PHYSICAL REVIEW LETTERS

VOLUME 14 12 APRIL 1965 NUMBER 15

INCOHERENT SCATTER FROM PLASMA OSCILLATIONS IN THE IONOSPHERE*

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(Received 16 March 1965)

With powerful radar installations, one can observe incoherent radar backscatter from the ionosphere provided the transmitter frequency is much larger than the plasma frequency, $\nu_p = (ne^2/m\pi)^{1/2}$, of the ionospheric electrons. The frequency spectrum of the returned power gives directly the spectrum of electron density fluctuations normally present in the ionospheric plasma with wavelength $\lambda/2$ where λ is the radar wavelength. For most experiments, it is true that

$$\alpha^{-2} \equiv (4\pi D/\lambda)^2 = 4\pi kT/\lambda^2 ne^2 \ll 1, \tag{1}$$

where D is the electron Debye length, T the electron temperature, and n the electron number density. Most of the returned power then lies in a central line with a frequency width of the order of the Doppler spread for ion thermal velocities.[1] However, theory[2] predicts that a smaller amount of power will be returned in a pair of sharp lines separated from the transmitter frequency by $\pm\nu_r$, where (in the absence of a magnetic field)

$$\nu_r = \nu_p(1 + 3\alpha^{-2})^{1/2}. \tag{2}$$

These "plasma" lines are caused by the Doppler shift introduced by scattering from weakly damped longitudinal electrostatic plasma oscillations with frequency ν_r, wavelength $\lambda/2$, and phase velocity $v_{\text{ph}} = \nu_r\lambda/2$. We wish to report the observation of these plasma lines at the Arecibo Ionospheric Observatory for ionospheric altitudes between 150 and 600 km where the plasma frequency lies between 3 and 8 Mc/sec. The radar wavelength is 70 cm (430 Mc/sec).

Four experiments have been performed (30 January, 1 February, 11 February, and 4 March 1965), each of which detected plasma line echoes. Some of the data obtained on 4 March 1965, between 1416 and 1533 local time, are displayed in Fig. 1. Transmitter pulses of duration 100 μsec and peak power 2.1 MW were emitted vertically at a rate of 220 pulses/sec. A bandpass receiver with bandwidth $B = 125$ kc/sec was tuned to a frequency separated from the transmitter frequency by an amount ν. The received power (which is mostly noise) was then measured as a function of time delay which is readily converted into the altitude of the pulse. The results are computer averaged over 4.8×10^4 pulses. The experiment is then repeated for a sequence of values of the frequency offset ν. The values of α for the data reported range between 7 and 12.

The sharp spikes on a curve in Fig. 1 occur at altitudes for which the plasma line frequency is equal to ν. In general, there are two such altitudes—one above and one below the region of maximum electron density located near 270 km. The width of these spikes is due mainly

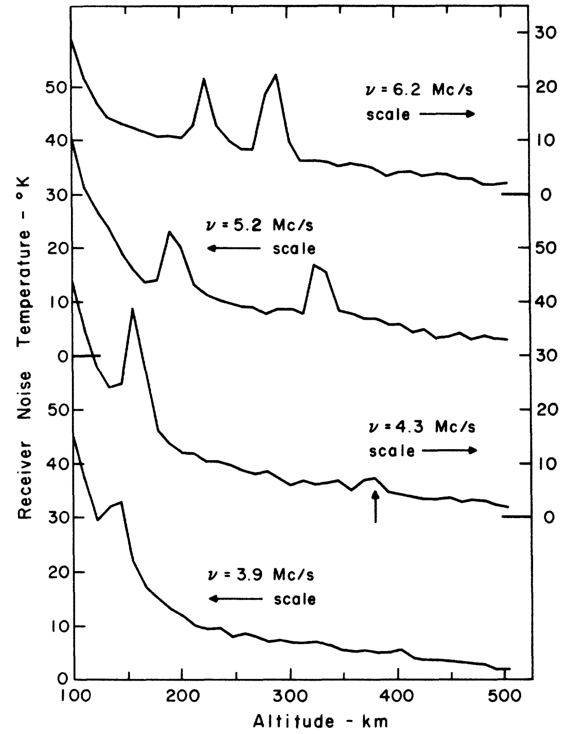

FIG. 1. Receiver noise temperature versus altitude. ν is the frequency shift from the transmitted frequency. Peaks represent regions of the ionosphere where the plasma frequency is ν. The noise temperature is measured using its asymptotic value of about 300°K as a zero level. The monotonic background decrease of noise temperature with altitude is an instrumental effect.

to the transmitter pulse length and the extent of the height interval for which the ionospheric plasma line frequencies lie within the bandwidth of the receiver. After a small correction for magnetic field and electron temperature effects, profiles for electron density n can be obtained from the ν_r-versus-altitude curve. Our present values for n at a few altitudes are compatible with previous (less accurate) measurements at Arecibo from ionosondes and the main (ion) component of ionospheric backscatter.[3]

The intensity of the plasma line is seen to depend strongly on plasma line frequency—in agreement with the prediction of a nonequilibrium theory[4] which allows for the presence of energetic photoelectrons. In thermal equilibrium the total intensity of the plasma lines is predicted to be smaller than that in the ion component by a factor α^{-2}. For a more general non-Maxwellian, one-dimensional, electron velocity distribution function $F(v)$, we can express the departure from thermal equilibrium by a velocity-dependent temperature, $T(v)$, defined in terms of the logarithmic derivative of $F(v)$:

$$mv/kT(v) \equiv -F^{-1}(v)(dF/dv). \tag{3}$$

In the absence of collisions[5] and for $\alpha \gg 1$, the rate of excitation of plasma oscillations[6] is proportional to $F(v_{\mathrm{ph}})$, and their rate of Landau damping is proportional to $(dF/dv)_{v=v_{\mathrm{ph}}}$. The total steady-state intensity in the plasma line is then inversely proportional to the logarithmic derivative of F, and the ratio of the intensity in the plasma lines to the intensity in the ion component is $\alpha^{-2}(v_{\mathrm{ph}}) = 4\pi kT(v_{\mathrm{ph}})/\lambda^2ne^2$.

In the daytime ionosphere, photoelectrons[7] are continuously produced by solar uv, mainly in the energy range 1 to 30 eV. The photoelectrons have a spatial density[8] about 10^{-6} of the ambient electron density, and their only contribution to the electron distribution is a high-energy tail which is much flatter than a Maxwellian. Accordingly, $T(v)$ is almost constant and equal to the ambient electron temperature T ($kT \approx 0.2$ eV) for energies up to about 14 times kT and increases rapidly to a value $kT(v)$ ~ 10 eV for higher energies. At altitudes where $E_{\mathrm{ph}} = mv_{\mathrm{ph}}^2/2 = m\lambda^2\nu_r^2/8$ exceeds $14kT$, one can expect enhancement of the plasma line intensity by a factor of $T(v_{\mathrm{ph}})/T \sim 50$. In the experiments reported here, E_{ph} lies in the region 3 eV $< E_{\mathrm{ph}} <$ 25 eV. For a quantitative comparison with experiment, it is necessary to include the effects of the geomagnetic field. When this is done, we calculate that, at altitudes above 300 km where the daytime temperature is about 2400°K, the enhancement should be complete (about a factor of 50) when $\nu_p > 5.3$ Mc/sec, and that the thermal equilibrium values hold for $\nu_p < 4.0$ Mc/sec. The measured intensity at the highest frequency (6.2 Mc/sec) in Fig. 1 indeed corresponds to an enhancement of roughly 50 (our absolute intensity calibrations are not yet very accurate). The enhancement of the 5.2-Mc/sec plasma lines is seen to be not quite complete, and there is a rather sudden drop in intensity for the 4.3-Mc/sec signal at the higher height. At altitudes below 200 km, the values for T are lower, and the enhancement persists to lower values of ν_p.

We are indebted to Professor W. E. Gordon for valuable advice and for help with the experiment.

[*] The Arecibo Ionospheric Observatory is operated by Cornell University with the support of the Advanced Research Projects Agency under a research contract with the U. S. Air Force Office of Scientific Research.

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[4] F. W. Perkins, Center for Radiophysics and Space Research Report No. RS58, Research Publications, Department of Electrical Engineering, Cornell University (unpublished); F. Perkins and E. E. Salpeter, to be published.

[5] Charged-particle collisions are discussed in detail in reference 4. The results are that charged-particle collisions can be ignored for the 430-Mc/sec experiments but are probably important at 40 Mc/sec and may prevent the enhancement of the plasma lines.

[6] Fast electrons leave a "Cherenkov wake" of charge density fluctuations. See D. Pines and D. Bohm, Phys. Rev. 85, 338 (1952).

[7] A. Dalgarno, M. B. McElroy, and R. J. Moffett, Planetary Space Sci. 11, 463 (1963).

[8] Above 300 km, the photoelectron density is mainly due to photoelectrons which were produced near 300 km and have escaped upwards without collision. These electrons are returned to the other hemisphere by the earth's magnetic field. For observations concerning the existence of photoelectrons from the conjugate hemisphere, see H. C. Carlson (to be published).

MULTICHANNEL RESONANCES IN THE FORWARD SCATTERING OF ELECTRONS BY HELIUM

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(Received 11 March 1965)

This Letter reports the observation of resonances in the forward, inelastic cross section for scattering of electrons by helium. Resonance structure occurs for incident electron energies between 22.4 and 22.8 eV in all four of the open channels. These channels correspond to excitation of the final-state, neutral-helium levels $(1s2s)\,^3S$, $(1s2s)\,^1S$, $(1s2p)\,^3P$, and $(1s2p)\,^1P$. A resonance is caused by interference between the direct excitation of the final state and excitation via an intermediate negative-ion state. The negative-ion states seen here are considered to be formed from the $n=3$ levels of helium (22.7-23.0 eV) since the observed resonances occur just below these helium levels. There is insufficient information to identify the negative ion configurations, but most likely the ones involved are $(1s3s^2)$, $(1s3s3p)$, and $(1s3p^2)$. Together with earlier reports of resonances in total scattering[1,2] and in the inelastic $2\,^3S$ channel at 72°,[3] there now have been observed six different manifestations of these resonances.

The apparatus employed has been described, and used previously in high-resolution elastic and inelastic electron-scattering experiments at incident energies considerably above threshold.[2,4,5] This Letter reports the use of the apparatus in a new mode of operation in which electrons with a fixed energy loss and near zero residual energy are observed after leaving the scattering chamber. The number of electrons collected is obtained as a function of the incident energy. Primary electrons in a narrow energy range are selected from a thermionic source by a hemispherical electrostatic deflecting monochromator and pass into the gas-filled ($\sim 5\times 10^{-2}$ Torr cm) collision chamber. A second hemispherical analyzer is adjusted so that those electrons that have lost a fixed amount of energy pass through it and are collected by a Faraday cup. It is estimated that scattering angles of more than 0.12 radian do not contribute significantly to the detected signal. The apparent energy resolution is 0.15 eV.

Figure 1 shows reproductions of X-Y recorder traces of electron current versus incident energy for fixed energy losses of 19.818 $(2\,^3S)$, 20.614 $(2\,^1S)$, 20.962 $(2\,^3P)$, and 21.216 $(2\,^1P)$ eV. Excessively large noise pulses have been deleted. The zeros of scattered electron current in Fig. 1 have been arbitrarily displaced. However, it can be said that the smooth part of the cross section in the triplet curves is no greater than the resonance structure, whereas the smooth part of the singlet cross sections is several times larger than the resonance fea-