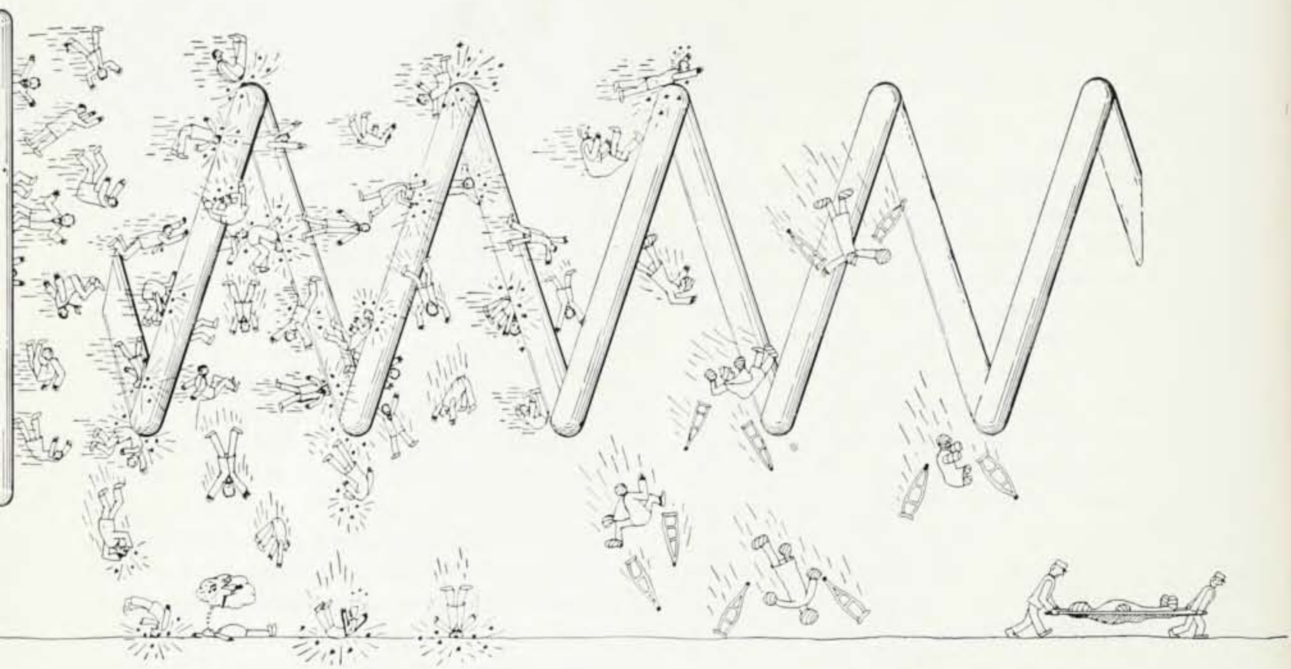
SPACE-CHARGE



Often the physicist, when he has found what he feels to be a satisfactory explanation of why a thing works, stores the answer and forgets the problem. Here is the story of how engineers took the physicists' ideas concerning plasma oscillations, used and developed them in their work, and now offer their results to the physicists for their use in new fields.

There is a good deal to physics besides nuclei, uncertainty, and relativity, as every hopeful student learns. Much of it, however, has disappeared from the forefront of science, some of it moving to the engineers, and the rest remaining mostly a storehouse of tools, useful in the free-for-all attack on the current frontier. I can remember that spectroscopy was once a romantic subject, with its explanation of the "nebulium" lines. So was the conduction of electricity through gases.

When, in 1930–31, Compton and Langmuir published in the Reviews of Modern Physics their much-referred-to articles on the conduction of electricity through gases, they summed up a great deal of pioneering work extending back through the last century. Thenceforward the field tended to break up into its component parts. The flow of electrons through high vacua became the province largely of the engineers who design and invent vacuum tubes and of the experts in electron optics and electron microscopy. Arcs and gas discharges in circuit breakers and thyratrons were important to power engineers. The fundamental problems of collision and ionization became nice tasks in the theoretical and experimental working-out of quantum mechanics. Although cathode emission, surface phenomena, and even the discharge as a whole are still studied intelligently by the relatively few men who work in

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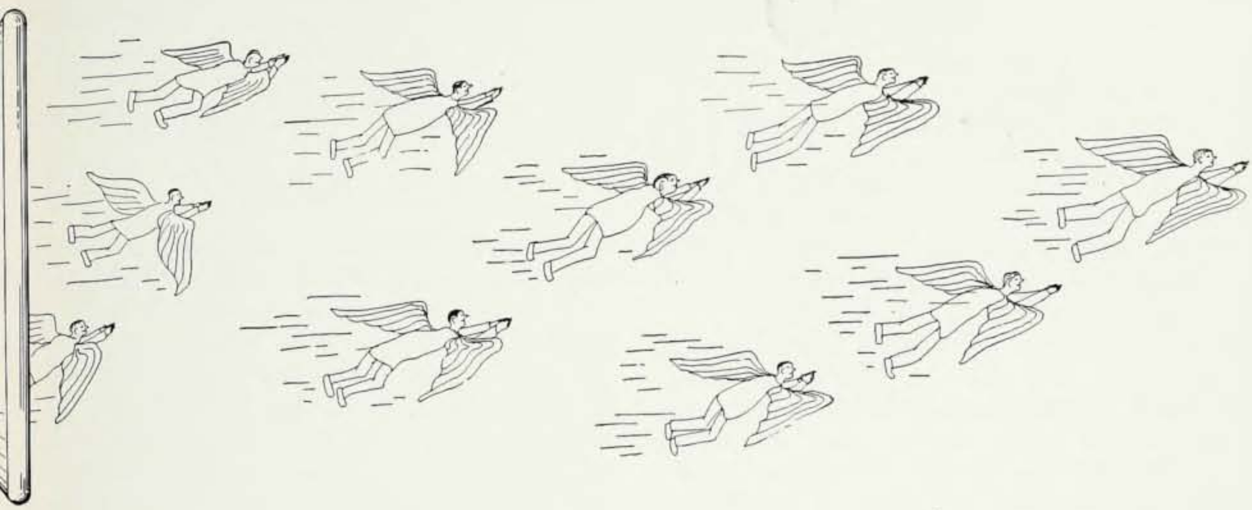
by *John R. Pierce*



Sketches by John G. Andary after Andrew V. Haeff

Haeff shows the electrons as angels who fly along and amplify the microwave signal. They have an easier time working with other angels, in the double-stream tube, than in doing work on the gross material circuit of the traveling-wave tube.

the field of physical electronics, no one will claim that the conduction of electricity in gases provides front page news these days.

I think that it might be interesting to trace some of the later consequences of ideas contained in that early paper in the Reviews of Modern Physics, just to see what happens to the tools supplied by physicists as they pass into the world of engineering. This is partly what I hope to do, because one of these ideas, that of plasma oscillations, which Langmuir and Tonks had first published in 1929, is directly related to a very new microwave device, the electron wave or double stream amplifier. It also turns out that this movement of ideas is not in one direction only. The very ideas taken by the engineers from the physicists and developed by them appear to be passing back into a currently lively branch of physics, or of astronomy, at any rate.

Plasma Oscillations

Langmuir and Tonks originally proposed their ideas and equations concerning plasma oscillations as an explanation for the electrical oscillations, in

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the frequency range of some hundreds of megacycles, which can be observed in operating gas tubes regardless of circuit connections. They ascribed these oscillations to fluctuations of density, and hence of charge, in the plasma, that neutral mixture of electrons and positive ions in equal quantities which forms a major portion of the discharge path in most gas tubes.

Electrons, which are light and are easily moved by electric fields, have mass or inertia like a pendulum. This is one essential ingredient of an oscillating system. The other is a restoring force, which in the case of a pendulum is the force of gravity, tending to pull the pendulum straight down. In the plasma, the restoring force is electric.

If the electrons are suddenly bunched together in one place they tend to fly apart because of electrostatic repulsion. Because they are so light, they fly apart so quickly that the heavy positive ions scarcely have time to move. As in the case of a swinging pendulum, the inertia of the electrons causes them to overshoot, and then again they are forced back toward a distribution of no net charge and no electric field. Thus, any uneven distribution of charge is not just wiped out by the quick movement of the electrons, but it results rather in an oscillation of the electrons with a frequency that can be calculated. This oscillating disturbance can constitute a standing wave, like the vibrations of air in an organ pipe, or a traveling wave, like the waves of sound in the open. It turns out that the greater the charge density, the faster the oscillation. If heavier particles were concerned, they would oscillate more slowly than electrons.

Over a period of some years physicists compared the plasma frequency, as given by the equation of Langmuir and Tonks, with the frequency of observed oscillations. A rough agreement was found, but it is hard to tell just what the electron charge density is in a gas tube. As a matter of fact, some would now argue that the agreement was largely fortuitous, and that in many cases the conditions assumed in calculating the plasma frequency could not exist stably. A rough general agreement can be explained, because any other frequency associated with electrons is apt to depend on the same parameters in about the same way. Whatever the plasma frequency has to do with gas discharges, however, it is a valid consequence of an assumed set of conditions, and it is bound to show up when conditions are right.

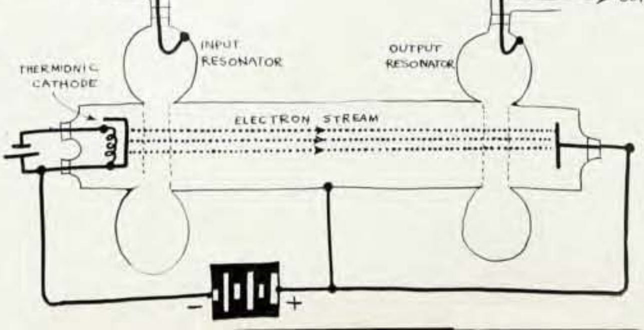
The Klystron

Now, whereas the density of electrons and their velocity distribution is uncertain in gas discharges, it is accurately known in vacuum tubes, in which a stream of electrons of a given density and velocity can be injected into a space which is essentially free of the influence of electric and magnetic fields. In 1939 a new vacuum tube came along in which long electron streams are very important. It is the klystron, a tube for amplifying microwave signals whose wavelengths are very much shorter than radio waves, of the order of centimeters, and whose frequencies are measured in thousands of millions of cycles per second (megacycles) in contrast to radio's thousands of cycles (kilocycles). The important thing to us here is the long electron stream.

Certainly the uniform distribution of electron charge which was assumed in the plasma oscillation equations is present in the klystron beam. If the positive charges are not distributed throughout the beam as ions, they can at least reside on the walls of the tube through which the beam passes, and a strong magnetic field in the direction of electron flow can be used to keep the electrons from moving out radially and joining the positive charges.

It can be no surprise, then, that the next appearance of the ideas involved in plasma oscillations came about in connection with the klystron. Hahn, and later Ramo, showed by an extended analysis that, for small signals, the microwave disturbance

When the klystron amplifies microwave signals, the field of the input resonator starts the electrons "swinging" toward and away from one another. The electrons become bunched together and constitute an alternating current which gives rise to the amplified output.



in the electron beam of a klystron can be represented by oscillations or waves of the electron space-charge, waves which are very similar to the simpler plasma oscillations that Langmuir and Tonks had discussed earlier. In the particular case of the klystron amplifier, the signal applied to the input resonator of the tube periodically gives the electrons a little more or a little less velocity—starts them swinging, so to speak. As the electrons move along the tube this velocity is changed to a displacement, involving an uneven electron charge density and hence an electron convection current. This current, passing through the output resonator, gives rise to the amplified output of the tube.

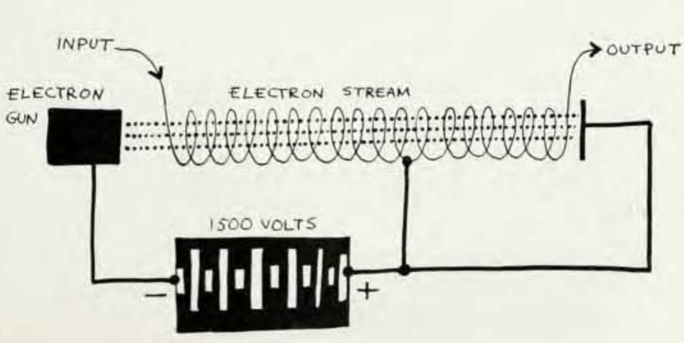
More generally, Hahn and Ramo showed that a disturbance on a beam of electrons can be represented as two space-charge waves, one traveling slower than the average electron velocity and the other faster. What we see when we examine a disturbance of the electron flow is an interference between, or adding up of, the two waves, as one passes the other. When the amplitudes of the two waves are the same, as in the klystron, first the velocities add up and the currents cancel (as at the input of the klystron) and then, further on, the currents add up and the velocities cancel (as at the output of the klystron). If the beam were still longer, so that the waves could slip further past one another, the currents would again cancel and the velocities add up, just as at the input.

The Traveling Wave Tube

One might think that, once it had been used in explaining the behavior of the klystron, the concept of space-charge waves would be used in connection with other vacuum tubes. This indeed proved to be the case. Toward the end of the war a new microwave amplifier called the traveling wave tube appeared, and since the war it has been extensively developed. In the traveling wave tube the wave nature of the device is even more apparent than in the klystron. In fact, it consists of nothing but a long coil of wire, or a helix, which is capable of propagating an electromagnetic wave at microwave frequencies, and an electron beam which is shot along the helix so as to interact with the electric field of the electromagnetic wave. The wave in the helix travels at about the speed of light along the wire, and hence progresses much more slowly along the axis of the tube—at perhaps a thirteenth the speed of light. The stream of electrons, accelerated by fifteen hundred volts, will have about the same speed as the axial speed of the wave on the wire. We can imagine that there will be a strong cumulative action as the electrons travel along in step with the fields of the helix, which gather them up something like a rolling snowball. The result of this interaction is that the signal on the helix grows stronger as it travels along, so that at the output its power may have increased as much as a thousand times.

A mathematical analysis of the traveling wave tube discloses a new type of wave. It isn't exactly an electromagnetic wave, like waves of light, or like radio waves in the open or in wave guides and helices in the absence of free electrons, for it involves not only electric and magnetic fields but fluctuations in the velocity and convection current of a stream of free electrons as well. Moreover, purely electromagnetic waves don't gain in energy as they travel. It isn't just like the space-charge waves in the klystron, either, for it involves electromagnetic fields. And the waves in the klystron do not increase in amplitude as they travel. It is a mixed wave, involving the phenomena of both electromagnetic and space-charge waves. Its new and important property is its property of growing stronger as it travels, where the waves in the klystron grow neither weaker nor stronger as they move along.

The very simple wave nature of the traveling wave tube is its chief virtue. In a klystron only a relatively narrow band of frequencies, those which



In a traveling wave tube a microwave signal is guided by a spiral wire or helix which winds around the electron stream. The signal gains power from the electrons which it forces into step.

are close enough to the normal resonant frequency of the input and output resonators to excite them effectively, can be amplified. The traveling wave tube has no resonant circuits. It is simply a wave transmission path which can amplify signals over a broad range of frequencies that differ by as much as a thousand megacycles.

Ion Oscillations

The increasing wave in the traveling wave amplifier does not mark the end of space-charge wave phenomena in vacuum tubes. The next waves were found quite accidentally through leaving a little gas in a traveling wave tube. The gas was ionized by the electron beam. The effect of this ionized gas was first noticed as a fluctuation in the fraction of the electron beam current intercepted by the helix, and as a corresponding modulation of the signal amplified by the tube.

An analysis of the situation was made along the lines initiated by Langmuir and Tonks. Here one dealt with a cloud of ions almost at rest, which could oscillate with a plasma frequency delineated by the ion charge density and the mass of the ions. In addition, there was a beam of fast electrons shooting through the ion cloud. What would be the effect of the fast beam of electrons? The analysis disclosed that at frequencies a little below the ion plasma frequency the interaction of the oscillating ions and the fast electrons could give rise to a sort of combined electron-and-ion space-charge wave which, like the wave in the traveling wave tube, would increase as it traveled. This growing wave, combined with a small amount of feedback, could explain the fluctuations observed in the electron stream of the traveling wave tube. Further, the predicted frequencies, which lay around one megacycle, were in the range of the frequencies observed (it isn't easy to be sure of the charge density or the mass of the ions).

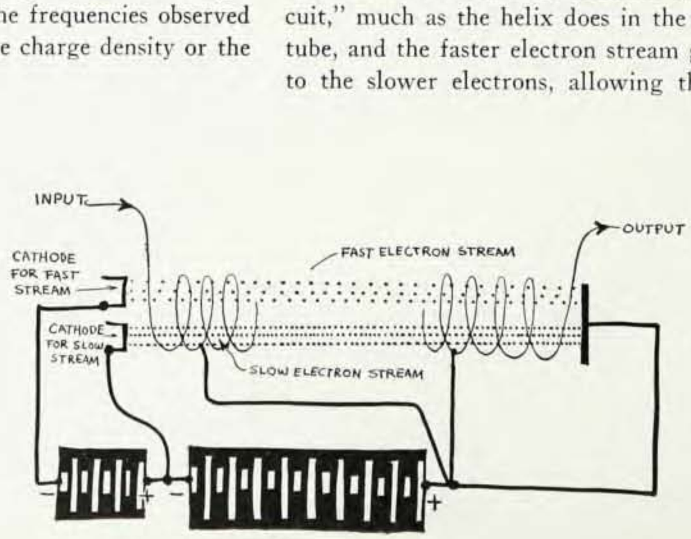
Here was an increasing wave of a purely ionic nature, involving only the inertia and the electric fields of the particles themselves, and not, as in the case of the traveling wave tube, involving the electromagnetic waves associated with a "circuit." Further, the analysis used in explaining the noise in the beams of traveling wave tubes, besides showing that shooting electrons past an oscillating plasma of ions could give rise to increasing waves, showed that, if a magnetic field were present, there should be increasing waves of the frequency of ions oscillating (or circling) in the magnetic field as well. In either case, the kinetic energy of the fast electron stream supplied the energy necessary for the growth of the waves as they traveled, and the oscillation of the ions played much the same part as the electromagnetic circuit does in a traveling wave tube.

Electron Wave Amplifiers

These increasing waves in the electron stream of the traveling wave tube were sheer nuisance. The next increasing waves to appear in an engineering context were not a nuisance, as one can see in reports from the Naval Research, Bell Telephone, and RCA Laboratories. They were used to obtain power amplifications of millions of times in the microwave region.

The new tube has two electron streams with slightly different velocities, produced by hot filaments held at different potentials, and traveling side by side over a considerable distance. When a disturbance of microwave frequency is impressed on these two streams, as, for instance, by a short helix fed with the input signal, an increasing wave is set up in the two streams. Here, if we wished to make a rather artificial distinction, we might say that the slow stream of electrons acts as the "circuit," much as the helix does in the traveling wave tube, and the faster electron stream gives up energy to the slower electrons, allowing the wave to in-

In the double-stream amplifier the stream of slow electrons takes power from the stream of fast electrons and a wave impressed on both gets stronger as it travels down the tube.



crease as it travels. When fast-moving, light electrons rather than slow-moving, heavy ions are involved, an increasing wave is attained at much higher frequencies, and so one attains a power amplification of millions of times in the microwave frequency range.

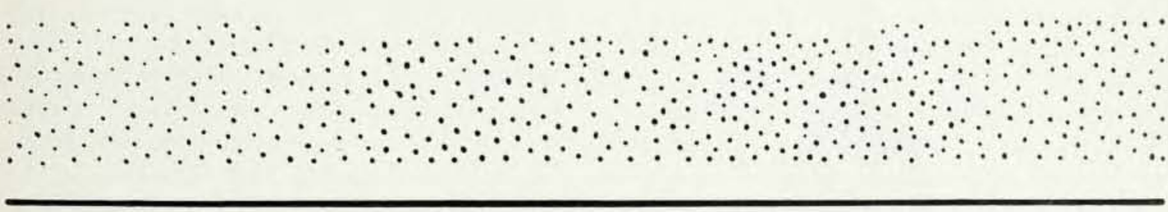
To the unwary, the device might look much like the klystron save for the substitution of short helices for resonators. But there is a fundamental difference. The space-charge waves set up in the electron stream of a klystron do not increase with distance; they merely change in relation to each other and so provide a means for turning a fluctuation in velocity into a fluctuation in current. The wave in the electron wave or double stream amplifier, however, grows with distance just as does the wave in the traveling wave tube, and the gain of the tube can be increased simply by making the distance of travel between the input helix and the output helix greater.

The traveling wave tube involves an increasing wave and so does the new tube. Is the new tube better in some practical way? It does have certain advantageous features. A traveling wave tube must have an electromagnetic circuit with a precisely correct and uniform velocity of propagation, matching the electron velocity, all along the electron stream. At very high frequencies, say, around thirty thousand megacycles per second, where the wavelength is only one centimeter and the transverse dimensions of the circuit must be considerably smaller, it is hard to make suitable circuits for traveling wave tubes. Too, when we have the circuits we must shoot the electrons along very close to them to get effective interaction. Some electrons are inevitably lost. The loss of electrons of course reduces the gain of the tube, and it can make the apparatus undesirably hot. Haeff has amusingly compared the traveling wave tube and the new tube in two drawings. In one, electrons pouring from the electron gun of a traveling wave tube are knocked silly in hitting the helix. In the other, the electrons from the two cathodes of an electron wave tube angelically fly along in empty space, not at all hindered in their task of amplifying a microwave signal.

Radio Astronomy

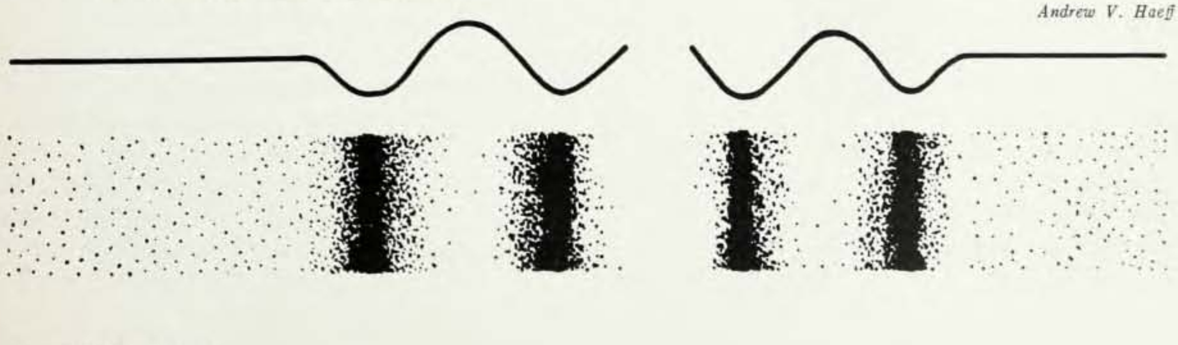
So far we have seen the ideas set forth in Langmuir's and Tonks' speculations concerning the physical phenomena of a gaseous discharge gradually expand and develop as they were used in the analysis and development of microwave amplifier tubes. I said at the beginning, however, that some of this development has been reflected back toward physics, to appear in a field quite different from that which Langmuir and Tonks originally had in mind. That field is astronomy.

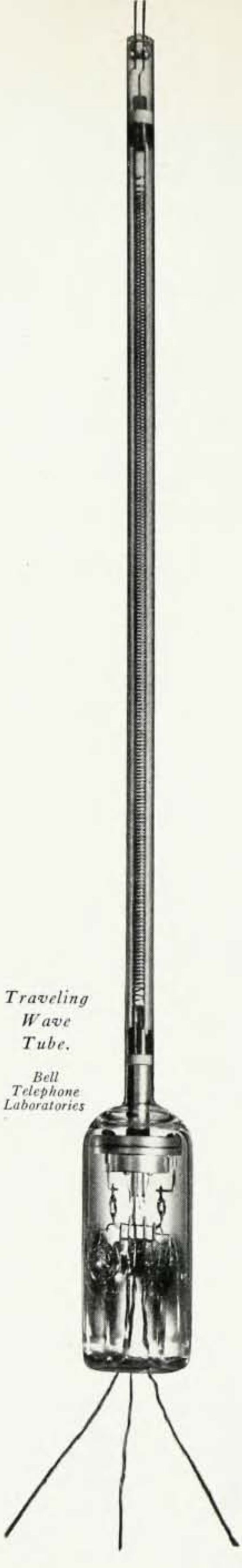
The observation of radiofrequency radiation from the heavens goes back to 1933, when Jansky found radiation from the Milky Way while studying



The waves are originating in the center of the electron stream when it is disturbed.

Andrew V. Haeff





Traveling Wave Tube.

Bell Telephone Laboratories

reception at a wavelength of fourteen meters. In 1942 Southworth measured radiation from the sun at one, three, and ten centimeters. It was in 1946, however, that Bowen and his colleagues, working at Sydney, Australia, observed something really startling in connection with two hundred megacycle radiation from the sun. Southworth had found radiated powers corresponding fairly well with the visual surface temperature of the sun, around six thousand degrees Centigrade. Bowen found an inconstant radiation which rose to peaks corresponding to temperatures as high as a million degrees! These peaks of radiation were found to be associated with sunspots; the mechanism which produces them was not immediately apparent. Since then, large bursts of radiation have been observed at other frequencies.

We are now in a fairly good position to speculate about this matter. We have seen that the presence of a cloud of charges which can oscillate, a cloud of either positive ions or electrons, together with a source of energy, such as a fast stream of electrons passing through the cloud, can give rise to waves which grow in amplitude as they travel. Such phenomena can occur in many frequency ranges, from the frequencies of oscillation of ions and electrons in magnetic fields up to and above the ion and electron plasma frequencies.

Bailey of the University of Sydney proposed something similar in Nature (April 17, 1948). His proposed source of energy is not a stream of fast particles, but the existence of an electric field in an ionized gas. Then, in the Physical Review for Nov. 15, 1948, Haeff proposed that the same waves that give amplification in the electron wave tube might account for the strong noise radiation from the sun. In the Physical Review for Sept. 1, 1948, Bohm and Gross turned the matter around and suggested that plasma oscillations in the very tenuous dust of space might accelerate cosmic ray particles, linear accelerator fashion. Other physicists have speculated about these matters privately.

Whatever the outcome, one thing seems certain. The space-charge waves deduced by Langmuir and Tonks, and transformed and developed in their application to microwave vacuum tubes, have got back, with something new clinging to them, into a field of physics entirely different from that in which they originated.