped to almost zero. There are still Geiger counters and certain other specialized devices being produced and used, but the overall properties of electric discharges in gases (plasmas) has almost become a lost art – of historical interest only – except among those still seeking the elusive 'continuous fusion reaction' and the proponents of the Electric Universe.

So a main motivation for this article is that information on electrical discharges is not easy to find in current literature (in spite of its growing potential importance in many fields of physics, astrophysics, atmospheric electricity, and engineering). The McGraw-Hill *Encyclopedia of Physics* has no entry for 'electrical discharge' or 'electric arc,' for example. The closest one can come at present are articles and books on 'plasma physics', which are almost exclusively mathematical and which contain little or no description of laboratory procedures or observations[2].

Searching the Internet for descriptions of what constitutes a glow-mode plasma discharge yields very little information other than where to purchase certain devices that have nonlinear volt-ampere characteristics of one sort or another. What follows is a brief tutorial explanation of the inherent physical properties of a low-pressure gas when excited by an electrical current.

We first will discuss what a plasma discharge looks like in the laboratory. What do we see when we set up a typical experiment to observe a plasma's physical structure?

As the second part of this primer we discuss the discharge's electrical properties and attempt to show a relationship between these electrical measurements and what we have observed earlier about the plasma's appearance.

The third and final part of this paper will attempt to relate our laboratory observations of part one, the measured electrical properties of part two, and what at least this author suspects is occurring on and around the Sun.

1. Visual Appearance of the Static Plasma Discharge

In the laboratory, applying a potential (voltage) difference between two electrodes placed inside a low-pressure gas can produce the phenomenon known as a plasma discharge. Electrons originating at the cathode and positive ions near the anode will be accelerated in opposite directions, collide, and transfer energy. J.H.W. Geissler[3] performed the first known experiment of this kind in the early 1850's. He was a glassblower by trade and quickly made his 'Geissler tubes' into sought after art objects. Later (1869-1875) Wm. Crookes[4] developed his Crooke's Tube which is sometimes erroneously credited as being the first plasma containing device. Actually the Crooke's tube requires a heated (thermionic) cathode to produce electrons, which are its exclusive charge carriers whereas in a Geissler tube both ions and electrons (a true plasma) are charge carriers.

Figure 1 shows the basic physical structure of a discharge. All of the component structures shown there are not always found in any given discharge, but depending on pressures, voltages, and dimensions, all have been observed in one discharge or another. There is a well-known relationship, called Paschen's Law, between the separation distance between electrodes, the pressure, and the applied voltage that must be met in order to initiate the discharge. Changes in any of those variables, or the type of gas used in the tube, will alter the appearance of the discharge.

Once the requirements of initiating a discharge have been met, a pair of electrons will enter into the discharge from the cathode. One is accelerated toward the anode and one recombines with an approaching +ion. Near the anode the incoming electron will ionize

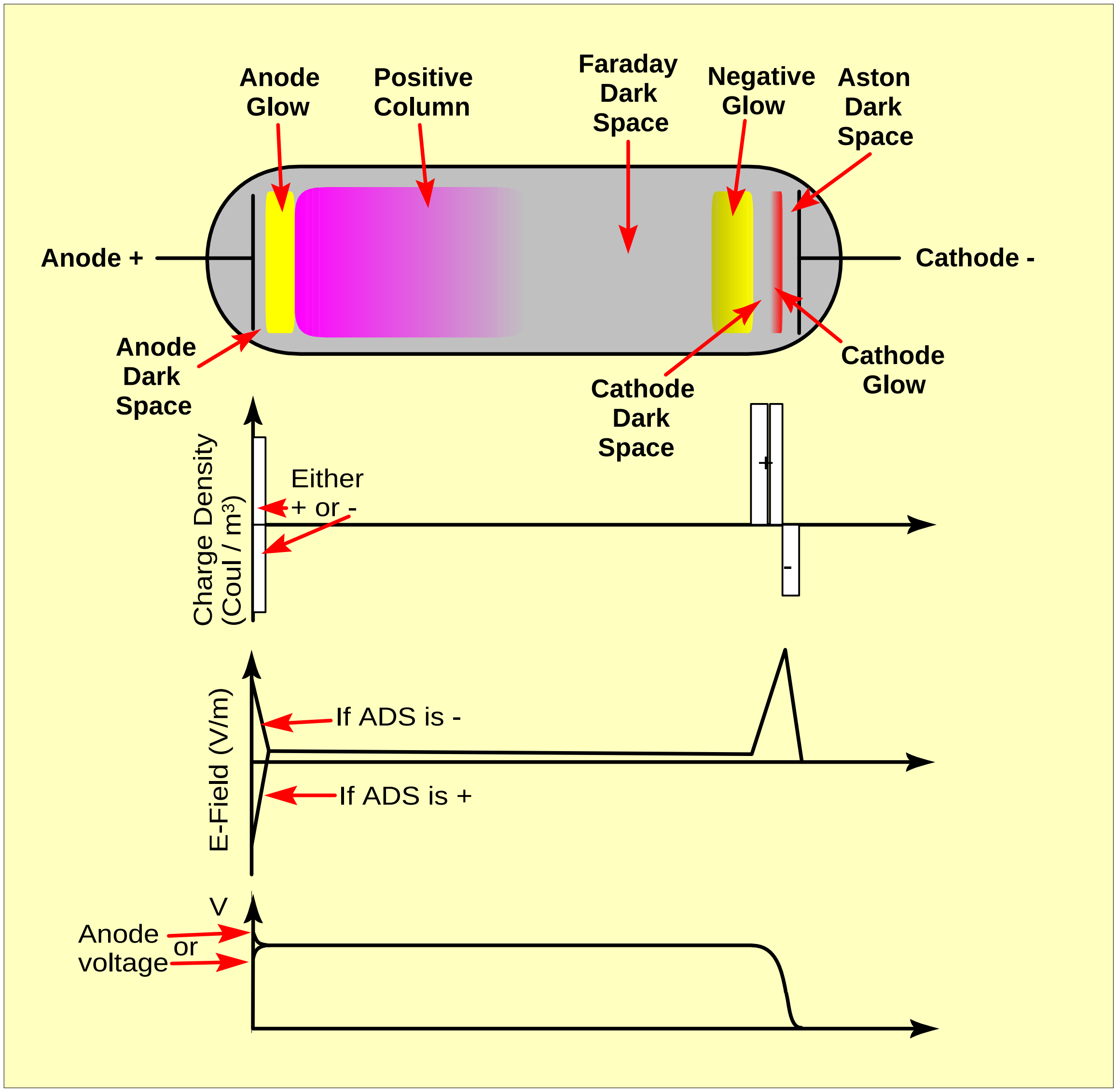

Figure 1 (Top). The physical appearance of an archetypical gas discharge. (Below) Charge density, *E*-field, and Voltage distributions within the tube. The bottom three plots will be discussed in parts two and three of this paper.

a neutral atom by collision and both the original electron and the newly liberated electron will leave the discharge together, entering the anode. At both the cathode and the anode, then, it is electron pairs that enter and leave the discharge. In the central part of the discharge +ions are moving toward the cathode and electrons are moving toward the anode. Both these movements contribute to the total current in the discharge (which is equal to the current in the external circuit). Only electrons are free to move in the external circuit (wires). Positive ions are created at the anode and neutralized by recombination at the cathode. They remain inside the discharge. If the electric current created by the ion and electron flows is sufficiently high, the ionized gas (plasma) can emit visible light.

In laboratory experiments such as this, additional electrons are sometimes produced by secondary emission from the cathode. The major, observed, physical properties of a typical laboratory discharge are described below. These physical structures appear over a wide range of operating conditions. A typical set of operating conditions for a laboratory discharge might be a voltage of about 1 kV, a total current of about 0.1 A, through air or Argon at a pressure of 0.01 psi[5] (~70 pascals). Our description of these structures starts at the cathode and proceeds toward the anode.

Also note there is an extremely low (but not zero valued) electric field throughout the positive column, Faraday dark space, and the negative glow region.

Cathode

In a laboratory discharge, the cathode is an electrical conductor, usually a metal, with a secondary emission coefficient (it has the ability to emit electrons when bombarded by incoming positive ions). Of course in cosmic plasmas, no metal electrodes are present.

Aston Dark Space

This is a thin region next to the cathode containing a layer of negative charge. It thus contains a strong electric field. Electrons are accelerated through this space away from the cathode. In this region stray initial electrons together with the secondary electrons from the cathode outnumber the ions. These electrons are too low density and/or energy to excite the plasma, so it appears dark.

Cathode Glow

This is the next structure out from the Aston dark space. Here the electrons are energetic enough to excite the neutral atoms with which they collide. (In air, this region is usually red due to the emissions by the excited atoms sputtered off the cathode surface, or the positive ions moving toward the cathode.) The cathode glow has a relatively high ion density. The axial length of the cathode glow depends on the type of gas and the pressure. The cathode glow sometimes clings to the cathode and masks the Aston dark space.

Cathode (‘Crooks’, ‘Hittorf’) Dark Space

This is a relatively dark region on the anode side of the cathode glow that has a moderately strong electric field and a relatively high ion density. It thus is a positive space charge layer. Thus, the cathode dark space, the cathode glow, and the Aston dark space constitute an effective double layer (DL) such that most of the remainder of the plasma experiences only low valued electric fields.

Negative Glow

This region is the site of the brightest intensity of the entire discharge. The negative glow has a relatively low electric field, is long compared to the cathode glow, and is most intense on the end near the cathode. Electrons that have been accelerated in the cathode region to high speeds produce ionization, and slower electrons that have already had inelastic collisions produce excitations. These slower electrons are responsible for the negative glow. The electron number density in the negative glow discharge is typically about 10^{16} electrons/m^3. As these electrons slow down, energy for excitation is no longer available and the Faraday dark space begins.

Glow Region

Faraday dark space

The electron energy is low in this region. The electron number density decreases by recombination and diffusion to the walls, the net space charge is very low, and the axial electric field is small.

Positive Column

This is the physically largest component of a normal discharge. The plasma is quasi-neutral. The electric field is weak, typically 1 V/cm (This is low considering that the terminal to terminal applied voltage can be of the order of 1000 V.) The electric field is just large enough to maintain a degree of ionization at its cathode end. The electron number density is about 10^{15} to 10^{16} electrons/m^3, and the electron temperature is typically in the range of 1 to 2 eV. In air, the positive column plasma is pinkish blue. As the length of the discharge tube is increased at constant pressure, the length of the cathode structures remains constant, and the positive column lengthens. The positive column is a long, uniform glow mode discharge, except when standing or moving striations, or ionization (Alfvén) waves are triggered by a disturbance. All this, of course, is observed in the laboratory.

In the case of the plasma surrounding the Sun, the solar corona is the positive column. The Faraday dark space extends out from the end of the corona to the heliopause (virtual cathode). A DL may exist between the positive column and the anode glow especially in a cosmic plasma such as the solar wind. This DL would occur only if the applied voltage were extremely high valued. A significant fraction of this high voltage would appear across this DL.

Anode Region

Anode glow

This region is usually brighter than the positive column, and is not always present in laboratory experiments. This is the boundary of the anode sheath. ‘Anode tufting’ is said to have been observed in this region, although no photographs of this phenomenon seem to have survived.

Anode dark space

The space between the anode glow and the anode itself is the anode sheath. It is a single layer of space charge. This layer can either be positive or negative depending on the size of the anode relative to the current density level it is carrying. There is a stronger electric field here than in the positive column.

Other Phenomena

Striations

Moving or standing striations are traveling waves or stationary perturbations in the electron number density that occur in partially ionized plasmas. In their usual form, moving striations are propagating luminous bands that appear in the positive column. In reality many apparently homogeneous partially ionized plasmas have moving striations. Standing striations can be easily photographed.

Abnormal Glow Discharges

In the normal glow mode, increasing current in a discharge tube leads to a very slow decrease in voltage. As will be discussed below, the current density to the cathode remains fairly constant. Beyond this normal glow range the current increases by covering a greater cathode region. Once the whole surface of the cathode is covered by the discharge, the only way the total current can increase further is to drive more current through the cathode by applying more voltage. This is called an abnormal glow discharge. The cathode voltage drop increases rapidly, and the dark space shrinks. Except for being more intensely luminous, the abnormal glow discharge appears very similar to the normal discharge. Sometimes the structures near the cathode blend into one another, providing a more or less uniform glow. As the voltage increases, the cathode current density also increases, ultimately heating the cathode and causing incandescence and thermionic emission. If the cathode gets hot enough to emit electrons thermionically, the discharge will transition into the arc mode.

2. How We Measure the Electrical Properties of a Gas Discharge

Suppose we put a gas (typically neon, argon or one of the noble gasses) into a closed glass tube that has two electrodes inserted into it and apply a voltage across these two terminals (exposed ends of the two electrodes). The terminal to which the higher voltage is connected is the anode of the tube and the other terminal is the cathode. Positive charges (as do all physical quantities) tend to move from regions of high potential energy to regions of low potential energy. “Water flows down hill” is a well-known popular statement of that fundamental idea. Voltage is a measure of the potential energy possessed by a positive electrical charge. So positive charges will move along a path away from a point of high voltage toward a point that is at a low voltage. Consider the electrical circuit shown in figure 2 that contains a plasma tube.

In this circuit, there is a voltage source whose voltage value, V_S , we can choose (and vary). There is also a resistor, R, whose value we can choose (and vary). The purpose of the resistor is to limit (control) the value of the current, I, that will go through the plasma tube. If we travel from the lower left-hand corner of the circuit up to the upper left-hand corner we will go through a voltage rise of V_s volts. So if V_s is a positive quantity (say +10V) then the voltage at the upper left hand corner is ten volts greater than the voltage at both lower corners.

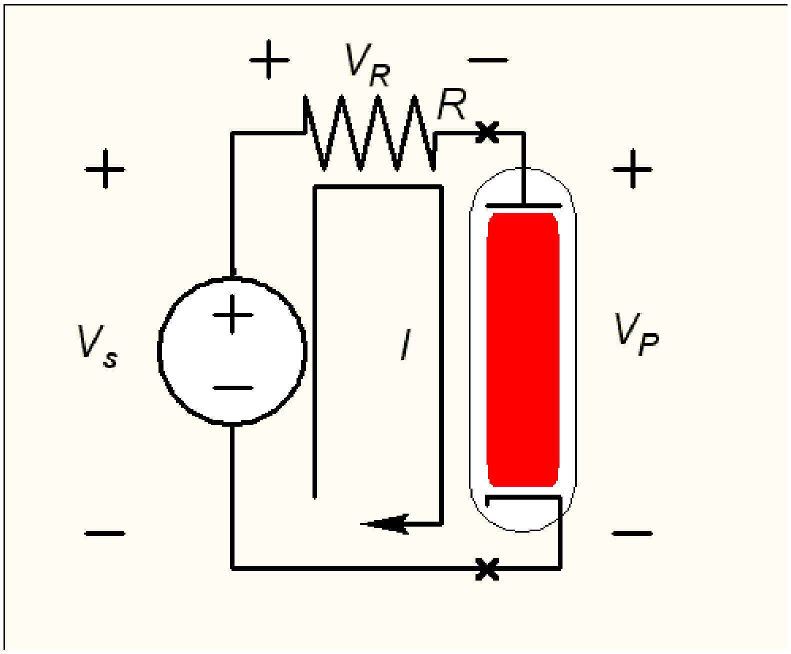

Figure 2. Laboratory circuit used to measure the Volt-Ampere characteristic of a plasma. Terminals X-X connect the external excitation circuit on the left to the plasma on the right.

The current, *I*, has the same value in Amperes at every point all the way around the circuit (there are no exits from which charge can escape).

Ohm's Law tells us that the voltage rise across a linear resistor (in this case moving from the upper right-hand corner to the upper left-hand corner) is directly proportional to the current through that resistor. So mathematically we have

$$V_R = IR \tag{1}$$

Also we notice that if the voltage at the upper left corner is +10 volts, it has to be that value whether we get there by going from the lower left to upper left corner or if we go in the counterclockwise direction around the loop to the right. In other words it is obvious that, summing voltage rises,

$$V_S = V_P + V_R \tag{2}$$

or

$$V_S - V_R - V_P = 0, \tag{3}$$

Demonstrating the fact that the sum of the voltage rises around any closed path in a circuit is zero. Equation 3 might also be written

$$V_P = V_S - V_R \tag{4}$$

Or, using (1),

$$V_P = V_S - IR \tag{5}$$

$$V_P = -RI + V_S \tag{6}$$

This last equation (6) has the form of a straight line (y = mx + b) which is evident when we plot it on a V_P *vs* I set of axes.

Figure 3 is a graphical description of the behavior of the part of the circuit in figure 2 that lies to the left of the two terminals shown by the two small X's in that figure. For example, if we raise the ohmic value of the resistor[6], *R*, in figure 2, then, in figure 3, the intersection[7] of the line with the horizontal axis (at $I = V_S / R$) will move toward the left; and the line[8] will become steeper.

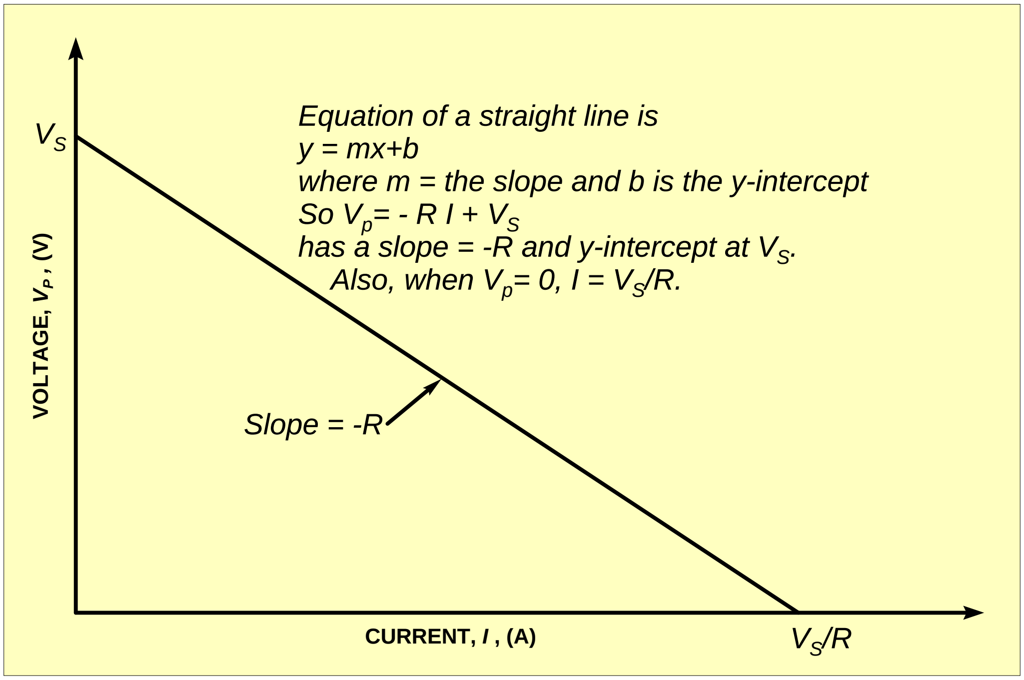

Figure 3. Plot of equation 6.

Varying the value of the voltage source will vary both intersections (end points of the line). *I* is, of course, the value of the current leaving the top terminal, X toward the right in figure 2. Every point on this so-called 'load-line' represents a pair of values (V_P, I) that satisfy the requirements of the circuit to the left of terminals X–X.

Plasma Voltage - Current Characteristic

The value of V_P, the voltage across the plasma tube, is a highly nonlinear function of the current, *I* (charge flow), down through the tube. This is shown in figure 4.

Every point on that plot represents a pair of values (V_P, I) that satisfy the requirements of the circuit to the right of terminals X – X, the plasma contained within the tube. A straight line drawn from the origin of figure 4 up to any particular point on the curve, (V_P, I), has a slope equal to V_P / I which is the effective bulk resistance of the plasma when it is operating at that point. This reminds us that the curve plotted in figure 4 represents an infinite set of single points, each of which represent a pair of numbers that define the voltage across and the current through the plasma at any given instant. Such a point (at which the circuit operates) is called an 'operating point'.

Bear in mind that the current, *I*, that is plotted on the horizontal axis in figure 3 is identically the current, *I*, that flows in the plasma and is plotted on the horizontal axis in figure 4. So the voltage, V_P, in figures 3 and 4 is the same voltage; it is the voltage produced by the circuit to the left of terminals, X–X, and is also the voltage across the plasma tube. Therefore figures 3 and 4 have the same identical axes and thus both figures can be superimposed on top of one another on this one set of axes. This is shown in figure 5.

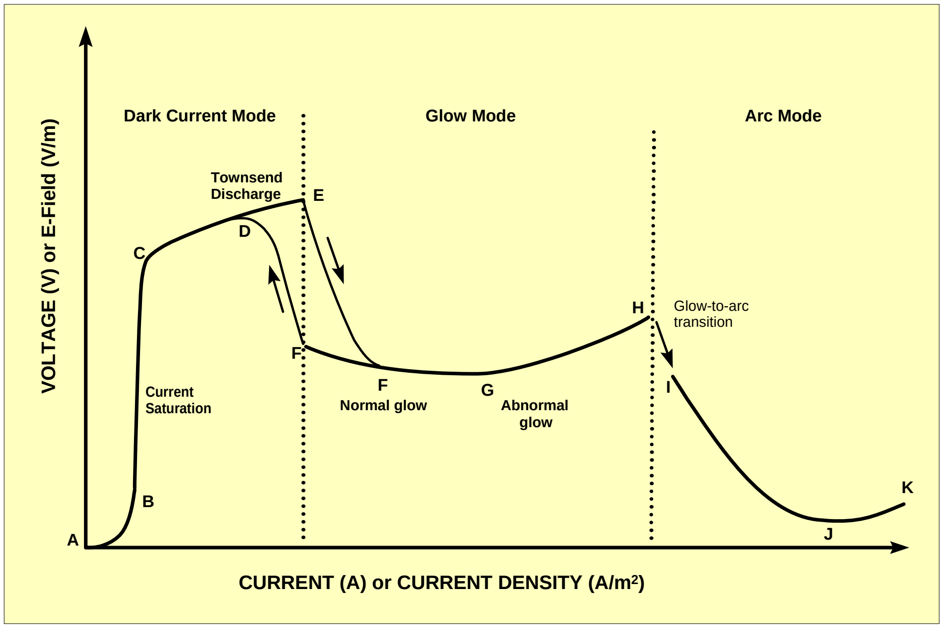

Figure 4 A typical static, plasma discharge, volt-ampere plot. It is obviously highly nonlinear. A similar plot for a linear resistor would be a straight line, starting at the origin (point A) and rising upward toward the right. The angle of the line would be determined by the ohmic value of the resistor. The slope of a line from the origin to any point on the curve = $V_p/I = R_p$ of the plasma.

Any point(s) of intersection of the load-line plot and the nonlinear volt-ampere plot of the plasma indicates possible pairs of (V_P , *I*) values at which the circuit might operate. Only at such intersection points are the requirements on the simultaneous values of V_P and *I* by both halves of the circuit satisfied. These are called "operating points".

Figures 4 and 5 are plotted with current on the horizontal axis. This is the opposite of the standard way *VI* plots are made in modern electronics. The original investigators of 'electric discharges in gasses' (plasmas) presented their results with current or current density plotted on the horizontal axis because it is the value of applied current density that uniquely determines the mode of operation of the plasma, rather than the applied voltage[9].

Clearly, in figure 5, the two points defined by letters D and G are each possible operating points. Which one will actually be chosen by the circuit will depend on the past history of how the circuit has been excited, but either one is theoretically possible. Sometimes an unpleasant surprise happens when the investigator is hoping for one operating point and the circuit jumps to the other.

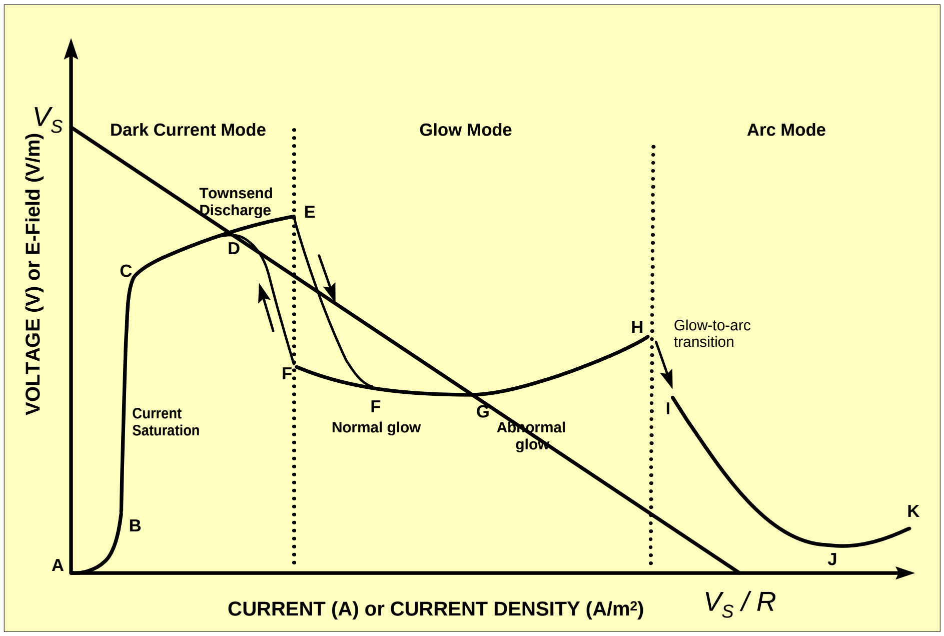

Figure 5. The plot of figure 3 superimposed onto figure 4. Obviously, the value of the current density determines in which mode the plasma will operate. Voltage across the tube has little effect.

Consider what would happen if we now maintain the source voltage, V_S , constant but increase the value of the resistance, *R*. The intersection of the straight "load-line" with the horizontal axis would move toward the left while the load-line's intersection with the vertical axis remains fixed. In that way the operating point might be repositioned, for example, to point C, and this would be the only possible location at which the circuit could operate – there being only one intersection between the load-line and the plasma *VI* plot for those values of V_S and *R*.

Conversely, lowering the ohmic value of *R* might result in point J becoming a possible operating point. In fact, because plasmas will attempt to lower the force on each charged particle, point J would be the probable result. If the electrodes were not designed to withstand a current of this magnitude, a melt-down of the tube might well occur.

By judiciously varying the V_S and *R* values, an investigator can trace out the entire non-linear plasma characteristic plot. (Remembering always not to select values that might unintentionally locate an operating point in the arc range.)

If conditions within the plasma are maintained such that only one plasma cell exists within the tube then no double layers divide the plasma into different cells. Under these conditions the general shape of this plot is the same for both external measurements (voltage applied across the electrodes vs. terminal current) and internal measurements (*E*-field strength at a point in the plasma vs. current density at that point). For this reason both axes in figures 3 and 4 carry two labels. Of course numerical values would be different depending on which quantities are being presented:

1. Overall quantities: V_P, the terminal voltage across the tube, vs. I, the total current (in Amperes) through the tube.
2. Point quantities: E, the electric field at a point in Volts per meter, vs. J, the current density in Amps per square meter of cross-section of the discharge.

The electrical characteristics of the discharge such as the breakdown ('sparking') voltage at which the discharge becomes visible, the overall shape of the volt - ampere characteristic, and the structure of the discharge (described in the previous section) all depend on the geometry of the electrodes, the shape of the vessel, the particular gas used, its pressure, temperature, and the electrode material. The shape and properties of the discharge volt-ampere plot in its various ranges are discussed below. Usually three general regions (modes) can be identified as shown in figures 4 and 5: the dark current mode, the glow mode, and the arc mode.

Notice that no point(s) on the curves plotted in figures 4 and 5 touch the horizontal axis. Every point in a plasma discharge requires a non-zero valued electric field strength to maintain the discharge. A typical charge carrier will act as shown in figure 6. An average velocity of that type of carrier will result that is proportional to the strength of the applied E-field. Thus $v_{Av} = \mu E$ where μ is the 'mobility' of that type of charge carrier.

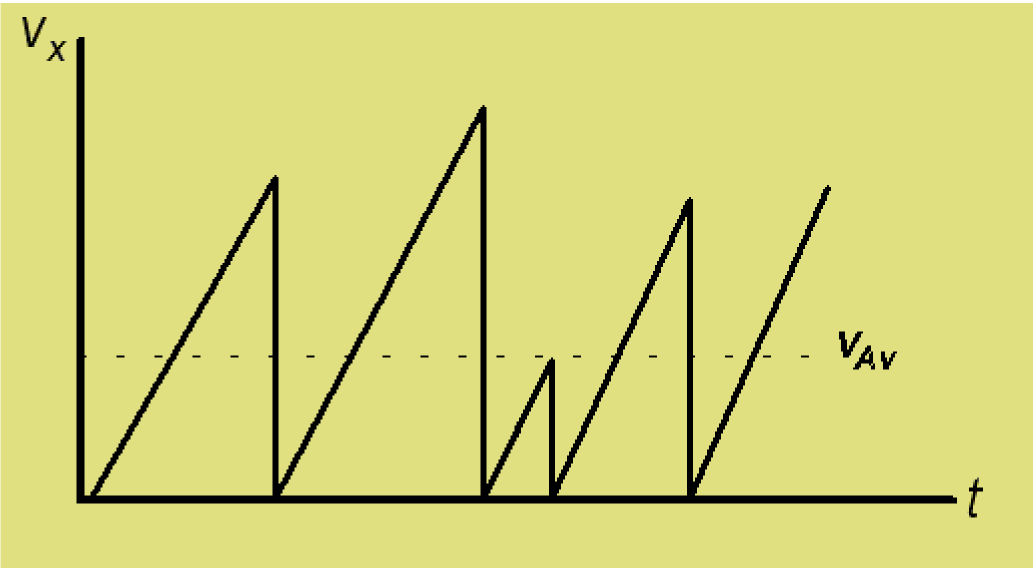

Figure 6. A constant strength electric field (force per unit charge) creates a constant acceleration. The velocity of each carrier will increase linearly with time until it collides with another particle. This produces an average velocity value, v_{Av} that is proportional to the applied field.

Dark Current Mode

The region of the plot between A and E in figures 4 and 5 is termed the dark current mode because, except for Townsend 'corona' discharges and the breakdown itself, the discharge remains invisible to the eye. The upper layers of Earth's atmosphere are dark-mode plasma. Radio frequency waves are refracted back down to the surface by this plasma. But it normally emits no visible light.

A to B

In this low-current stage of the process, the electric field applied along the axis of the discharge tube sweeps out the ions and electrons created by ionization from background radiation. Background radiation from cosmic rays, naturally radioactive minerals, or other sources, produces a constant and measurable degree of ionization but not enough to make the plasma visible to the human eye. The ions and electrons drift to the electrodes in the weak applied electric field producing a weak electric current. Increasing the applied voltage sweeps out an increasing fraction of these ions and electrons.

B to C

If the voltage between the electrodes is increased enough, eventually, at point B, all the available electrons and ions are being swept away, and the current 'saturates' (does not increase further even though an increasing voltage is applied). The value of the current, when it saturates, depends linearly on the radiation source strength – this is a property used in some radiation counters. A charged particle that penetrates into the inter-electrode space will cause an abrupt (transient) change in the current, I, that can be sensed by an external ammeter.

C to D

If the voltage across the tube is increased beyond point C, the current will again rise. The electric field is now strong enough so that the electrons initially present in the plasma can acquire enough kinetic energy, before reaching the anode, to ionize neutral atoms. This region of increasing current is called the Townsend discharge region.

D to E

'Corona[10]' discharges occur in this Townsend region due to high electric field strengths near sharp points, edges, or wires just prior to electrical breakdown (transition from dark to glow mode). If the current level is high enough, corona discharges are actually dim glow discharges – visible to the eye. For low current levels, the entire corona is dark, as appropriate for the dark mode. Related phenomena include the silent electrical discharge, an inaudible form of filamentary discharge, and the brush discharge, a luminous discharge in a non-uniform electric field where many Townsend-type discharges are active at the same time and form streamers through the plasma. When observed at the mastheads of sailing vessels, such visible Townsend discharges are called *St. Elmo's Fire*.

E

As the electric field becomes ever stronger, a liberated electron may also ionize another neutral atom leading to an avalanche of electron and ion production. Electrical breakdown (transition from dark to glow mode of operation) can occur. At this breakdown ('sparking') voltage, V_B, the current may increase by a factor of 10^4 to 10^8, and is usually limited only by the internal (ballast) resistance of the power supply connected across the electrodes. If this resistance has a comparatively high ohmic value[11], the discharge tube cannot draw enough current to break down the gas, and the tube will remain in the Townsend region with small 'corona points' or 'brush discharges' being evident on the electrodes. If the internal resistance of the power supply is relatively lower, then the plasma will break down and move into the normal glow discharge mode. The breakdown (or 'sparking') voltage for a particular gas and electrode material depends on the product of the pressure and the distance between the electrodes as expressed in Paschen's law (1889).

Paschen's Law

As discussed above, in order to ionize the neutral atoms within the tube, an electron must acquire a certain minimum energy (the ionization energy). It does this by falling through a sufficiently large voltage drop and thus attaining a required velocity. If it collides with anything before attaining this velocity, it will not have the required kinetic energy to perform the ionization. So the discharge tube length (distance between electrodes) must be larger than the 'mean free path' (average distance between collisions) of the electrons in the discharge. By lowering the pressure in the tube we can remove potential collision candidates. Of course if the pressure is lowered too far, there will be nothing left to collide with after the ionization energy has been attained. Paschen's Law quantifies the trade-off among the three determining quantities: distance between electrodes, applied voltage, and pressure in the tube. For example, if the applied voltage is fixed, then there is an optimum value of the product, *pd*, where *p* is the pressure and *d* is the distance between electrodes.

Glow Mode

The glow discharge mode owes its name to the fact that the plasma becomes luminous. The plasma glows because the electron energy and number density are high enough to generate visible light by excitation collisions and recombinations. The applications of glow discharge include TV displays, fluorescent lights, dc parallel-plate plasma reactors, magnetron discharges used for depositing thin films, and electro-bombardment plasma sources. The auroras observed in Earth's (and other planet's) polar regions are plasma in the glow mode. So are neon advertising signs. The solar corona is a glow mode discharge. It is essentially completely ionized.

F to G (Normal Glow Mode)

After a discontinuous transition from E to F, the plasma enters the 'normal glow' region, in which the voltage is a slightly decreasing function of the current. This is thus a region of negative dynamic resistance. In this range, plasma can decrease the *E*-field strength at any given point inside it by increasing the current density (using less than the full cross-section of the tube). This moves the operating point toward the right, squeezing the plasma discharge down into filaments, and it will do so. The filaments observed in the outer, low current density region of the solar corona are examples of this effect. The electrode current density is independent of the total current in this mode. This means that the plasma is in contact with only a part of the electrode surfaces at low currents in this range. As the current density is increased from F toward G, the fraction of the cathode occupied by the plasma increases, until plasma covers the entire cathode surface at point G.

G to H (Abnormal Glow Mode)

In the 'abnormal glow' range (to the right of point G), the voltage increases with increasing current in order to force the electrode current density above its natural value to provide the required current.

Hysteresis at the Glow / Dark Mode Transition

Starting at point G and *reducing* the value of current or current density (moving to the left on the plot), a form of hysteresis is observed in the volt-ampere characteristic. On the way back down, the visible glow discharge maintains itself at considerably lower currents and current densities than at the original point F and only then, at a new point F, makes a transition back up to the Townsend region at point D.

Arc Mode

H to K

At point H, the electrodes become sufficiently hot that, in the lab, the cathode emits electrons thermionically. If the DC power supply has a sufficiently low internal resistance, the discharge will undergo an abrupt glow-to-arc transition. In cosmic plasma there is no metal cathode and so arc mode is achieved via an avalanche increase in the total number of current carriers. Arc mode emission is characterized by copious amounts of intense ultra-violet light as well as brilliant broad-spectrum EM radiation including visible light. Arc mode plasma is orders of magnitude more radiant than glow-mode.

I to J

The arc regime, from I through J is one where the discharge voltage decreases steeply as the current increases (negative dynamic resistance). This causes filaments to form in the lower current density region of the arc mode. Natural lightning is clearly one example of such filamentation. Negative dynamic resistance occurs until a sufficiently large current level is achieved (point J). Above that point, the voltage increases slowly as the current increases. In this higher current density arc mode range, the discharge is not filamented.

3. Space Plasmas vs. Laboratory Experiments

Several of the component structures observed in laboratory plasmas are in one-to-one correspondence with observed solar and cosmic phenomena. But there are at least two significant differences that must be recognized.

1. The single most important difference between the laboratory plasma described above and that which surrounds the Sun is that in the laboratory, the tube containing the plasma usually has a cylindrical shape with the anode and cathode being almost the same size. However, the solar plasma is spherical. This has several effects:
   - The vector calculus mathematics used in Maxwell's equations to describe the electric field in such plasmas gives different results depending on the morphology (cylindrical or spherical) of the discharge. See: On the Sun's Electric Field .
   - Because of the spherical geometry of the heliosphere, the current density is much higher in the neighborhood of the Sun's anode than it is at the (virtual) cathode (the heliopause). The ratio of cathode area to anode area is proportional to the square of the ratio of the radius of the heliopause to the radius of the Sun: (radius of the heliosphere/radius of the Sun)^2 = $(1.8\text{x}10^{13}/4\text{x}10^{8})^2 \sim 2\text{x}10^{9}$. So the heliosphere's surface area is 2 billion times the area of the Sun's surface. Therefore, extremely relatively high

current density occurs at the anode. This puts the anode ‘glow’ discharge of the photosphere into the arc mode.

- The Sun emits power at a rate of approximately 65-million watts/sq meter from its photospheric surface. This is equivalent to a power output of 42 kW from each square inch of that surface. It is difficult to imagine that a plasma discharge in anything other than arc mode could radiate 42 kW of power from each square inch of its surface area. The light from over forty 1000-watt light bulbs radiating from a one square inch area must come from a continuous arc-mode plasma. Some people may think the word ‘arc’ is synonymous with ‘lightning bolt’ – a jagged, often branching, and randomly shaped discharge. It is not. The word ‘arc’ refers only to the mode in which a given plasma can be. Often, continuous, steady-state plasma is in arc mode.

Figure 7. A continuous high current density arc-mode plasma.

2. There are no metal electrodes anywhere in space and this includes the solar plasma discharge. The cathode is a *virtual* one and is at a vast distance from the anode (the body of the Sun). This is not unique. For example, the St. Elmo’s Fire discharges sometimes visible at the mastheads of sailing vessels and along power transmission cables have no real cathode. Their electric paths spread out and end on negative charges located at remote distances – at virtual cathodes. In a thunderstorm, a cloud electrode may simply be a region of excess charge distributed over a volume. In cosmic plasmas (including the ‘solar wind’) because there are no material cathodes, some of the phenomena described above such as thermionic or secondary emissions from a (metallic) cathode are impossible and thus are not present.

Conclusion

The author hopes this relatively brief primer on the visual appearance, structure, and electrical properties of plasma may answer some questions and/or eliminate some confusion about this important and still emerging area of physical engineering-science. Much of it has been gleaned from what are now historical scientific books and papers.

The empirical scientific method has three components: observation, hypothesis making, and experimental testing. Mathematical derivations should not replace observations made in the laboratory. But the observations discussed here seem to have faded into the obscurity of time while mathematical derivations multiply unboundedly. There is arguably a need to reproduce some or all of these observations in order to be able to judge what are and what are not viable explanations for observed cosmic phenomena.

D. E. Scott

[1] See: Mulder, J.G.W., *Gas-Discharge Tubes*, http://www.electricstuff.co.uk/ch1.pdf
[2] A case in point: One of the most highly recommended modern texts on plasma physics is Paul M. Bellan's *Fundamentals of Plasma Physics.* Its index makes no mention of: glow or dark modes, Paschen's Law, Townsend discharge, anode glow, or the name Birkeland. It does contain: action integral in Lagrangian formalism, dielectric tensor elements, Grad-Shafranov equation, Vlasov equation, Sweet-Parker reconnection, and the Yukawa solution, (among many other similar entries). See: http://www.amazon.com/Fundamentals-Plasma-Physics-Paul-Bellan/dp/0521528003/ref=sr_1_fkmr0_2?s=books&ie=UTF8&qid=1347127180&sr=1-2-fkmr0&keywords=Bellan%E2%80%99s+Fundamentals+of+Plasma+Physics.
[3] See: Geissler tubes: http://www.crtsite.com/page6.html
[4] See: Crookes' tubes: http://en.wikipedia.org/wiki/Crookes_tube
[5] A bewildering variety of different units are used to describe the pressure of a contained gas. For example: 1Atm = 101,325 P = 29.92 inch/Hg = 1013 millibar = 760 torr; 1 millibar = 100 P; 1 P = 10 dyne/cm^2; 1 inch/Hg = 3386 P; 1lb/in^2 = 6895 P = 51.7 torr… etc. *ad infinitum, ad nauseum.* The SI unit is the pascal.
[6] This resistor is often called the "ballast resistor" or just the "ballast."
[7] This value of current can be found by setting $V = 0$ in equation 6. This is equivalent to placing a short circuit across terminals X-X in figure 2. The resulting value of current is therefore called the 'short-circuit current.'
[8] Such a plot, which is due to all parts of the circuit except the plasma tube itself, is called a "load-line." This is because electrical engineers think of everything that is ***not*** the active device being studied as constituting a "load" on that device. The nomenclature is counter-intuitive, but widely accepted.
[9] See: http://encyclopedia2.thefreedictionary.com/Electric+Discharge+in+Gases especially figure 3.
[10] This nomenclature was used historically to describe the unusual shape of this kind of discharge. It should not be confused with the Sun's corona, which is an altogether different plasma phenomenon.
[11] Very high values of both V_S and R result in a steeply inclined load-line approximating a current source that enables the investigator to limit the operating point to a range that does not get outside the range D to E in figure 4.

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