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SPECTROSCOPIC STUDY OF A HELIUM ARC

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16. Abstract

A plasma source which has the characteristics desired for astrophysical spectral measurements is described. A high-frequency (1 MHz) capacitor discharge through an arc tube containing needle electrodes heated helium to kinetic electron temperatures varying from 10 eV to over 100 eV. Diagnostic measurements included time-resolved spectroscopy and high-speed photography.

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SPECTROSCOPIC STUDY OF A HELIUM ARC

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SUMMARY

A transient plasma was produced in helium, having an ambient pressure of 700 torr, by discharging a capacitor storing 10 J through a 0.5-mm, two-electrode gap. The temperature of the helium plasma was measured spectroscopically by comparing the intensity ratio of the HeI 4921 Å line to the HeI 4713 Å line. It was found that conditioning the electrodes by electrical discharge increased the electron temperature from 10 eV to over 100 eV.

Microscopic examination of electrodes after conditioning indicated that many sharp points with radii of approximately 1 μ were produced. These sharp points generated electric fields of over 10^7 V/cm at their surface. The high electric fields caused field emission electron currents of 5×10^7 A/cm^2 to flow from the surface of the emitter points. These high current densities of electrons, along with the high electric field, are responsible for the observed electron temperatures.

INTRODUCTION

For laboratory studies of astrophysical spectra, it is desirable to have a simple plasma source that is variable in temperature and density of charged particles. The range of greatest interest extends from temperatures of 5000 to 10^7 °K, and charged particle densities (electrons plus ions) from 10^9 to 10^{22}/cm^2.

One plasma source that has been used extensively for laboratory spectral studies is a simple transient arc. Such a source is generated when a capacitor is discharged through two electrodes surrounded by the gas being studied. Electron temperatures of 10 eV (1.16×10^5 °K) are normally attained.

In this study, it has been found that, when commercial steel phonograph needles were used for electrodes in the transient arc, the electrodes could be conditioned by capacitor discharge to produce sharp points on the surface. These sharp points emit electrons by high field emission. The electrons are accelerated near the points and heat the interelectrode gas. This heating by electron bombardment is very efficient, resulting in electron temperatures that are much higher than normally attained in arcs. Temperatures in excess of 100 eV were indicated in this study.

A similar technique has recently been proposed as a method of producing a dense thermonuclear plasma (ref. 1).

DESCRIPTION OF THE EXPERIMENT

A schematic diagram of the experiment is shown in Figure 1. An arc developed when a capacitor storing 10 J of energy at a potential of 20 kV was discharged through the arc tube, with a frequency of 1 MHz. The peak current was 7000 A. The peak current density at the surface of 1-μ-diameter emitter points was estimated to be more than 10^7 A/cm^2.

Backlighted streak pictures were taken to study the hydrodynamic motion of the heated material. The time resolution of the streak camera was 20 nsec.

Standard spectral techniques were used to measure the temperature of helium in the arc. The spectrograph recorded a 500-Å interval centered on any selected wavelength in the visible region. It can also be used with a single or double exit slit. Each slit has an Amperex Model XP-1023 P.M. detector to indicate the spectral line intensity as a function of time. The time resolution of the detector was 2.0 nsec.

The arc source was a tube with a holder for two needle electrodes. A picture of the holder is shown in Figure 2. The electrodes were commercial steel phonograph needles. The tips of the needles were rounded, and had an effective radius of approximately 50 μ. The spacing between needle tips was 500 μ. A magnified picture of the tip of a new needle is shown in Figure 3a. This needle was carefully selected by microscopic examination for its smooth surface. A scale is indicated in the figure.

A magnified picture of an electrode through which the capacitor has been discharged several times is shown in Figure 3b. The scale is indicated in the figure. This conditioning by capacitor discharge produces many sharp points, some of which are seen at the tip of the electrode in the figure. Only a few points appear in the picture, due to the limited depth of field of the microscope. The radii of some points were estimated to be approximately 1 μ. This technique for making efficient electron field emitter surfaces to generate intense electron beams has been used previously (ref. 2). In other studies*, points as small as 50Å in diameter have been observed on copper surfaces following electrical discharges.

The temperature of helium was measured spectroscopically, by comparing the intensity ratio of the HeI 4921 Å line to the HeI 4713 Å line (ref. 3). This method is applicable for kinetic electron temperatures ranging from 10 to 100 eV.

*Lees, W.L.: NASA Electronics Research Center, Private Communication

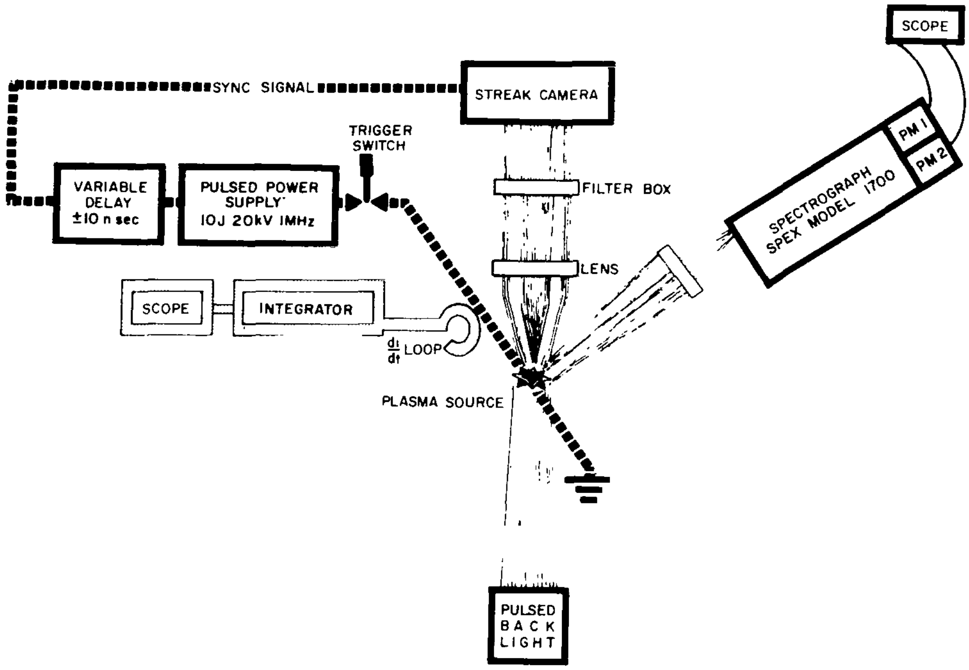

Figure 1.- Schematic diagram of transient arc experiment

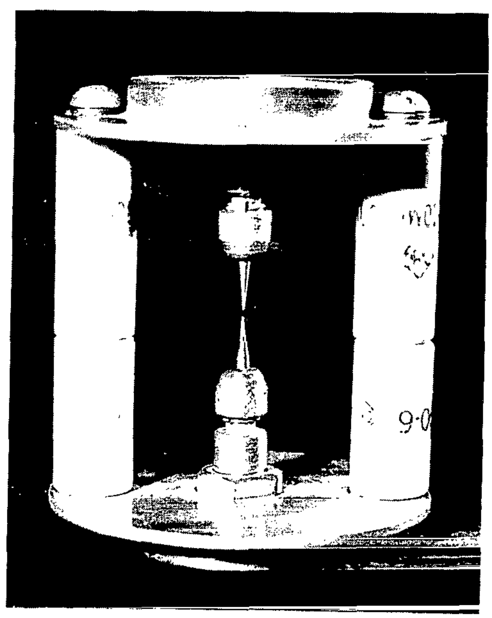

Figure 2.- Arc tube electrode structure

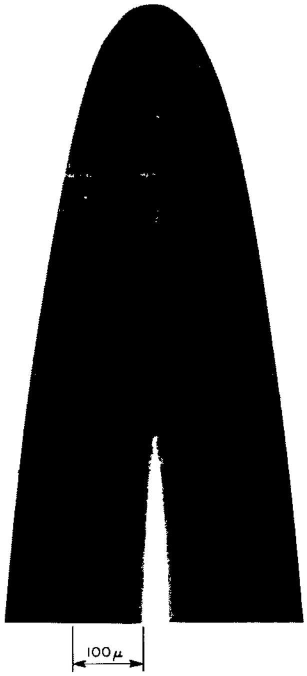

Figure 3a.- New needle electrode

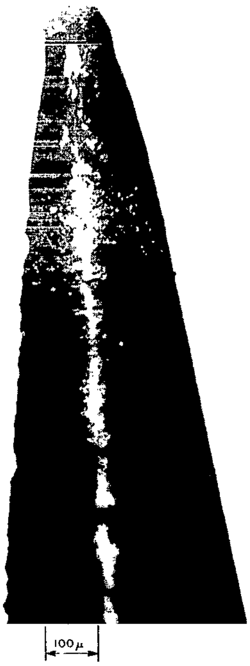

Figure 3b.- Conditioned needle electrode

Time-integrating pictures showing the spectrum of helium in the transient arc, extending from 4600 to 5000Å, are shown in Figure 4. Two exposures were taken, one with a 0.5 N.D. filter in the optical system, and one with a 1.0 N.D. filter in the optical system. These pictures qualitatively illustrate the strengths of these two lines relative to the other spectral features of helium.

Figure 5 is a plot of relative intensity vs. wavelength for the 4921-Å and the 4713-Å spectral lines, 0.8 μsec after the initiation of current flow in the transient arc. To obtain these results, a double-exit slit was used with the spectrograph. An Amperex XP-1023 P.M. detector was mounted on each slit. The curves were then obtained by firing many shots, one for each wavelength setting of the monochromator. Temperature was estimated by integrating the two curves to obtain the relative spectral line intensities, and comparing the results with calculated intensity ratios given (ref. 3). The kinetic electron temperature of the helium arc, 0.8 μsec after the initiation of current flow, was 41 eV (4.75×10^5 °K).

EXPERIMENTAL RESULTS

As indicated previously, electrodes conditioned by electrical discharge produce increased temperatures in the helium arc. This effect is illustrated in Figure 6. The intensity ratio of HeI 4921/4713 Å spectral lines is plotted against the shot number. To obtain these data, needles were carefully selected for smooth surfaces. Separate curves of intensity ratio are plotted for 0.6, 0.8, and 1.0 μsec after the initiation of current flow. For the 0.6-μsec delay, the intensity ratio of the two spectral lines increases from 1 to 17 during six discharges of the capacitor.

For intensity ratios of the two spectral lines up to 5.5, the data can be interpreted in terms of the kinetic electron temperature. The corresponding temperature is shown on the right ordinate. For a 0.6-μsec delay after initiation of current flow, the kinetic electron temperature exceeded 100 eV (1.16×10^6 °K) on the second capacitor discharge.

Figure 7 shows a plot of electron temperature vs time during a single discharge of the capacitor through the helium arc. A peak kinetic electron temperature of 75 ev was attained 0.2 μsec after the initiation of current flow in the electrical circuit.

HEATING MECHANISMS

The transient helium arc was heated to its maximum temperature at the first current peak of the electrical discharge. As

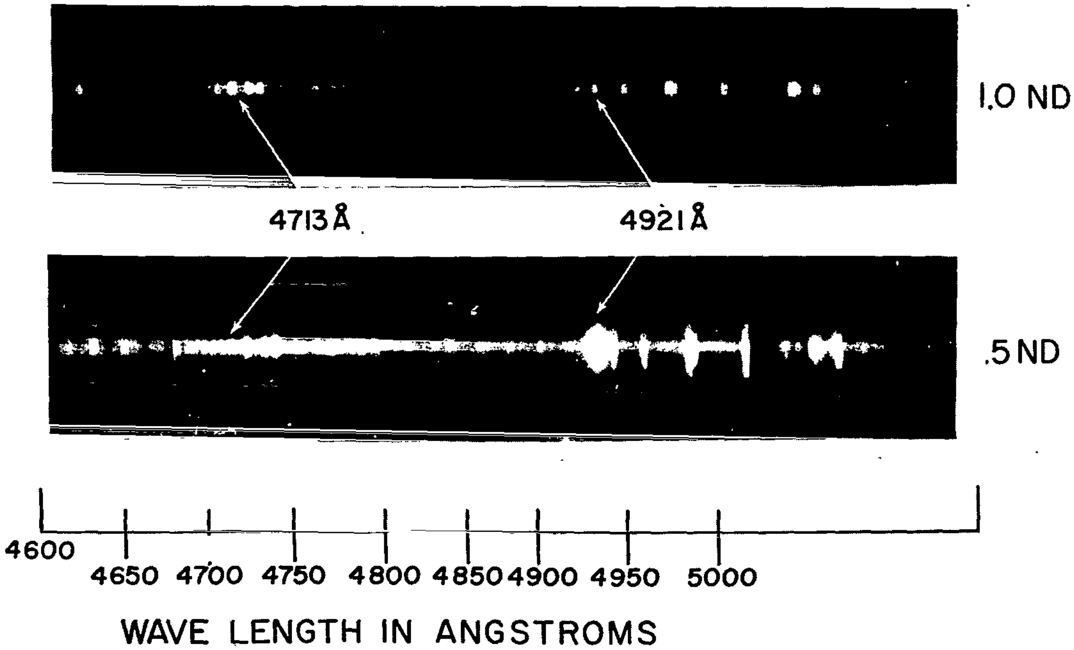

Figure 4.- Time-integrating spectra-transient arc (monochromator 4790, He gas, pressure = 100 torr)

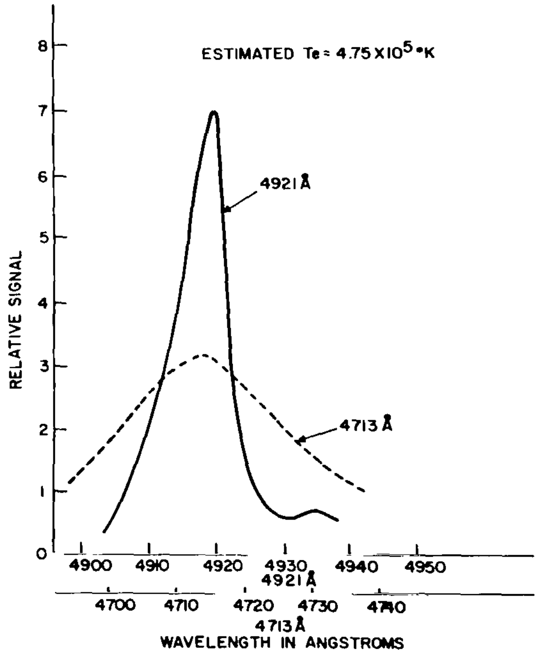

Figure 5.- Profiles of 4921Å and 4713Å He lines 0.8 μsec after initiation of discharge

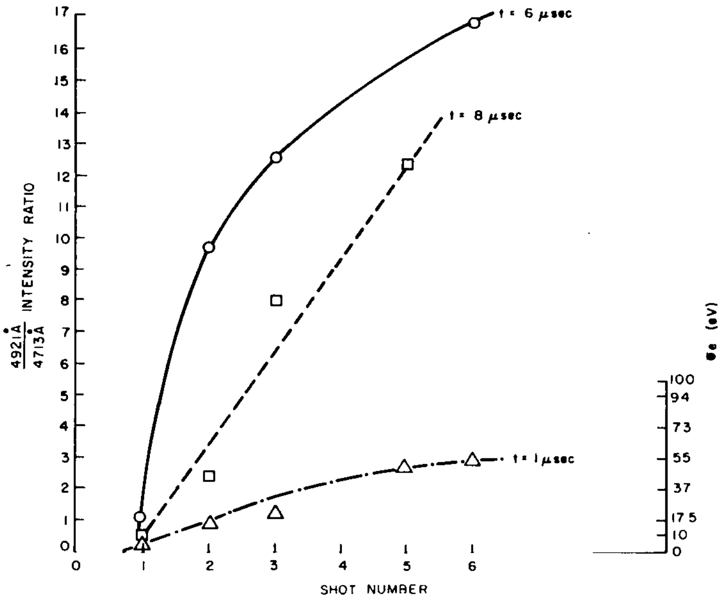

Figure 6.- Effect of electrode conditioning on the intensity ratio HeI4921Å/HeI4713Å and electron temperature

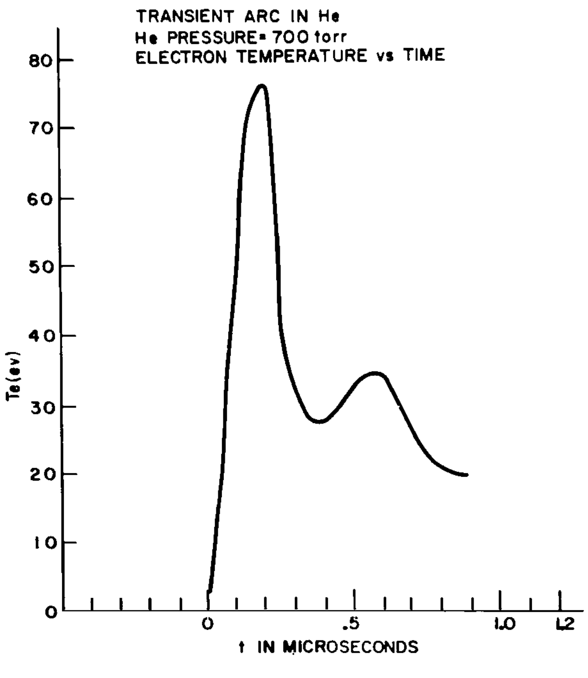

Figure 7.- Electron temperature of the transient arc

indicated in Figure 7, the peak temperature occurred 200 nsec after the initiation of current flow. The arc source then cooled rapidly and increased only slightly during the second current peak at 600 nsec.

During the first 200 nsec of the discharge, the heating was due primarily to electron bombardment. Near sharp points on the surface of the cathode, electron energies and current densities were very high. The combination of high electron energies and high current densities was responsible for the experimental results obtained.

Heating by electron bombardment was reduced after the first half-cycle of current flow. The arc then degraded into resistive heating of the gas.

The arc tube was a diode (see Figure 2) having two needle-shaped electrodes. Each tip had a radius of curvature of 50 μ. The needles were further sharpened when a current pulse was passed through them. After sharpening, the needle was covered with hundreds of sharp points, which had radii of about 1 μ. When a 10-kV pulse was applied across the arc tube, a potential gradient in excess of 1.8×10^7 V/cm existed at 1-μ diameter points on the cathode. A high current density of electrons was then discharged from the cathode by field emission. The tip of the needle quickly became heated, and more electrons were emitted by thermal emission. The emitted electrons were accelerated in the high electric field near the electrode. The electrons then caused two further effects. Some formed a space-charge cloud, reducing the field at the cathode and retarding the further emission of electrons; others bombarded the inter-electrode gas, heating and ionizing it. The ions moved to the cathode and reduced the space charge; they were very effective in this because of their low velocity. The reduction in space charge permitted the acceleration of larger electron currents from the cathode.

As the regenerative process proceeded, enough interelectrode gas became ionized to allow an ordinary arc to strike between electrodes.

Following is a discussion of how the high electric fields and current densities were developed during the first current rise of the transient arc.

The basic theories of electron field emission are discussed in several prominent articles on the subject (refs. 4-6). The electric field strength for a hemispherical point of radius, r, separated a distance, R, from an infinite plane (ref. 8) is given approximately by:

$$F \cong \frac{2V}{r \ \ell n \frac{2R}{r}} \tag{1}$$

where: F = electric field gradient in V/cm

V = potential across the arc tube

r = radius of electrode

R = spacing between electrodes.

For two needle electrodes, the field near each electrode would be described by Eq. (1), if R were replaced by $\frac{R}{2}$ and 2V were replaced by V.

For a needle with a tip radius of 50 μ and an applied potential of 10^4 V across the arc tube, the electric field gradient is $1.25\text{x}10^6$ V/cm at the surface of the electrode. For a 1-μ diameter point, the corresponding field is $1.8\text{x}10^7$ V/cm.

The electron field-emission current is adequately described by the well-known Fowler-Nordheim equation (refs. 5,6):

$$J = \frac{1.54\text{x}10^{-6}F^2}{\Phi} e^{-\frac{6.83\text{x}10^7 \ \Phi^{2/3} f(y)}{F}} \tag{2}$$

where: J = field emission current in A/cm^2

F = electric field in V/cm

Φ = electric work function of cathode material in eV

f(y) = dimensionless elliptic function of the field strength and the cathode material.

The Fowler-Nordheim equation has been solved by several authors, and the results are summarized by Dyke and Dolan (ref.8). These results indicate that, for an electric field of $1.8\text{x}10^7$ V/cm, the electron current density is approximately $5\text{x}10^7$ A/cm^2.

From these results, and from the experimental observations, it is concluded that:

(1) Electron bombardment of the gas near electrode surfaces is a prime heating mechanism in the helium arc experiment;

(2) The electron temperature is increased when sharp emitter points occur on the surface of the electrodes;

(3) The combination of high electric fields and the resulting high electron currents are responsible for electron temperatures in excess of 100 eV, which have been measured.

CONCLUSIONS

It has been observed that conditioning commercial steel phonograph needles by discharging current through the needles surrounded by helium produces points on the surface of the needles having diameters as small as 1 μ. When the capacitor potential of 10 kV is applied across a 500-μ gap between two such conditioned needles, in a 700-torr atmosphere of He, electrons are emitted from the sharp points.

The experimental results obtained are consistent with the generation of intense electron beams by high field emission. The electrons bombard and heat the helium gas between electrodes, producing electron temperatures in excess of 100 eV.

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