THEORY AND OBSERVATION OF IONOSPHERIC PLASMA FLUCTUATION DYNAMICS

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Introduction

Shortly after the launching of the first man-made satelllites, W.E.Gordon (1958) suggested that some of the measurements that were performed in situ by satellites could be made by means of ground based radar techniques. Two very large radar observatories, one in Jicamarca, Lima, Peru, and the other in Arecibo, P.R., were built for this purpose. Soon after, French scientists built a bistatic radar for the same purpose, followed then by a few other installations. Recently, Germany, United Kingdom, France, Norway, Sweden and Finland have built EISCAT, a multinational Incoherent Scatter facility in the Scandinavian Artic. The technique has proved to be much more powerfull than originally envisioned. We could say that our modern understanding of the ionosphere is in great part due to the observations made with these Instruments

The technique is known in the literature as Incoherent Scatter or Thomoson Scatter when applied to ionospheric plasmas in thermodynamic equilibrium. But, the same instruments have been also succesfully used when the plasmas are not in thermal equilibrium, i.e. when the electron density fluctuations responsible for the scattering show some coherence. Hence, we shall use here the term Ionospheric Scatter technique whenever we want to stress its more general application.

The technique is not limited to the study of the ionosphere. The technique is based on the theory of plasma fluctuation dynamics and as such can be considered as an experimental tool for the study of Plasma Physics in general. In this regard, it has made important contributions in validating the goodness of Plasma Kinetic Theory mathematical models.

Our intention in this paper is to give an introduction of the theory and practice of the Ionospheric Scatter Technique, with emphasis on the contributions it has, and it can make, in the more general field of Plasma Physics and in Fluctuation Theory in particular. The paper is addressed to the plasma physicist who is having his first contact with this technique.

The theoretical base of the technique involves - as most problems of concern to Plasma Physics - cumbersome mathematics. We shall try to give sufficient heuristical insight into the theory and at the same time briefly present the solid theoretical and mathematical foundations on which is based.

Brief Description of the Radar Incoherent Scatter Technique

The Incoherent Scatter Technique or, in more general terms, the Ionospheric Radar Scatter Technique is based on the analysis of the statistical properties of radar returns from the ionosphere. Typically, with this technique, the ionosphere is illuminated by a radio electromagnetic pulse with frequency between 50 to 1000 MHz. The ionosphere is transparent to these waves and most of the radio energy goes through, but for a very small fraction which is scattered in all directions by the free electrons. A small fraction of this scatter energy is collected by the receiving antenna. The contributions from different volumes at different ranges are discriminated by their corresponding time delay between the time of pulse transmission to the time of reception. Usually, the same antenna used for transmission is used for reception in a radar fashion. Many ranges are observed simultaneously in parallel.

Relationship between the Statistical Properties of the Signal Received and the Dynamics of the Medium.

Heuristic Description

The signals received in an ionospheric scatter radar experiment result from the linear superposition of the contributions from each scattering electron within the scattering volume defined by the beam pattern and the pulse length. Each contribution has a phase which depends on the radial position of the electron and a phase rate which depends on the radial velocity of it. Since the positions and velocities of the electrons define a random process in space and time, it is expected that the superposition of their contributions, i.e. the received signal, be also a random process in time.

Intuition would tell us that the power of the signal received should be proportional to the number of electrons and that the frequency spectrum of the signal received should be spread around the transmitter frequency with a spectral width determined by the Doppler shift corresponding to the thermal velocity of the electrons. This would indeed be the case if the position of the electrons would be independent from each other, when at distances smaller than the radar wavelength. But, this does not occur in the real world; not with the densities encountered in ionsopheric plasmas and the wavelength of the radars used. When the interpartical dependance (Coulomb interaction) is taken into account, it results that the power received is close to one half the electron density (if the plasma is in thermodynamic equilibrium) and the spectrum has a width which correspond to the thermal velocity of the ions and not of the electrons.

The theory which predicts the exact spectral shape of the radar returns in terms of the thermodynamic properties of the medium -when in thermodynamic equilibrium - is referred to as the Incoherent Scatter Theory. This theory is based on very solid grounds and has been fully tested experimentally, as we will have a chance to see later. Although length constrains for the present paper will not allow us to go into it fully, we shall later present the starting point and the general conclusions. The reader is referred to the work by Dougherty and Farley (1960, 1963), Farley (1964, 1966), Fejer (1960, 1961), Hagfors (1961), Rosenbluth and Rostoker (1962), Salpeter (1960, 1963) and Woodman(1967) for details.But first, let us try to explain heuristically and qualitatively the conclusion about the roll of the ions stated earlier .

Let us first consider a plasma model with no ions. In order to take care of the collective charge of the electrons, let us replace the ions by a continuous and rigid fluid of constant positive charge with a charge density equal to the average of the electron density, in order that the plasma be neutral in the average. As far as the electron gas is concerned, we will consider a realistic electron plasma model. Because of Coulomb electron-electron repulsion, we expect that the probability to find another electron in the vecinity of any of them should be low and directly related to their distance. In terms of electron densities, we would expect that, if we label a particular electron, the average density of the others will show a hole around the labeled electron. This is the classical Debye problem, which when solved give us a cusped shape for the electron hole with a characteristic length (Debye length) given by $h^2=KT/4e^2n\pi$ with typical ionospheric values of the order of ten centimeters.

The integrated charge of the electron hole is equal to the charge of the electron in the center, effectively shielding its electric field and confining it to a few Debye lengths. If we illuminate this plasma with an electromagnetic wave, with a wavelength larger than the

Debye length, the labeled electron would oscillate and exite a scattered wave. But so would the hole around the electron, with an intensity equal to that of the electron. The scatter field of the hole of electrons would scatter but with opossite phase. Both scattered waves will cancel each other with the net result that our hypothetical model would not scatter at all.

This is not what one observes in a real experiment. To obtain any scattering we need to include the nature of the ions.

If we let the ions come into the picture, we have a realistic situation. As before, we can label a particular ion and find that the electrons would cloud around it, and that the other ions would make a similarly shaped hole. The cloud of electrons and the hole of ions around the labeled ion produce similar shielding as before, with the difference that half of the shielding is due to the ion hole and half to the electrons, as expected from an equipartition of energy point of view. If now, we illuminate the plasma with an electromagnetic wave, the ions, because of their much larger mass, would produce negligable scattering, but the electron hole with half charge, would produce scattering equal to the negative of what it would be produced by half a single electron. This explains the factor of one half stated before. Furthermore, as the ion moves, the electron cloud will follow it adiabatically and will scatter at a frequency equal to the transmitter frequency plus a Doppler shift determined by the proper projection of the velocity of the ions. Hence, eventhough it is the electrons who are responsible for the scattering, the intensity and the dynamics of the scattered field is determined by the dynamics of the ions and not by the electrons. This includes the width of the frequency spectrum of the signal which, as we concluded earlyer, is determined by the thermal velocity of the ions.

It is clear, then, that for a given composition, the width of the spectrum would be a measure of the ion temperature. In fact, since the expected ion composition in the inosphere is confined to three major constituents, namely O+, He+ and H+ (also NO+ and O2+ at lower altitudes) it is possible, by excluding unrealistic temperatures, to determined the ionic composition as well.

Figure 1 show a theoretical calculated spectrum, F(w), for the case of O+, no magnetic field and no collisions. We shall say more about the mathematical theory later on. The control of the ions over the spectral width is evident for the case where the radar wavelength is larger than Debye length we have discussed. But note that when when the probing wavelength of the radar is smaller than the wavelength, the spectrum has a width comparable to the thermal velocity of the electrons. In this case only the labeled electron contributes to the scattering. The electron hole is large enough to make cancelling positive and negative contributions because of opposite pnases of the illuminating as well as scattered-wave. The spectral line at the plasma frequency is a consequence of the tendency of the plasma to oscillate at this frequency. It is exited by the motions of the very fast electrons at the tail of the Maxwellian distribution. The total power under this line is a small fraction of the power under the ion-controlled part of the spectrum.

It should be clear by now the potential of the Incoherent Scatter Technique in the study of Ionospheric plasmas. We have mentioned already five properties of the medium which can be measured by the technique namely: density, temperature, O+, He+ and H+ composition. We can easily add to the list the three components of the plasma bulk velocity by simple Doppler shift arguments. Two components, those perpendicular to the magnetic field, are a measure of the Electric Field, since for the small collission frequencies present in the Ionosphere, the ions and electrons gyrate along the magnetic field and they all drift perpendicular to the magnetic field with a velocity given by $\underset{\sim}{E} \times \underset{\sim}{B}/B^2$.

Theoretical approach

The starting point in a theoretical approach is, as in the case of above heuristic description, the linear superposition of the contributions of each electron. Let $s_i(t)=s(\underset{\sim}{x}_i(t),\underset{\sim}{v}_i(t))$ be the contribution of single electron position at x_i. Then, the signal at the receiver end of an Ionospheric Scatter radar is given by

$$S(t)=\sum_i s_i(t) \tag{1}$$

It is possible to express the right hand side in terms of a spatial microscopic integrals and instantaneous density of electrons, $n_e(\underset{\sim}{x},t)$. This density is a random process in space and time and hence, $S(t)$ is a random process in time. It is fully characherized by its correlation function, $C(\tau)$, defined as:

$$C(\tau)=\langle S(t)S^*(t+\tau)\rangle \quad , \tag{2}$$

Replacing the integral equivalent of (1) into (2), one obtains an expression of the form:

$$C(\tau)=\int d^3\underset{\sim}{x}\,d^3\underset{\sim}{r}\,dt'd\tau'\chi(t;t',\underset{\sim}{x})\chi^*(t+\tau;t'+\tau',\underset{\sim}{x}+\underset{\sim}{r})R(\underset{\sim}{r},\tau') \quad , \tag{3}$$

where $R(\underset{\sim}{r},\tau)$ is the space-time autocorrelation function of the electron density defined as:

$$R(\underset{\sim}{r},\tau)=\langle n_e(\underset{\sim}{x},t)n_e(\underset{\sim}{x}+\underset{\sim}{r},t+\tau)\rangle \quad , \tag{4}$$

and $\chi(t;t',\underset{\sim}{x}')$ is a deterministic function which describes the signal received, $s(t)$, in the case an electron appears instantaneously in $\underset{\sim}{x}'$ at t'.

The important fact about equation (3) is that $C(\tau)$ is a functional of $R(\underset{\sim}{r},\tau)$, which defines the medium, and $\chi(t;t',x')$, a Kernell which defines the instrument. Under certain conditions, or justifiable approximations, one can write

$$C(\tau) = K\hat{R}(2\underset{\sim}{k},\tau) \quad , \qquad (5)$$

where $\hat{R}(2k,\tau)$ is the spatial Fourier transform, k is the wave number of the incident illuminating radiowave and K is a constant of proportionallity.Notice that only the fluctuations with wave-number 2k contribute to the radar signals. Fourier components with different wave-number do not contribute because of self interference, i.e. for every region in space which contributes to the echoe with a given phase, there is another which contributes with opposite phase.

Equation (5) can be written instead in terms of its temporal Fourier transform, F(w),i.e. the more familiar frequency power spectrum of the signal and the wave-number-frequency spectrum, $\bar{R}(2k,w)$, of the electron density fluctuations of the medium under observation, namely:

$$F(w) = K\bar{R}(2k,w) \qquad (6)$$

Equation (5) ,or more generally, (3), is the basis of the Ionospheric Radar Scattering Technique. Essentially, they both tell us that it is possible to infer from the statistical properties of the radar signal received, information about the statistical properties of the medium. The power of the technique can be appreciated if one recalls that a fluctuating medium is fully characterized by its space-time (or wave-number and frequency) autocorrelation function (or spectrum), which we are effectivelly meassuring remotely from the ground

In the case of thermodynamic equilibrium, it is possible to obtain theoretical expressions of $\hat{R}(2k,\tau)$, or of its Fourier transform, $\bar{R}(2k,w)$, in terms of the thermodynamical parameters that define the medium, as we shall see in more detail later on. These parameters can then be obtained by comparing the experimental versus the theoretically determined values of $C(\tau)$.

We have already discussed heuristically and qualitatively the effects of temperature composition and bulk or drift velocity on $F(w)$. We can add other parameters like collision frequency, electron over ion temperature ratio, direction and magnitude of the magnetic field. All of these parameters can be measured as a function of time and altitude, which makes possible in turn the measurement of the macroscopic properties of the medium and its dynamics. Figures 2 to 5 show profiles and contour plots of some of these parameters to illustrate this potential. (see Evans, 1969, and Walker, 1979 for further examples).

When the medium is not in thermodynamic equilibrium and specially when it is in an unstable state, it is not possible to obtain analytical - or even numerical - expressions for $\hat{R}(2k,\tau)$. Nevertheless, expessions (3) to (5) are still valid and one can obtain still usefull information from the experimentally determined $C(\tau)$ or $F(w)$. This information is usually limited to the physical interpretation of the first three moments of $F(w)$.

The zeroeth moment, i.e. the area under $F(w)$, or equivalently, the value of $C(\tau)$ at $t = 0$, $C(0)$, is a direct measure of $\langle\hat{n}_e^2(k)\rangle$, the electron density fluctution variance at wave number 2k. In the case of a turbulent plasma, for instance, it is a direct measure of the turbulence intensity. Figure 6, illustrates the potential of the technique for the study of the morphology of F-region ionospheric irregularities. This picture gave an important clue (Woodman and La Hoz, 1976) about the physical mechanisms responsible for F-region equatorial irregularities, a phenomena that had been studied close to 50 years and for which there was no valid physical explanation.

The first moment is a measure of the mean Doppler shift of the echoes and directly related with the radial velocity of the medium. It has been used to measure winds at mesospheric heights (Fig. 7) and electric fields and turbulence behaviour at the E and F region of the ionosphere (see Kelley and Fejer, 1980, for a review).

The second moment is a measure of the frequency spread of the spectrum and can be interpreted either as the lifetime of a wave with 2k wave-number or as the variance of turbulent velocities in a turbulent medium.

Ionospheric Scatter Radars as an Experimental Tool for Plasma Physcis.

We have discussed the potential of Incoherent Scatter or Ionospheric Scatter Radars for the study of the state of the ionosphere and the physical processes which take place in it . The potential of these instruments is not limitec to this application: they can make important contributions in the understanding of the dynamics of waves and turbulence in plasmas in general.

We can think of the ionosphere as a natural plasma laboratory without any problems of confinement. It is unbounded and, hence, mathematical modelling is simpler. It is usually in thermodynamic equilibrium, which also simplifies modelling. Ionospheric plasmas can also present instabilities, either because of the existance of large enough density gradients or because counter-streaming of ions and electrons. Some of these instabilities can be scaled to similar conditions in laboratory plasmas, and what is learned about plasmas in the ionosphere can be applied to the laboratory.

We have just seen above that radar techniques permit a direct study of plasma fluctuations. As mentioned before, the fluctuation field is completely determined by the space-time autocorrelation function of the fluctuating parameter. Radar technics permit the direct experimental evaluation of the spatial Fourier transform of the electron density correlation function, $\hat{R}(2k,\tau)$ evaluated at a particular wave number 2k. Other fluctuating quantities like electric field fluctuations, can be related to it.

Radar measurements are statistisal in nature related to statistical properties of the electron density random field. But they can also be interpreted in terms of the deterministic behaviour of deterministically exited wave in the same plasma. It can be shown (Weinstock 1966, Woodman 1967) that the temporal behaviour of $\hat{R}(2k,\tau)$ as a function of τ, is exactly the same as the temporal behaviour -as a function of t- of an electron density wave $n_e(2k,t)$, responding to a particular initial perturbation. This should not be surprising since the dynamics of a thermally and randomly exited wave should not be different than the dynamics of a deterministic externally exited one, provided it is in the linear regime.

One of the principal objectives of the kinetic theory of plasmas is to give us the laws of behaviour of the $f(\underset{\sim}{x},\underset{\sim}{v},t)$, or its corresponding density $n(\underset{\sim}{x}, t)$. Radars permit an experimental determination of the time behaviour of one of the Fourier components, $\hat{n}_e(2k,t)$, of $n_e(\underset{\sim}{x},t)$, to be compared with theoretically determined values of the same (see below). The wavelenghth dependance, although fixed for a particular radar, can also be checked by scaling the results from different characteristics lenghts of the ionospheric plasma, for instance Debye lengths, mean free path, gyro radius, etc. Ionospheric radar experiments give perhaps the best experimental confirmation of the goodness of plasma kinetic theory models.

Theory of fluctuation dynamics

Woodman (1967) has shown that $R(\underset{\sim}{r},t)$ can be expressed as the product of two densities, namely:

$$R(r,t) = n_e n_e'(r,t) \qquad (7)$$

where n_e is the actual electron density of the medium and $n_e'(\underset{\sim}{r},t)$ is the electron density of the same medium but disturbed at time t=o and r=0 by the presence of an "average electron". More precisely, $n_e'(\underset{\sim}{x}, t)$ is the solution of an initial value problem such that

$$n_e'(\underset{\sim}{x},t) = n_e + \int d^3\underset{\sim}{v} f_e(x,v,t) \qquad (8)$$

where $f_e(\underset{\sim}{x},\underset{\sim}{v},t)$ is given by the solution of the linearized set of integro-differential equations:

$$\frac{\partial f_\mu}{\partial t} + \underset{\sim}{v}\cdot\frac{\partial f_\mu}{\partial \underset{\sim}{x}} + \underset{\sim}{v}*\Omega_\mu\cdot\frac{\partial f_\mu}{\partial \underset{\sim}{v}} - \nu_\mu\frac{\partial}{\partial \underset{\sim}{v}}\cdot v f_\mu - u_\mu^2\nu_\mu\frac{\partial}{\partial \underset{\sim}{v}\cdot\partial \underset{\sim}{v}} f_\mu =$$

$$\sum_\eta w_\mu^2\frac{Z_\eta}{Z_\mu}\int d^3\underset{\sim}{x}\, d^3\underset{\sim}{v}\,\frac{\underset{\sim}{x}-\underset{\sim}{x}'}{4\pi|\underset{\sim}{x}-\underset{\sim}{x}'|}\cdot f_\eta(\underset{\sim}{x},\underset{\sim}{v},t)\frac{\partial}{\partial \underset{\sim}{v}}\varphi_\mu(\underset{\sim}{v}) \qquad (9)$$

with initial conditions:

$$f_\mu(\underset{\sim}{x},\underset{\sim}{v},t)\Big|_{t=o} = \delta_{\mu e}\delta(\underset{\sim}{x}) - n_\mu e^2 Z_\mu \exp(-|\underset{\sim}{x}|/h)/KT|\underset{\sim}{x}| \qquad (10)$$

There is one equation of the form (9) and (10) for every μ, where μ stands for the electrons, e, and each one of the different ion species. Ω_μ is the gyrofrequency, ν_μ an effective Fokker Plank collision frequency, u_μ is the thermal velocity, w_μ the plasma frequency and Z_μ the charge number corresponding to the different ions (=-1 for the electrons). The function $\varphi_\mu(v)$ is a Maxwellian distribution. $\delta_{\mu e}$ is equal to zero exept for the electron specie

Equations (9) are a set of extended Vlasov equations, where the effect of collisions and magnetic field is included. Collisions are modelled in terms of a Fokker-Plank collision model. The different equations coresponding to the different species are coupled through the self consistent electric field represented on the right hand side of the equations.

Despite the formidable appearance of equations (9) and (10), they can be solved analytically. The equations have been solved by Woodman (1967) including numerical evaluations and discussions of the functions $\hat{R}$ $(2k, \tau)$, (hence of $C(\tau)$) for typical values of the ionosphere and for the wavelength of the Incoherent Scatter radar at Jicamarca, Lima, Peru (2k = 0.021 cm-1). The solution is found in terms of the space-time Fourier Laplace transform, $\bar{n}_e(\underset{\sim}{\xi}, z)$, of $n_e(\underset{\sim}{x}, t)$, which is given by:

$$\bar{n}_e(\underset{\sim}{\xi}, z) = \bar{I}_e(\underset{\sim}{\xi}, z) - \frac{1}{Z_e \xi^2 h_e^2} \cdot \frac{\bar{S}_e(\underset{\sim}{\xi}, z) \sum_\eta Z_\eta \bar{I}_\eta(\underset{\sim}{\xi}, z)}{1 + \sum_\eta \frac{1}{\xi^2 h^2} \bar{S}_\eta(\underset{\sim}{\xi}, z)} \tag{11}$$

and $\bar{I}_\eta(\underset{\sim}{\xi}, z)$ and $\bar{S}_\eta(\underset{\sim}{\xi}, t)$ are in turn the Laplace transforms of $\hat{I}_\eta(\underset{\sim}{\xi}, t)$ and $\hat{S}_\eta(\underset{\sim}{\xi}, t)$ given by:

$$\hat{I}(\underset{\sim}{\xi}, t) = H(\xi) \exp\left(- \frac{\xi_\parallel^2 u^2}{\nu^2} (\nu t - 1 + \exp(-\nu t)) - \frac{\xi_\perp^2 u^2}{\nu^2 + \Omega^2} (\cos 2\theta + \nu t \cos(\Omega t - 2\theta)) \right) \tag{12}$$

$$\hat{S}(\underset{\sim}{\xi}, t) = \frac{\hat{I}(\xi, t)}{H(\xi)} \left(\frac{\xi_\perp^2 u^2}{\nu^2 + \Omega^2} (\sin\theta + \exp(-\nu t) \sin(\Omega t - \theta)) + \frac{\xi_\parallel^2 u^2}{\nu^2} (1 - \exp(-\nu t)) \right) \tag{13}$$

where I, S, ν, Ω, θ stand for I_μ, S_μ, ν_μ, Ω_μ, θ_μ for each of the ion species and the electrons. Here θ =arctn (ν/Ω).

Since C(τ) depends on the spatial Fourier transform $\hat{R}(2k,\tau)$ of R(r,τ),we need only to perform the Laplace inverse of $\bar{n}_e(\underset{\sim}{\xi},z)$ and evaluate it for the particular wave vector 2kIt is not our intention to overwhelm the reader with the cumbersome formulas shown in (11) to (13). Our intention is to show the solid grounds on which the theory is based,and that analytical expressions for the theoretical shape of the density correlation function exist, with no approximations other than the ones that go into modelling the ion-ion and electron-ion collisions, and the linearization of the kinetic equations, highly justified for the small thermal fluctuations.

Numerical evaluations of the theoretical shapes of the autocorrelation function, C (τ), have been performed using above formulas. Figures 8 to 10 show some of these computations, where some of the parameters have been varied to discuss their effect.

Despite the complexity of these functions, we can discuss their shape in physical terms. Let us start with curve A in Figure 8 which corresponds to pure O+ and a wave vector parallel to the direction of the magnetic field. Under these conditions, the dynamics of a fluctuation wave is not affected by the magnetic field and has a shape identical to the case where there is none.This curve corresponds to the transform of F(w) shown in Figure 1 for a = 0.0024.

Based on equations (7) and (8) ,We can interpret, C(t), as the time history of a wave,$\hat{n}_e(2k,t)$,with wave-number 2k = 0.0021 cm-1 whose initial conditions are those corresponding to equations (10). It corresponds to an electron wave which follow adiabatically an ion wave, with almost the same amplitude. Both form a quasi-neutral perturbation.Because of the free streaming of the ions, in a time comparable to the time it takes an average ion to travel half a wavelength, the initial ion wave is almost dissipated. The actual dissipation of the wave at this time(~1msec), as shown in figure 8, is not complete; the reason being, that the neutralization of the Coulomb forces is not exact. The faster thermal motion of the electrons, try to impose a faster diffusion than the ions would allow, producing a polarization field. This field produces a secondary disturbance in the background plasma, such that, when the initial wave has been dissipated, a negative amplitude wave has been created as a result of the repulsion produced by the residual positive charge in the original perturbation. This secondary wave diffuses in turn, producing this time a positive terciary wave. The resultant sequence is the slight oscillation depicted in figure 8. The decay of the wave is exponential, and after a few characteristic times the wave amplitude has been reduced to practically zero.

Figure 8 illustrates the nature of damping in plasma waves. If we consider the case of a wave vector slightly off perpendicular, let us say curve E, we see practically the same time history as before, but if we wait long enough, after a time corresponding to a gyro-period (40 times longer than the diffusion characteristic time) the amplitude of the wave practically resurrects to a value comparable td the initial one. The damping of the wave can be identified with ion Landau damping, and the "resurrection" is evidence that this type of damping does not increase the entropy of the wave. The order of the plasma is still there, despite the disappearance of the initial perturbation.The ions stream away from their original position, destroying the original perturbation, but come back to the same field line after a gyro period.

Not shown on Figure 8 are some small high frequency oscillations corresponding to the plasma frequency. These oscillations are predicted by theory,(see frequency spectra on Fig. 1) their amplitude is small as compared to the fluctuations produced by the discrete nature of the ions. Theory (Perkins et al, 1965) predicts they should be enhanced whenever there is a population of electrons with velocities which match the phase velocity of the plasma wave under observation ($v= w_e/2k$). This velocity range is almost empty in purely thermal distributions, but are enhanced under the presence of photoelectrons. This enhancement has been observed experimentally and has been used to inferred information about the electron density (defines w_e) and the physics of photoelectron production in the ionosphere.

Figure 11 shows experimental measurements of the "resurrection" of plasma fluctuations in the ionosphere under the presence of the magnetic field.We could have also show thousand of experimental curves showing agreement with the theoretical shapes for τ's close to the origin. They constitute the basis for the success of Incoherent Scatter Theory in determining the different parameters that define the state of the ionosphere.

It is this type of agreement which gives us great confidence in the validity of the Incoherent Scatter theory and technique, and in the validity of Plasma Kinetic Theory including the theory on the dynamics of fluctuations.

The beauty of the incohent scatter technique is that despite the complex dependance of $C(\tau)$ on all of the parameters that define the medium, the large number of degrees of freedom and the complexity which this function has with respect to time, the experimentally determined values agree with the theoretical predictions, within the expected statistical errors of the measurement.

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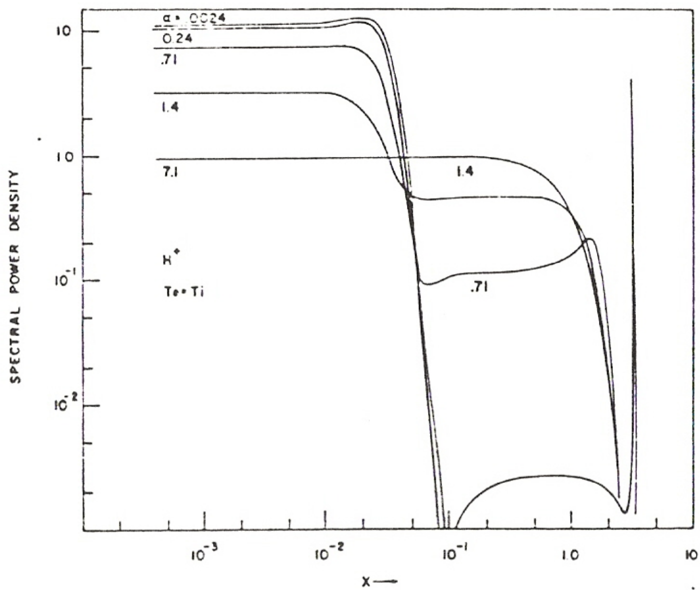

Fig.1. Theoretical computations of the spectral power density of Incoherent scatter signals for different values of the parameter 2kh, where h is the Debye length. They correspond to the case of no collisions, no magnetic field. The Doppler scale is normalized with respect to the electron thermal velocity. Note that the spectral width correspond to the ion thermal velocities, when the wavelength $2\pi/k$ is larger than the Debye length.

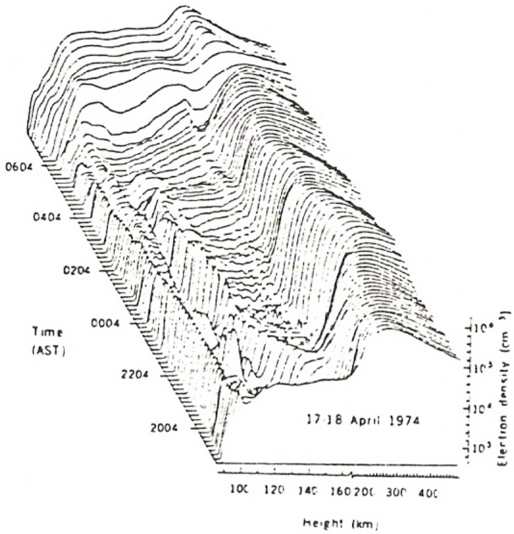

Fig. 2. Electron density profiles measured at Arecibo.the scale from 90 to 170 has been expanded to show Sporadic E structure. (R.M. Harper, personal communication).

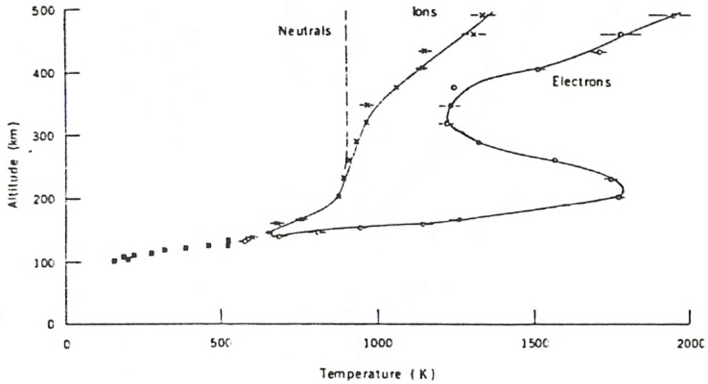

Fig. 3. Ionospheric temperatures measured at Arecibo. Notice that the temperature of the electron, ion and neutral gas is not the same. Temperature of the neutrals has been inferred theoreticalliy. (Harper, personal communication).

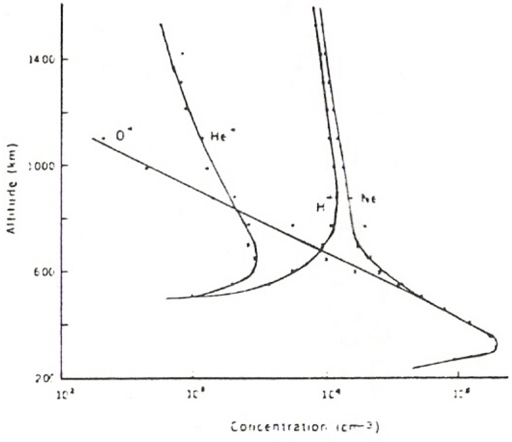

Fig.4. Ionic composition and total electron content measured at Arecibo. (Hagen and Hsu, 1974).

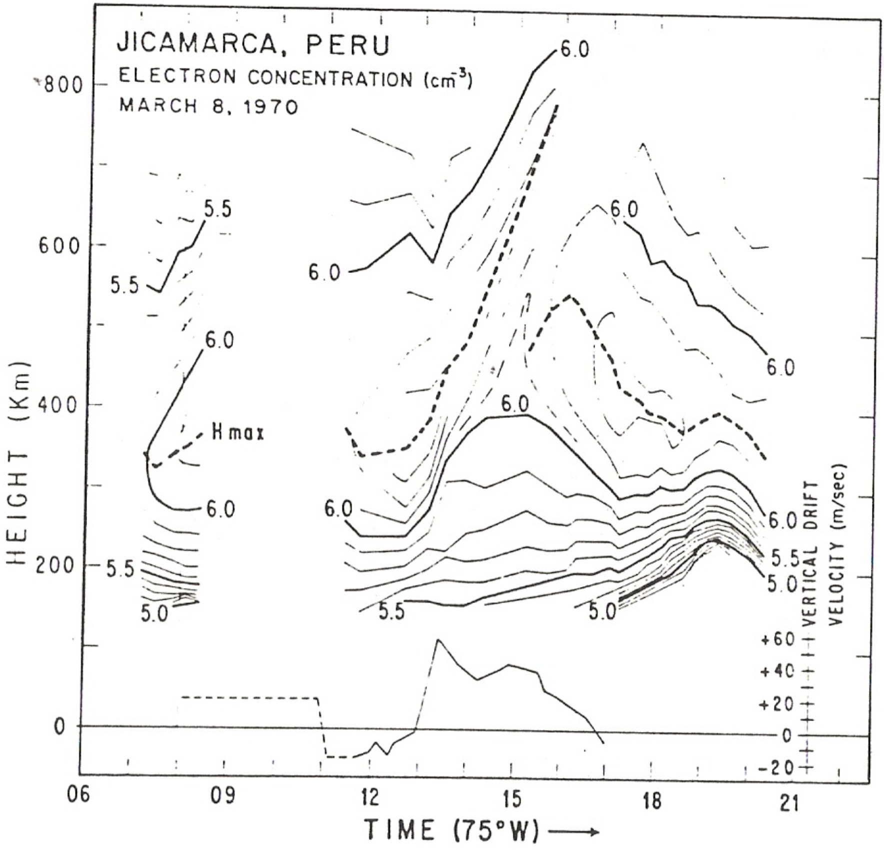

Fig. 5a. Electron density contours as a function of time and altitude and vertical drift velocities measured at Jicamarca during one of the largest magnetic storms of the previous solar cycle. (Woodman, et.al., 1972).

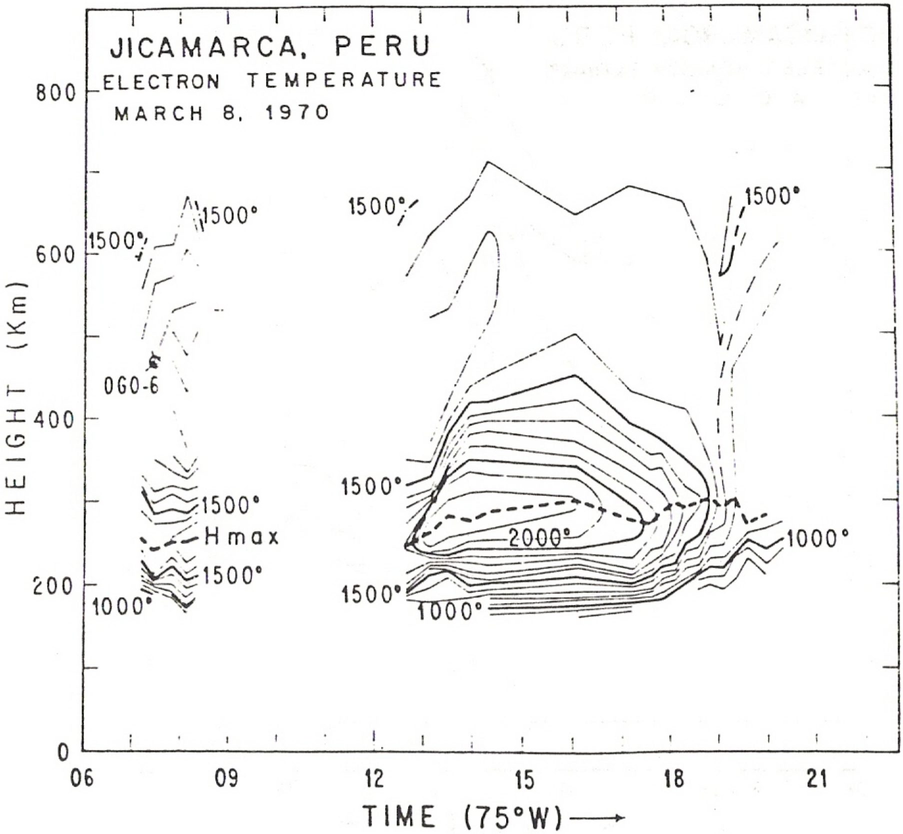

Fig. 5b. Electron temperature contours for the same date as in Fig. 4. (Woodman, et. al., 1972).

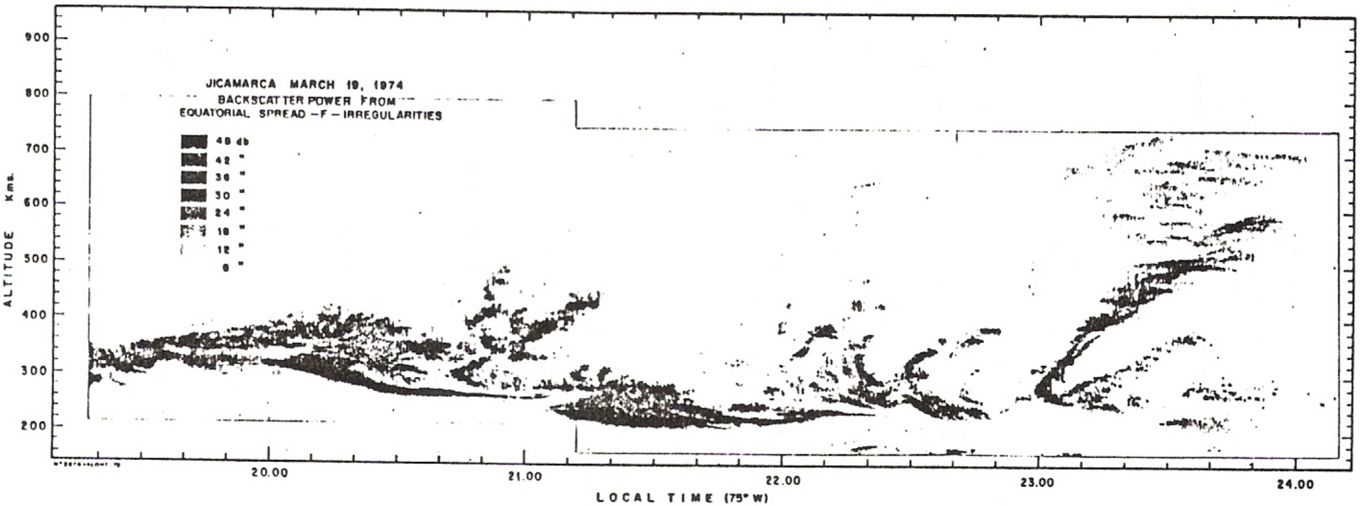

Fig. 6. Range-Time-Intensity plot of backscatter power from F region irregularities responsible for Equatorial Spread-F. The plume shown at 23:00 gave an important clue in the understanding of the formation of irregularities on the top, stable side of the ionosphere. It is caused by the turbulent wake of a "bubble" of low density plasma which has floated to 800 kms. of altitude (Woodman and La Hoz, 1975).

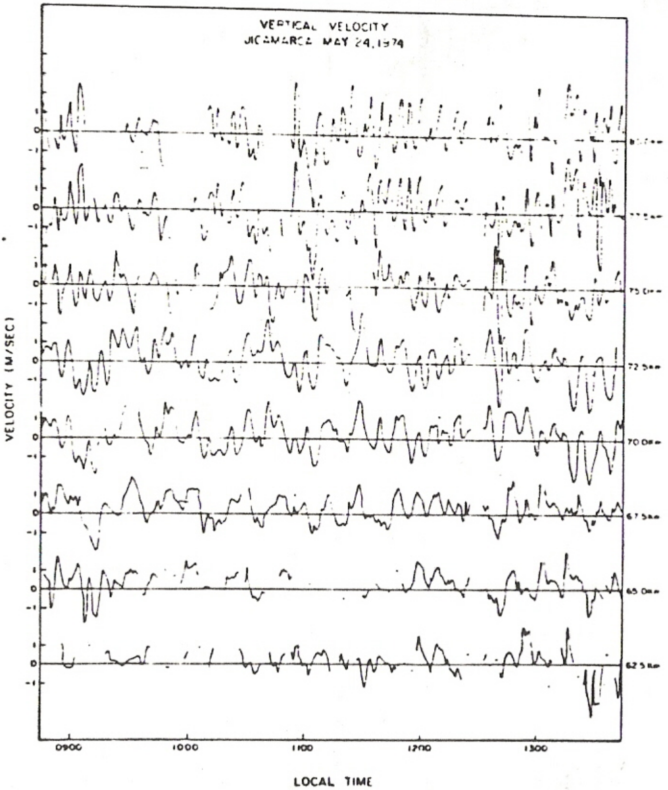

Fig. 7. Vertical velocities at mesospheric heights measured at Jicamarca. In this case ion-neutral collisions are so high that the plasma fluctuations produced by neutral turbulent mixing are tracers of the neutral velocities. The velocity fluctuations are in the gravity (Bouyancy) wave domain. (after Harper and Woodman, 1977).

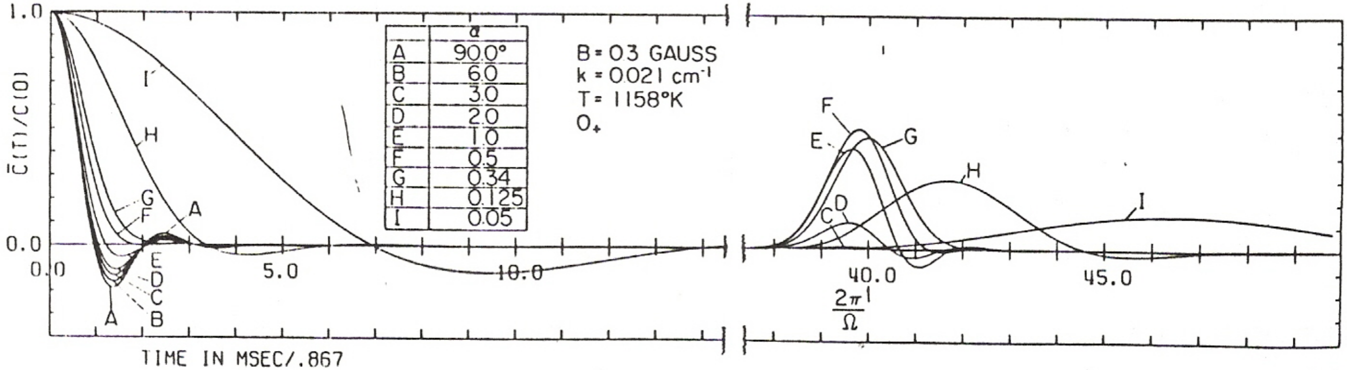

Fig. 8. Numerical computations for a theoretical calculation of C(t) for a O+ plasma and the parameters shown in the figure. Collisional effects are not included. The curve can also be interpreted as the time history of a quasi-neutral wave of wave-number k = 0.0024 cm-1. Notice that the wave after practically having died after 4-5 millisecond, comes back to life after a gyro-period. This is evidence of the constant entropy nature of Landau damping (Woodman, 1967).

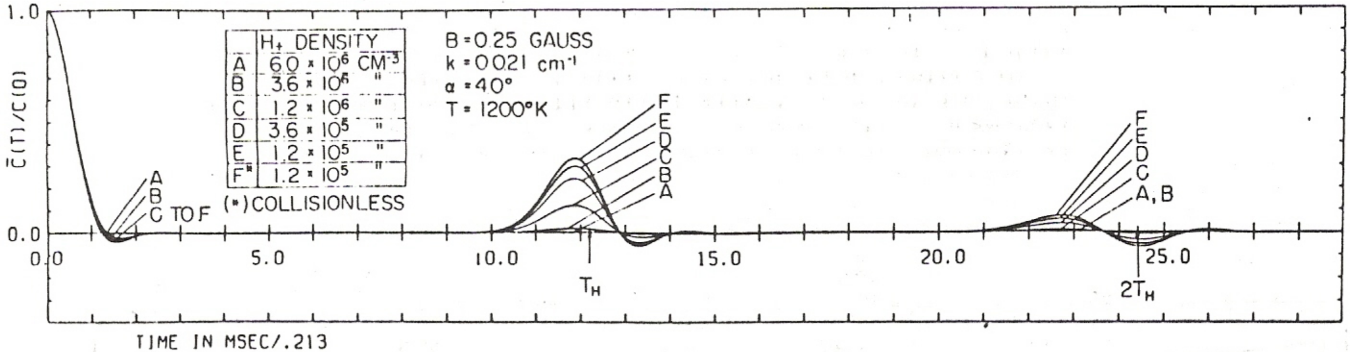

Fig. 9. Same as in Figure 8, but showing the effect of ion ion collisons.

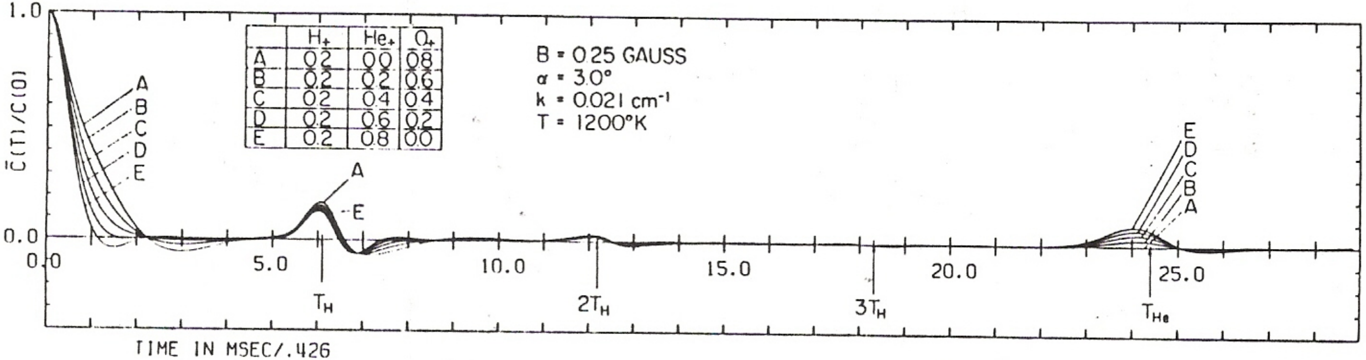

Fig. 10. Same as in Figure 8, but showing the effect of different ionic composition.

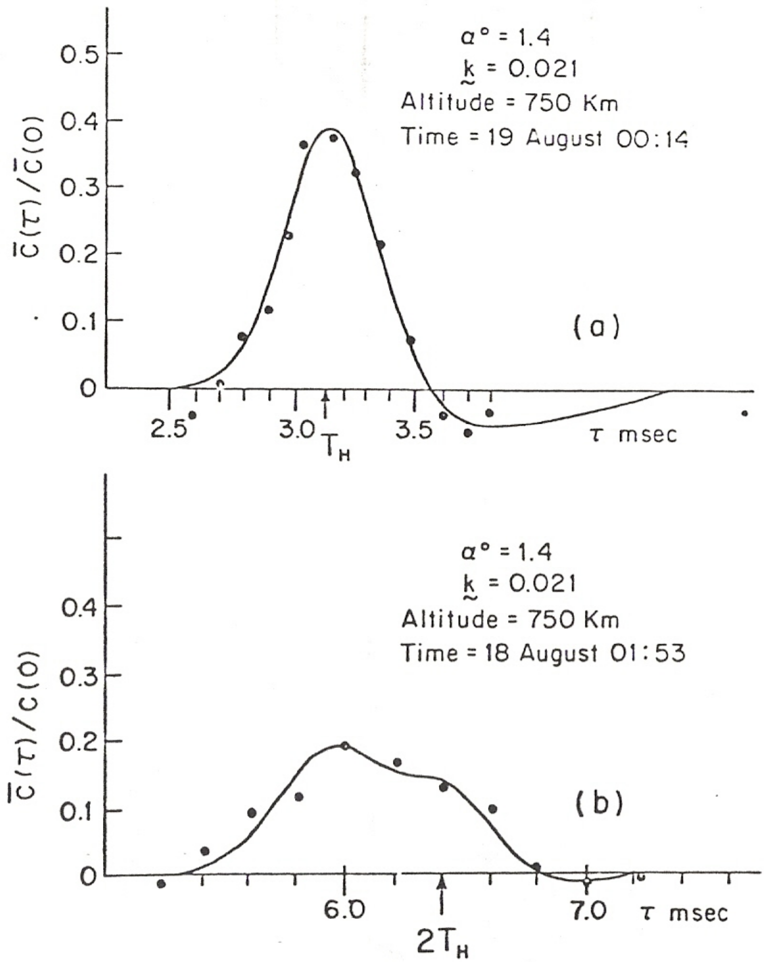

Fig. 11. Comparison between calculated values of the correlation function at time delays corresponding to one and two gyro periods. Notice the almost perfect agreement, despite the complexity of the theoretical prediction (see text). In this case O+, H+ composition and ion-ion collision are included. (Woodman 1967, Farley 1967).