

cisely the plane grating formula. It will be noted that, with the exception of two, all of the points fall to the right of the regions of "anomalous dispersion," and that none of them falls in this region. It is due to this circumstance presumably that the displacements of the electron diffraction beams from their x-ray analogues display no marked abnormalities. It will be noted also that although the values of  $\mu$  calculated from the diffraction beams are rather scattered they are not inconsistent with the dispersion curve constructed from the more precise data of the reflection beams.

<sup>1</sup> Davisson and Germer, *Proc. Nat. Acad. Sci.*, **14**, 317 (1928).

<sup>2</sup> Davisson and Germer, *Nature*, **119**, 558 (1927); *Phys. Rev.*, **30**, 705 (1927).

<sup>3</sup> Eckart, *Proc. Nat. Acad. Sci.*, **13**, 460 (1927).

<sup>4</sup> Bethe, *Naturwiss.*, **15**, 787 (1927).

<sup>5</sup> Bethe, *Ibid.*, **16**, 333 (1928).

<sup>6</sup> Andrewes, Davies and Horton, *Proc. Roy. Soc.*, **117**, 660 (1928).

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## OSCILLATIONS IN IONIZED GASES

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In strongly ionized gases at low pressures, for example in the mercury arc, the free electrons have a Maxwellian velocity distribution corresponding to temperatures that may range from 5000° to 60,000°, although the mean free path of the electrons may be so great that ordinary collisions cannot bring about such a velocity distribution. Electrons accelerated from a hot cathode (primary electrons), which originally form a beam of cathode rays with uniform translational motion, rapidly acquire a random or temperature motion which must result from impulses delivered to the electrons in random directions.

In this laboratory we have been studying these phenomena<sup>1</sup> in detail during the last 4-5 years, but the mechanism underlying the Maxwellian distribution and its extremely short time of relaxation have not been understood. At an early date it occurred to me that electric oscillations of very high frequency and of short wave-length in the space within the tube might produce a scattering of the kind observed, but calculation showed that average field strengths of several hundred volts per centimeter would be necessary and this seemed an unreasonable assumption. Experiments capable of detecting oscillations of the electrodes with amplitudes greater than 0.2 volt failed to show such oscillations.

Ditmer<sup>2</sup> although unable to detect oscillations, concluded that oscilla-

tions of frequencies higher than  $10^8$  probably caused the scattering but was not able to suggest why there should be such oscillations.

Penning<sup>3</sup> detected oscillations of frequencies from  $3 \times 10^8$  to  $6 \times 10^8$  per second and found that the electron scattering and the oscillations nearly always occurred together. No cause was assigned for the oscillations.

Dr. Tonks and I have repeated and have confirmed Penning's observations. The amplitude of the oscillations is small, less than 0.2 volt, and frequencies up to  $1.2 \times 10^9$  have been observed. These waves, which are of well-defined frequency, appear to depend on the presence of the ultimate electrons (low velocity electrons) and can be observed in any part of the bulb. Other oscillations of much lower frequency ( $2 \times 10^7$  to  $20 \times 10^7$  per second) can be observed in regions transversed by the primary electrons, which are injected into the tube with velocities corresponding to 25 to 70 volts. These oscillations and the scattering of the primary electrons are observable only when the current of primaries is raised to 10 milliamps. or more.

It seemed that these oscillations must be regarded as compressional electric waves somewhat analogous to sound waves. Except near the electrodes, where there are *sheaths* containing very few electrons, the ionized gas contains ions and electrons in about equal numbers so that the resultant space charge is very small. We shall use the name *plasma* to describe this region containing balanced charges of ions and electrons.

For purposes of calculation we may consider the plasma to consist of a continuum of positive electricity having a charge density  $\rho$  with free electrons distributed within it, the average electron space charge being  $-\rho$ . If the electron temperature is zero, the electrons will probably arrange themselves in a face-centered cubic space lattice (close packed arrangement).

Any electron after displacement from its equilibrium position oscillates about that point with a frequency  $\nu$  which is given approximately by

$$\nu^2 = \frac{e}{m} \cdot \frac{\rho}{3\pi} = \frac{e^2 n}{3\pi m} \quad (1)$$

where  $n$  is the number of electrons per cubic cm.,  $e$  is the charge and  $m$  the mass of the electron. At low temperatures or high electron densities (actually if  $T < 0.001 n^{1/3}$ ) the plasma is thus a kind of crystalline gas.<sup>4</sup> However the electron temperature will ordinarily be far too high to permit this kind of structure even if it were consistent with the actual discontinuous distribution of positive charge. We must therefore consider that the electrons move rapidly throughout the plasma.

By means of the Boltzmann and the Poisson equations, Debye and Hückel<sup>5</sup> have shown that under equilibrium conditions in a plasma, the average potential near a charged plane varies according to the law

$$V = V_0 e^{-x/\lambda_D}$$

where  $x$  is the distance from the plane,  $\epsilon = 2.718$  and  $\lambda_D$  which we may call the Debye distance, is given by

$$\lambda_D = \sqrt{\frac{kT}{4\pi n e^2}} = 6.92 \sqrt{\frac{T}{n}} \text{ cm.} \quad (2)$$

where  $T$  is the temperature of the electrons.

Thus at any distance from the plane which is large compared to  $\lambda_D$ , the average potential and the average electric field become zero. However, when the potential of the plane is changed it requires a certain time for the redistribution of charges to occur and these transient fields are not given by the Debye-Hückel theory.

*Plasma Oscillations.*—If throughout a volume of dimensions large compared to  $\lambda_D$  we change the concentration of electrons by some transient external means, the resulting electric fields act in such a direction as to equalize the concentration, but the potential energy of these fields is converted into kinetic energy of the electrons so that oscillations occur, and electric waves may result.

Mr. Harold Mott-Smith has worked out the theory for infinite trains of harmonic compressional waves of length  $\lambda$  traveling through a uniform plasma containing electrons of negligible velocity. He finds that the velocity of propagation of the waves  $v$  is given by

$$v = \lambda \sqrt{\frac{e}{m} \frac{\rho}{\pi}} \quad (3)$$

Thus no matter what the wave-length, the frequency ( $v/\lambda$ ) in sec.<sup>-1</sup> is

$$\nu = \sqrt{\frac{e}{m} \cdot \frac{\rho}{\pi}} = 8980 \sqrt{n} \quad (4)$$

which is  $\sqrt{3}$  times that given by equation (1) for the oscillations of single electrons.

Since the velocity is proportional to the wave-length, the waves show high dispersion and the group velocity of the waves turns out to be zero. That is, although these waves can propagate through space with the velocity  $v$  they transmit no energy.

Dr. L. Tonks has proved that if the electron density in any region within the plasma is slightly altered so that the potential distribution is  $f(x, y, z)$ , then after the time  $t$  it is  $f(x, y, z) \cos 2\pi\nu t$ , where  $\nu$  has the value given by equation (4). This is a stationary wave which remains of constant wave shape and does not spread.

In these derivations it was assumed that the wave-length  $\lambda$  (or the grain size) of the disturbance  $f(x, y, z)$  is so large that the plasma electrons do not

move distances comparable to  $\lambda$  during one period ( $1/\nu$ ) of the oscillations. This condition is satisfied if  $\lambda$  is large compared to the Debye distance  $\lambda_D$ .

*Beam Oscillations.*—A beam of electrons moving with a uniform translational velocity  $v$  and containing  $n_1$  electrons per cm.<sup>3</sup> may contain similar oscillations of a frequency  $\nu_1$  which may be calculated from equation (4) by placing  $n = n_1$ . In order that these beam oscillations may be unaffected by the plasma electrons it is necessary that their wave-length  $\lambda_1$  shall be small compared to  $v/\nu$ , where  $\nu$  is the frequency of the plasma oscillations. With electron beams of 50 volts energy  $v/\nu$  is usually about  $50\lambda_D$  and thus beam oscillations can exist having a wide range of wave-lengths whose frequency can be calculated by equation (4). Since  $n_1$  is far smaller than  $n$ , the beam frequency  $\nu_1$  will be less than  $\nu$ , but because of the Doppler effect the waves will appear to have different frequencies according to the direction from which they are observed. Transversely, the frequency may be  $\nu_1$  but longitudinally frequencies as high as  $v/\lambda$  may occur.

The oscillations that we have observed seem to be in general accord with this theory. Measurements of  $n$ , the concentration of ions, by means of the positive ion currents and calculation of the frequency  $\nu$  from this by equation (4) give values that agree reasonably well with the definite frequencies of about  $10^9$  that are found by using a Lecher system. The broad band of lower frequencies from  $10^7$  to  $10^8$  sec.<sup>-1</sup> which are observed only in the regions traversed by the primary electrons appear to correspond to beam oscillations which are spread over a range in frequencies by the Doppler effect and the non-uniform concentration of the primary electrons.

The smallness of the observed amplitude of the oscillations in the experiments is readily explained by the fact that the plasma oscillations do not transmit energy, or rather, that energy can be transmitted only because of some second order effects neglected in the elementary theory. Thus it is probable that the plasma oscillations may well be of sufficient amplitude to cause the electron scattering that brings about a Maxwellian distribution.

*Ionic Plasma Oscillations.*—In a recent paper J. S. Webb and L. A. Pardue<sup>6</sup> have described experiments which showed oscillations in low pressure discharges in air with frequencies that ranged from 1 to 240 kilocycles. The frequency increased with the current and with the voltage and decreased in general as the pressure increased. It seems possible that such oscillations might be ionic oscillations in agreement with equation (4) where  $m$  is now the mass of the ion. If the electron temperature is very high compared to the ion temperature, as should be expected at high pressure, the diffusion of the electrons will set up fields which tend to make the concentration of ions uniform so that equation (4) should apply.

A more complete analysis by Dr. Tonks, assuming a Maxwellian dis-

tribution of electrons but negligible ion temperature, shows that when the wave-length  $\lambda$  of the ionic oscillations becomes small compared to  $2\pi\lambda_D$  (calculated by equation (2) from the electron temperature) the frequency approaches the limiting maximum value given by equation (4), and the group velocity approaches zero. On the other hand, as  $\lambda$  becomes large compared to  $2\pi\lambda_D$  the wave velocity and the group velocity both approach the limiting maximum value

$$v = \sqrt{kT_e/m_p} = 3.9 \times 10^5 \sqrt{T_e m_e/m_p} \text{ cm. per sec.}$$

The frequencies  $v/\lambda$  thus decrease as the wave-length increases just as in the case of sound waves. These waves are in fact electric sound waves and their frequencies lie in the range of Webb and Pardue's experiments.

*Thermal Equilibrium of Plasma Oscillations.*—Any arbitrarily selected volume (of dimensions large compared to  $\lambda_D$ ) which we may choose within a plasma may be regarded as a harmonic oscillator, whose damping coefficient will be of the order  $\lambda_D/\lambda$ . Since electrons, with a velocity distribution corresponding to  $T_e$  are continually entering and leaving this selected volume or cell, the oscillator should acquire on the average  $1/2 kT_e$  of kinetic energy and  $1/2 kT_e$  of potential energy (electrostatic field) for each degree of freedom. The kinetic energy of the oscillator is included in that of the electrons which cooperate to produce the oscillation but the potential energy is a new factor, not included in the ordinary theory of electron motions.

If we have  $N$  independent cells per unit volume the total energy density of the electric field of the oscillations is  $3/2 NkT_e$ ; equating this to  $X^2/8\pi$ , where  $X$  is the field intensity, gives

$$\left. \begin{aligned} X^2 &= 12\pi NkT_e \\ \text{or } X &= 2.16 \times 10^{-5} \sqrt{NT_e} \text{ volts per cm.} \end{aligned} \right\} (5)$$

If there were no lower limit for the wave-length of harmonic plasma oscillations, we could put  $N = n$  the concentration of electrons, as in the Debye theory of the specific heats of solids. We have seen that the potential distribution  $f(x, y, z)$  in any plasma oscillator is arbitrary. Thus to find  $N$  we might expand  $f(x, y, z)$  into a Fourier's series, breaking off the series when we have reached the permissible grain size: the number of independent parameters thus fixes  $N$ . Perhaps a better way of attacking the problem is to assume that there are  $n$  independent oscillators per unit volume but those of shorter wave-length are non-harmonic and are highly damped so that for these the time average of the potential energy may be far less than the average kinetic energy.

For the present we can obtain an approximate value of  $N$  by assuming that harmonic oscillators are possible down to the wave-length  $\lambda = \alpha\lambda_D$ ,

where  $\alpha$  is a small numerical factor that probably lies between 2 and 10.

Thus  $N = 1/(\alpha\lambda_D)^3$  and from equation (5) and (2) the field strength  $X$  is

$$X^2 = 96\pi^{3/2}\alpha^{-3}(kT)^{-1/2}n^{3/2}e^3 \quad (6)$$

or

$$X = 1.17 \times 10^{-6}\alpha^{-3/2}n^{3/4}T^{-1/4} \text{ volts per cm.}$$

For a typical low pressure gas discharge in which  $n = 10^{11}$  and  $T = 10^4$  this gives  $X = 4$  volts per cm. if we assume  $\alpha = 3$ . This is the mean field intensity of plasma oscillations in thermal equilibrium with the ultimate electrons. According to equation (4) the frequency would be  $2.8 \times 10^9$  per second, corresponding to that of a radio wave of wave-length 10 cm.

*Electric Fields Due to a Random Distribution of Electrons.*—Let us compare these fields produced by the plasma oscillations with those to be expected from a random distribution of electrons. We assume provisionally that the positive charge in the plasma is continuous, and that the probability per unit volume for the occurrence of electrons is constant throughout the plasma. The radius of a sphere which contains on the average one electron is

$$r_1 = (3/4\pi n)^{1/3} = 0.62 n^{-1/3} \quad (7)$$

The average field  $X_1$  at the center of the sphere averaged for all positions of the electron is

$$X_1 = 3e/r_1^2 = 1.12 \times 10^{-6}n^{2/3} \text{ volts cm.}^{-1} \quad (8)$$

The effect of all the other electrons (out to  $r = \infty$ ) increases the average field only about 10.3%. Thus the average field  $X_a$  at any point in space is

$$X_a = 1.23 \times 10^{-6}n^{2/3} \text{ volts cm.}^{-1} \quad (9)$$

This field is always stronger than that of the plasma oscillations, as given by equation (6). In our example in which  $n = 10^{11}$ , we find  $X_a = 26.5$  volts per cm. as compared with our estimate of 4 volts per cm. for the plasma oscillations.

Most of the effects produced by the local fields depend upon the square of the field strength so that we are usually interested in the root-mean square field which we shall denote by  $X_m$ . If the electrons are regarded as point charges the value of  $X_m$  at any fixed point is infinite. In the neighborhood of any given electron, however, according to the Boltzmann equation the average concentration of electrons is

$$n\epsilon^{-a/r}$$

where  $a = e^2/kT = 1.66 \times 10^{-3}/T$  cm. (10)

We thus find that the mean field  $X_m$  which acts on any electron because of the presence of all the others is given by

$$\left. \begin{aligned} X_m^2 &= 4\pi nkT \\ \text{or} \\ X_m &= 1.25 \times 10^{-5} \sqrt{nT} \text{ volts cm.}^{-1} \end{aligned} \right\} (11)$$

from which  $X_m = 396$  volts per cm. if  $n = 10^{11}$ ,  $T = 10^4$ .

The mean field  $X_r$  due to all electrons that lie at a distance greater than  $r$  (when  $r \gg a$ ) is found to be

$$\left. \begin{aligned} X_r^2 &= 4\pi ne^2/r \\ \text{or} \\ X_r &= 5.08 \times 10^{-7} \sqrt{n/r} \text{ volts cm.}^{-1} \end{aligned} \right\} (12)$$

If we put  $r = \lambda_D$  as given by equation (2)

$$X_D = (4\pi ne^2)^{3/4} (kT)^{-1/4} = 1.93 \times 10^{-7} n^{3/4} T^{-1/4} \text{ volts cm.}^{-1} \quad (13)$$

Comparing this with equation (6) which gives the field due to plasma oscillations we see that the two equations are identical if  $\alpha = 3.31$  which is a reasonable value. We may conclude that the fields due to plasma oscillations in thermal equilibrium with the electrons are of about the same magnitude as the fields acting at any point originating from all electrons at distances greater than  $\lambda_D$ . We have assumed, however, that the electrons are distributed at random, that is, as if they were uncharged. According to Debye-Hückel, the charges cause the distribution to be more uniform so that the field due to electrons at distances greater than  $\lambda_D$  should disappear. The field of the plasma oscillations thus take the place of the field that is forbidden by the Debye-Hückel theory. The definite frequency characteristic of these oscillations makes them, however, essentially different from the irregularly fluctuating fields that they replace.

*Energy Delivered to Electrons by the Field.*—If a steady electric field of intensity  $X$  acts for a time  $\tau$  on an electron which is initially at rest, the electron acquires the energy

$$E = X^2 e^2 \tau^2 / 2m$$

The fields acting on a given electron resulting from a random distribution of neighboring electrons fluctuate rapidly in direction and magnitude. If  $\tau$  is the time of relaxation of these fields we may consider roughly that during each interval  $\tau$  the field is steady, and of magnitude  $X$ , but in each interval the direction is independent of that in the preceding or following intervals. In a time  $t$  which is large compared to  $\tau$  the total energy acquired by an electron is then

$$E = X^2 e^2 \tau t / 2m \quad (14)$$

The field produced by electrons at a distance  $r$  will fluctuate at a rate such that, approximately

$$\tau = r/v$$

where  $v$ , the velocity of the electrons, is

$$v = \sqrt{8kT/\pi m} = 6.23 \times 10^5 \sqrt{T} \text{ cm. sec.}^{-1}$$

By integrating (14) over all values of  $r$  from 0 to  $r$  we find that the rate  $W_r$ , at which energy is acquired by a given electron is

$$W_r = \pi^{3/2} e^4 n (2mkT)^{-1/2} \log_e \left( \frac{rkT}{1.78e^2} \right) \text{ erg. per second.} \quad (15)$$

By dividing this into  $\frac{3}{2} kT$  we find the time of relaxation of the electrons, that is, the time required for an electron to gain or lose the average energy. Multiplying this time by the velocity  $v$  we find an approximate value for  $\lambda_e$ , the free path of an electron. This free path, which may be defined as the average distance an electron travels before losing most of its energy of motion in that direction, is thus

$$\left. \begin{aligned} \lambda_e &= \frac{6}{\pi^2} \frac{(kT)^2}{e^4 n} \frac{1}{\log_e \left( \frac{rkT}{1.78e^2} \right)} \\ \text{or} \\ \lambda_e &= \frac{9.5 \times 10^4 T^2}{n \log_{10} (r/1.78a)} \end{aligned} \right\} \quad (16)$$

where  $a$  is given by equation (10). We have seen from equation (12) that the field produced by the more distant electrons is small compared to that due to the nearer electrons. However, because of the fact that the field of the distant electrons fluctuates more slowly, this field becomes important in determining the energy transfer between electrons. Thus, according to equation (15) the rate of energy transfer increases indefinitely as  $r$  approaches infinity. It is clear that equations (12) and (15) are applicable only for values of  $r$  that are not much greater than  $\lambda_D$  since the field of electrons at a greater distance fluctuates periodically at a frequency which no longer decreases as  $r$  increases (plasma oscillations).

In our example  $n = 10^{11}$ ,  $T = 10^4$  and thus by equation (2)  $\lambda_D = 2.2 \times 10^{-3}$  cm. Putting these in equations (10) and (16) we find  $a = 1.66 \times 10^{-7}$  and the free  $\lambda_e$  is 24.6 cm. The experimental data obtained with mercury arcs shows effective free paths very much shorter than this. With a 0.1 ampere arc in a 3-cm. tube containing mercury vapor saturated at 15° C. we found<sup>7</sup>  $T = 36000^\circ$  and  $n = 3.4 \times 10^9$  and yet the Maxwellian distribution, which was destroyed at the tube walls by the removal of the fastest electrons, re-established itself within one centimeter, so that  $\lambda_e$  must have been less than 1 cm. But under these conditions equation (2) gives  $\lambda_D = 2.3 \times 10^{-2}$  cm. and by equations (10) and (16)  $a = 4.6 \times 10^{-8}$  cm. and  $\lambda_e = 6600$  cm. Thus the fields due to a random distribution of electrons are not capable of accounting for the observed short free path.



The fields due to the plasma oscillations also deliver energy to the electrons. The oscillations of large wave-length, being harmonic and only slightly damped, deliver very little energy, but the plasma oscillations of the shortest wave-length,  $\alpha\lambda_D$ , are highly damped and the electrons which are being acted on are moving distances comparable to  $\alpha\lambda_D$  during a single period of the oscillations. Thus as a rough approximation we may consider the time of relaxation  $\tau$  of the field  $X$  to be equal to  $1/2\nu$ , a half period. The rate at which energy is delivered is then by equations (14) and (4)

$$W_0 = X^2 e^2 \tau / 2m = 1/4 X^2 e \sqrt{\pi/mn} \quad (17)$$

Assuming that the oscillations are in thermal equilibrium with the electrons,  $X$  is given by equation (6) so that equation (17) becomes

$$W_0 = \frac{24\pi^3 \alpha^{-3} e^4 n}{(mkT)^{1/2}} \quad (18)$$

Comparing this with the rate at which energy is delivered by the field of electrons distributed at random, equation (15), we find

$$W_0/W_r = \frac{82.1}{\alpha^3 \log_{10} (r/1.78 a)} \quad (19)$$

As before we may identify  $r$  with  $\lambda_D$ ; then if  $n = 10^{11}$  and  $T = 10^4$  we find that  $W_0 = W_r$  if  $\alpha = 2.8$ . Thus plasma oscillations in thermal equilibrium, although their fields are much weaker than those produced by the nearer electrons, contribute about as much as the latter to the energy interchanges between electrons. Any complete theory of the kinetics of a plasma cannot ignore the plasma oscillations.

*Plasma Oscillations of Greater Amplitude.*—To account for the experimentally observed electron-scattering the amplitude of the plasma oscillations must be far greater than that which corresponds to thermal equilibrium with the electrons. Then, too, with thermal equilibrium, the maximum energy of the electrical oscillations in a coupled Lecher system would be  $kT$  whereas actually the oscillations that Penning and we have observed are far more intense than this.

In a mercury arc or a discharge with a hot cathode, ions are continually being generated in a random manner throughout the plasma, and are diffusing to the walls of the tube and to the anode where they recombine with electrons. The electrons set free by the ionization process (secondary electrons) usually have far higher energies than the ultimate electrons in the plasma so that the secondaries are rapidly separated from the ions which were simultaneously produced. Thus the ionization tends to create a random distribution, whereas the electric field in accord with the Debye-Hückel theory, tends to make the field more uniform. In this way energy

is delivered to the plasma oscillations, particularly to those of large wave-length, so that the amplitudes become larger than those corresponding to thermal equilibrium.

In a plasma containing  $n$  electrons per unit volume, let us consider a sphere of volume  $V$  and radius  $r$ . With a uniform distribution of electrons there would be  $nV$ , which we may call  $q_0$ , electrons in the sphere. But with a random distribution the actual number  $q$  will differ from  $q_0$  by an amount whose average value is  $\sqrt{q}$ . Thus the average charge of the sphere is  $\pm e\sqrt{q}$ . Assuming this charge to be uniformly distributed within the sphere, the total electrostatic energy of the field (of which  $5/6$  lies outside the sphere) is

$$E = (3/5)qe^2/r = (4\pi/5)e^2r^2n \quad (20)$$

and the field at the surface of the sphere is

$$\left. \begin{aligned} X_r^2 &= (4\pi/3)ne^2/r \\ \text{or} \quad X_r &= 2.9 \times 10^{-7} \sqrt{n/r} \text{ volts per cm.} \end{aligned} \right\} (21)$$

If the sphere is of large size compared to  $\lambda_D$  the electrostatic energy given by equation (20) becomes the potential energy of a spherical plasma oscillation which is only slowly converted into thermal energy. Let us compare the energy  $E$  of equation (20) with the energy  $1/2kT$  which is the average potential energy of the plasma oscillation in thermal equilibrium. Expressing  $kT$  by equation (2) in terms of  $\lambda_D$  we find

$$\frac{E}{1/2kT} = \frac{2}{5} \left( \frac{r}{\lambda_D} \right)^2$$

We see that the energy associated with a sphere of radius  $r$  is equal to  $1/2kT$ , the value required for thermal equilibrium, if  $r = 1.58\lambda_D$ , but this energy increases in proportion to  $r^2$ . Thus, if  $n = 10^{11}$ ,  $T = 10^4$ ,  $\lambda_D = 2.2 \times 10^{-3}$  and we had initially a random distribution of electrons, the energy of the plasma oscillations associated with a sphere of 3 cm. radius would be  $2 \times 10^6$  times greater than if there were thermal equilibrium.

This may possibly account for the amplitude of the observed oscillations detected by the aid of a Lecher system, but it hardly seems able to explain the observed scattering which must depend on the plasma oscillations of shorter wave-length, for these are not so far from the conditions of thermal equilibrium.

We are now investigating other possible causes that may produce plasma oscillations of large amplitude.

<sup>1</sup> Langmuir, *Phys. Review*, **26**, 585 (1925); *Zeit. Physik*, **46**, 271 (1927).

<sup>2</sup> Ditmer, *Phys. Review*, **23**, 507 (1926).

<sup>3</sup> Penning, *Nature*, Aug. 28 (1926), and *Physica*, **6**, 241 (1926).

<sup>4</sup> The possibility of gaseous crystals in stellar atmospheres has been recently considered by Eddington, *Monthly Notices, Roy. Astron. Soc.*, **88**, 369 (1928).

<sup>5</sup> Debye and Hückel, *Phys. Zeitsch.*, **24**, 185, 305 (1923).

<sup>6</sup> *Bull. Amer. Phys. Soc.*, **3**, 19 (1928).

<sup>7</sup> Langmuir and Mott-Smith, Jr., *General Electric Review*, **27**, 766 (1924). Table XIV.

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## EVIDENCE THAT THE COSMIC RAYS ORIGINATE IN INTERSTELLAR SPACE

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If it may be regarded as established by the evidence heretofore advanced<sup>1</sup> that the cosmic rays are the signals sent out through the heavens of the creation of the common elements out of positive and negative electrons, the next important question to attempt to answer is "where are these creative processes going on?" To this question there are two different sorts of possible answers, as follows:

(1) In the stars where pressures, densities and temperatures may, one or all, be enormously high, or else

(2) In interstellar space where pressures, densities and temperatures are all extraordinarily low.

In both of these localities matter exists under extreme and as yet unexplored conditions, and in view of the history of the last thirty years of physics, it would no longer be surprising if matter were again found to behave in some hitherto unknown and unexpected way as a new field of observation is entered.

Of the two foregoing alternatives we think it possible to eliminate the first and to establish the second with considerable definiteness, and that for the two following reasons.

*First.*—If the mere presence of matter in large quantities and at high temperatures favored in any way the atom-building processes which give rise to the cosmic rays, then it is obviously to be expected that the sun, in view of its closeness, would send to the earth enormously more of them than could any other star. But the fact is that all observers are agreed that the change from midday to midnight does not influence at all the intensity of the cosmic rays. This can only mean that *the conditions existing in and about the sun, and presumably also in and about other stars as well, are unfavorable to the atom-building processes which give rise to these rays.*

Since, however, the rays do come to us at all times, day and night, and, according to all observers, at least very nearly equally from all directions—according to some, as accurately as they have as yet been able to make the