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Cathode Dark Space and Negative Glow of a Mercury Arc

CHARLES G. SMITH
Raytheon Manufacturing Company, Newton, Massachusetts
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Means were evolved to observe the cathode dark space of the mercury arc, the object being to measure the thickness and evaluate therefrom the voltage gradient at the cathode to distinguish between field and emission theories of electron liberation. A magnetic field transverse to the arc drives it in the opposite direction to the force involved. This *wrong way* motion made it possible to race the arc spot over smooth mercury while ions, electrons, and vapor were blown rearward. Photomicrographs showed a negative glow, its image in the mercury, and a space between; evidently twice the dark space. A one-ampere arc had a dark space of 0.001 cm; a hundred times too large for the field theory, and causing excessive space charge limitation of current unless compensating ionization occurs throughout said space. Phenomena in the negative glow must cause the needed ionization and also intensive electronic bombardment of the cathode. This is assumed to cause cumulative excitation of the liquid resulting in emission of electrons and light. A continuous spectrum originates—within the limits of measurement—at the liquid.

THE mercury arc cathode spot displays intensive electronic phenomena apparently not explained by inter-relationships of well-known factors. Outstanding problems are briefly stated. The low pressure arc goes the *wrong way*[1,2] (opposite to the electromagnetic push) in any transverse magnetic field less than about 5000 oersteds. Electrons are liberated from the liquid at the cathode spot in sufficient numbers to supply the arc current[3] of 4000 amperes per sq. cm. Evidence from studies of vapor pressure[4] yielding a surface temperature less than 200°C and the possibility of extinguishing the arc[5] within 10^{-8} sec. clearly indicate that the electrons are not liberated by ordinary thermionic means; and if the present work proves valid, the electrons are not extracted by electrostatic force, because the field is too weak.

It is the object of the present work to view the free cathode spot with a microscope to find the dark space, if possible, and the negative glow; and to measure the thickness of the dark space and to evaluate therefrom the approximate voltage gradient at the cathode surface. A further object is to discuss the implications of the findings and point out in particular that the inferred voltage gradient at the cathode is entirely too small for the field theory[6] of electron liberation, and also that a powerful ionizing agent must be operative right at the liquid surface.

The dark space has not heretofore been observed because of gross turbulence at the arc spot caused by blasting vapor, spraying mercury, electromagnetic forces, and an arc pressure[7] of 80,000 dynes per sq. cm exerted upon the liquid.

Photo-micrographic studies of the free cathode spot are here made possible by exploiting two properties of the low pressure arc in a transverse magnetic field. First, the arc moves at right angles to the horizontal component of such field in exactly the opposite direction to that expected. This retrograde motion is pronounced at low pressure and persists or even increases as the anode is brought closer to the cathode. Speeds

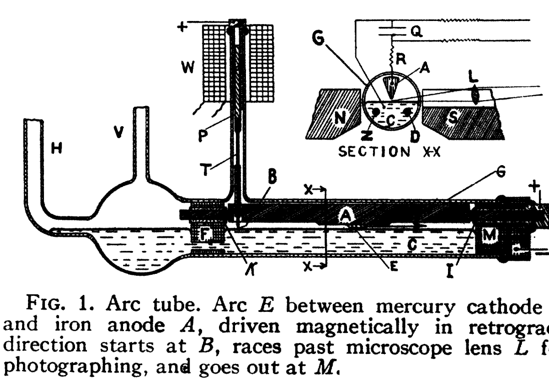


FIG. 1. Arc tube. Arc E between mercury cathode C and iron anode A, driven magnetically in retrograde direction starts at B, races past microscope lens L for photographing, and goes out at M.

[1] C. G. Smith, Phys. Rev. **62**, 48 (1942); Phys. Rev. **64**, 40 (1943).
[2] N. Minorski, J. de phys. et rad. **9**, 127 (1928).
[3] A. Guntherschulze, Zeits. f. Physik **11**, 74 (1922); L. Tonks, Physics **6**, 294 (1935).
[4] L. Tonks, Phys. Rev. **54**, 634 (1938); J. V. Issendorf, Physik. Zeits. **29**, 857 (1938).
[5] G. Mierdel, Zeits. f. tech. Physik **17**, 452 (1936).
[6] I. Langmuir, Gen. Elec. Rev. **26**, 731 (1923).
[7] E. Kobel, Phys. Rev. **36**, 1636 (1930).

exceeding one hundred meters per second are attainable. The second usable property shows itself when the magnetic field has a vertical component. Besides the rapid motion due to the transverse component of the field, the arc moves slowly away from the obtuse angle between field and mercury surface and toward the acute angle. By employing a magnetic field in the form of a long narrow, shallow arch the lines of which cut the liquid surface in two points, the arc can be made to race along in an accurately predetermined straight line under the middle of the magnetic archway. At a sufficient speed the arc cannot sensibly depress or otherwise disturb the serenity of the mercury surface until it has made its transit past a microscope. The retrograde feature of the motion is particularly valuable because the average electromagnetic force upon the ions and electrons results in a mechanical action driving the vapor from the arc spot to the rear while the arc glides forward over smooth mercury free from disturbances that might otherwise have preceded it.

APPARATUS

Two sections of the arc tube are shown in Fig. 1. G is a glass tube 2.8 cm in external diameter, containing mercury cathode C and iron anode A. Pieces F and M of non-magnetic stainless steel are fastened together rigidly by two rods of the same material, imbedded in the mercury and shown at Z and D in the upper section. The anode A is supported on insulators K and I inserted into F and M, respectively. A hole through A permits passage of a tungsten rod T down to the mercury surface. T is fastened to a small iron plunger P that can be raised by a coil W to break contact with the mercury at B. V is connected to a mercury diffusion pump. H connects with a bulb containing mercury for distillation into tube G. NS represent pole pieces of an electromagnet each pole face of which extends from F to M. The anode A is wedge shaped, and being of iron distorts the magnetic field making it into an arch concave toward the mercury just below the anode. This arched field holds the arc in a line as it races along under the anode. Without the arched field the arc may wander about free from definite control by the position of the anode.

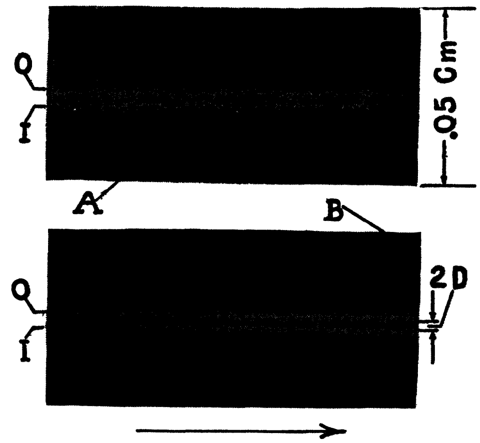


FIG. 2. Photomicrographs of one-ampere mercury arc cathode spot racing once past a microscope, with velocity of 70 meters per sec. 0 = negative glow. I = image of 0 in surface of cathode. $2D$ = twice the cathode dark space. A is a direct enlargement of negative. B is enlargement made while sliding paper horizontally.

A small arc energized by an auxiliary circuit is started at the tungsten mercury contact B when the iron plunger P is raised by the coil W. The current at B is limited to about one-half ampere and the voltage on open circuit is about 40. The anode A takes over the arc current as the discharge at B goes out. The arc spot E races to the right with positive column trailing. The energy for the arc is supplied by a condenser Q of 160 microfarads charged to 440 volts. Current from Q flows through R, a limiting resistance. The charge on the condenser is quickly exhausted, and the arc goes out soon after reaching the end of its track. This quick cessation of current prevents excessive distillation of mercury. After things have calmed down another shot can be made. Lens L used in making photomicrographs is an archromat of 3.5-cm focal length.

PHOTOGRAPHY OF NEGATIVE GLOW AND DARK SPACE

Photomicrographs were taken with a magnification of 7.9 and utilized a single traverse of the arc spot racing at 70 meters per sec. past the microscope. This showed two bright streaks 0 and I, the negative glow and its image in the mercury, respectively. The space between the two is twice the dark space. Figure 2 with its attendant scale shows the situation for a one-ampere arc. The cathode dark space is about 0.001 cm, and the glow is roughly 0.004 cm thick. The light along the axis of the camera made an angle of 3° with the horizontal. Lens aperture was 4 mm. The total arc drop was 15 volts as determined by an oscillograph. The magnetic field at the mercury surface is inferred from the velocity of the spot to be about 1500 oersteds. When the axis of the camera made an angle of more than 5° with the horizontal, it was not possible to find a double line represented by 0 and I. One line was found. At the higher angle the reflected light must come from a slightly distorted mercury surface too near the arc spot. At the small angle of 3° the reflected component comes from a point some distance nearer the camera and sufficiently flat to yield a good image.

The drawing of Fig. 3 is a pictorial representation of the observations. The arc moves in the direction of the arrow S. O is the negative glow, and I its image in the mercury surface M. A possible source of light at the liquid surface is omitted from the drawing. D represents the cathode dark space and P the positive column.

The brilliant and surprisingly thin negative glow must be a region of potential maximum[8] (by analogy with similar situations). It is assumed to be a region wherein a relatively high electronic temperature is established because it is the recipient of much of the enormous energy input of the primary electrons leaving the cathode surface and gaining approximately ten electron volts of energy before plowing into the negative glow. The essentially mechanical energy of these primary electrons is mostly converted into electronic thermal energy and radiation. The majority of the electrons in the negative glow must have a temperature, and consequently some of these electrons have energies in excess of the ten electron volts of the primaries. Therefore, electronic diffusion back to the cathode against the potential drop is to be expected. The magnitude of this diffusion seems to be about one-third of the rate at which primaries leave, if the electron temperature in the glow is 45,000°K, a value found to be applicable for an energy balance at the cathode as previously considered.

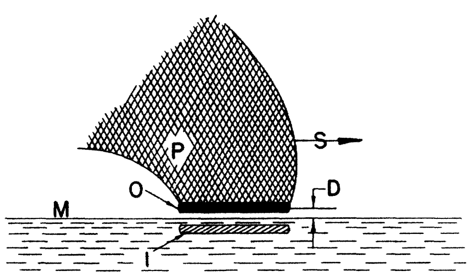


FIG. 3. Pictorial sketch of racing cathode spot. 0 = negative glow. I = image of 0 in cathode surface M. P = positive column. D = cathode dark space. S shows direction of motion.

Ionization in the dark space is required to neutralize a part or all of the negative space charge that would otherwise impose limitations upon the current density at the cathode. Without any ions the electronic current i across a space d impelled by a voltage drop V is $i=2.33\,Vd^{-2} \times 10^{-6}$ ampere sq cm. When $d=0.001$ cm and $V=10$ volts, $i=74$ amperes, an insignificant value compared to the arc current of approximately 4000 amperes per sq. cm. If now we assume uniform rate[9] of ionic production throughout the dark space at the optimum rate to reduce space charge, we may multiply the 74 amperes by 2.86, and we are still far below 4000. If more ions are generated than the optimum, we merely destroy the upper end of the dark space by creating a surplus of ions that are relatively slowly swept down to the cathode. Therefore, the ionization needed to permit the observed current across the dark space is apparently improbable by ordinary means though the ionization is evidently present. A remaining recourse in the dilemna is to fall back upon the processes that create and maintain an intense plasma such as the negative glow. It is the author's belief that a satisfactory understanding of a plasma will involve more than our present knowledge of electronic ballistics and ion formation. For example, there are matters such as the saturation current[10] of a gaseous conductor, the inadequacy of accepted theory in dealing with electronic distribution in a magnetic field transverse[9] to a positive column, and the rapid

[8] K. T. Compton and C. Eckart, Phys. Rev. **25**, 139 (1925); M. J. Druyvesteyn and F. M. Penning, Rev. Mod. Phys. **12**, 151 (1940).

[9] I. Langmuir, Phys. Rev. **33**, 954 (1929).

[10] A. W. Hull, Elec. Eng. (Nov., 1934).

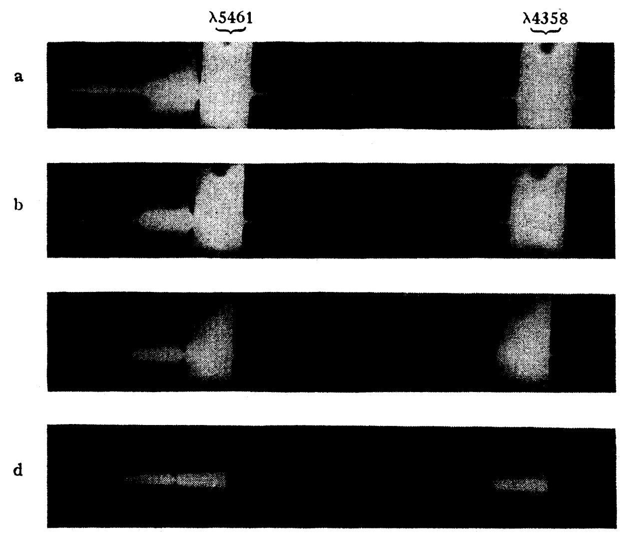


FIG. 4. Photomicrographic spectral observations of moving arc. Horizontal line is the continuous spectrum at surface of the mercury. The line spectrum shows above the mercury surface and also below, due to reflection in the mercury. Number of traverses of arc past microscope for $a=2700$, $b=900$, $c=300$, $d=100$.

establishment[11] of an electronic temperature. These major effects may require additional knowledge for even an approximate understanding. The net charge in the dark space would seem to be the difference between relatively large numbers of ions and electrons, respectively, which in turn are there partly as a result of processes of ionization and recombination in the negative glow, and the extension of these processes downward into the dark space, the understanding of which must involve a better basic understanding of a plasma.

The liquid cathode must suffer an intense electronic bombardment since ions are being created at its very surface. Such bombardment was previously postulated to result in cumulative electronic excitation of the liquid surface, the liquid then becoming an emitter of electrons and also of light—presumably a continuous spectrum.

SPECTRA

A much-widened slit of a spectroscope was placed where the moving magnified image of the arc spot might cut across it. Light from the vapor of the arc and the reflection in the mercury surface give rise to the broad spectrum lines shown in Fig. 4, where a was made by 2700 traverses of the arc past the microscope, $b-900$, $c-300$, and $d-100$, respectively. The horizontal streak is the continuous spectrum originating apparently at the very surface of the mercury and only there. The emergent light from the arc made an angle of about 10° with the horizontal. In order to record the line spectrum it was necessary to employ ten traverses of the arc spot past the microscope lens. The red portion of the continuum was observable after about a hundred traverses. Numerous traverses of the arc spot give rise to poor definition of the image, due probably to slight differences in level of the mercury and small variations in the arc track along the surface of the mercury. Even so, the line of the continuum is remarkably sharp, except where faint lines of HgII and HgI superposed upon it make slight bulges. The identity of these was determined by other observations not published. There is a long portion at the red side of λ4358 that is quite narrow. Measurement of the vertical depth of this region together with the total magnification of 7.2, including that of the spectroscope, shows that the apparent vertical dimension of the source giving the continuum is about .001 cm. However, it may be that the horizontal width of the arc streak is really causing the apparent vertical dimension; and actually the continuum may originate in the liquid surface itself. If we wish to reduce the effect of the horizontal width, we should view the arc spot at a smaller angle to the horizontal, but this seems to reduce the total light of the continuum, and the necessary labor for this observation was

[11] I. Langmuir, Phys. Rev. **26**, 585 (1925); A. F. Dittmer, Phys. Rev. **28**, 507 (1926).

not carried out, though it should be. A more direct way of fixing the spatial origin of this light may consist in a study of the polarization of the continuum near grazing angle of emission, since a bright emitter is expected to show light strongly polarized[12] with electric vector vertical. The continuous spectrum does not terminate near λ4358 as indicated in Fig. 4. Films more sensitive in the violet show an extension into the ultraviolet.

CONCLUSION

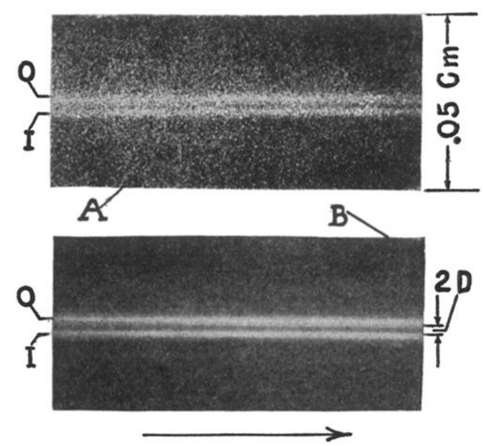
The moving mercury arc cathode spot driven rapidly in the characteristic retrograde direction by a transverse magnetic field has been studied microscopically. A thin, brilliant disk-like negative glow, the apparent heart of the arc problem, has been found. It is mostly within 0.004 cm of the liquid surface. This finding shows that we have hitherto been handicapped in studies of the arc either with probes or by spectral means. The probes fail because the negative glow is too close to the liquid to admit of insertion of a probe. Spectral studies of this region have been frustrated by light from the relatively enormous, though intrinsically less brilliant, adjacent regions of luminous vapor. In short, both electrically and optically there has heretofore been little or no direct study of the important negative glow. The glow is evidently a region of potential maximum and this means that our previous estimate of about 10 volts for the cathode potential drop is too low.

The observation of a cathode dark space of 0.001 cm yields a gradient at the cathode of about 10,000 volts per cm. This low value makes the field theory of electron extraction untenable for the low pressure arc; and this seems to be true even if one should postulate pointed areas over the liquid, because space charge limitations that are already too great would be still further augmented, if the current distribution were constrained by pointed regions. The large dark space would seem to make other theories untenable unless ions are produced throughout the dark space and especially at its lower boundary, to reduce negative space charge. The ionizing agent in this region is not explicitly understood.

The micro studies have shown that the continuous spectrum comes either from a region about 0.001 cm thick at the cathode surface or else from the cathode itself. This latter origin does not necessarily imply that the liquid is hot enough to be incandescent. The concept that the liquid is excited in a cumulative way[1] resulting from bombardment by electrons diffusing down from the negative glow was outlined previously. The present study lends support to that concept.

My obligations to Harvard University in whose physical laboratory the work was done are very great. To Professor T. Lyman, the writer owes the opportunity to work and the inspiration to carry on in this field.

[12] A. G. Worthing, J. Opt. Soc. Am. 13, 636 (1926).



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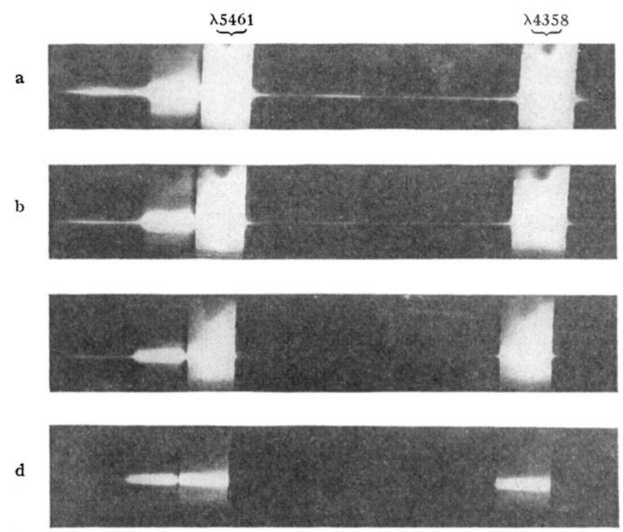

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