By

T.H. Stix

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WAVES IN PLASMAS: SOME HISTORICAL HIGHLIGHTS*

Thomas H. Stix

Plasma Physics Laboratory, Princeton University
P.O. Box 451, Princeton, New Jersey 08544 USA

Abstract: To illustrate the development of some fundamental concepts in plasma waves, a number of experimental observations, going back over half a century, are reviewed. Particular attention is paid to the phenomena of dispersion, collisionfree damping, finite-Larmor-radius and cyclotron and cyclotron-harmonic effects, nonlocal response, and stochasticity. One may note not only the constructive interplay between observation and theory and experiment but also that major advances have come from each of the many disciplines that invoke plasma physics as a tool, including radio communication, astrophysics, controlled fusion, space physics, and basic research.

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1. Introduction

The papers to be presented at this conference through the next few days will span a very large number of topics, and to give an introductory talk that will be relevant to this broad array of interests and disciplines is indeed an intimidating task. What I have chosen to do, therefore, is not to try to look at all the things going on in plasma physics today -- about many of which you will be hearing -- but rather to look back at some common origins. The emphasis in this talk will be on concepts pertinent to plasma waves and even at that, there has been no attempt to make the review comprehensive or complete. I apologize for the omissions, and apologize also that in mentioning just a few specific experiments and authors' names, I shall be leaving out major scientific contributions made by so many others.

2. Dispersion

A major reward in the study of plasma physics is the very richness of the subject: even pictured just as a conducting fluid, the plasma medium can still be anisotropic, inhomogeneous, lossy or almost lossfree, and dispersive. By the word "dispersive," it is implied that the dielectric properties of the medium depend on the frequency of the wave, hence the velocity of the wave through the medium also depends upon the wave frequency. As an example, the rainbow stems from the dispersion of the sun's rays by water droplets in the atmosphere. And perhaps the first property documented for plasma waves concerned their dispersive character. The observations are described in colorful fashion by Barkhausen /1/ in 1919. He relates that audio amplifiers were used extensively on both sides of the Front in World War I, to eavesdrop on enemy telephone conversations. In a simple circuit, shown in Fig. 1, wires from two ground points, perhaps a few hundred

meters apart, are connected to an amplifier (V) which feeds a telephone receiver (T). The World War I military telephone systems -- long single lines with ground return -- were evidently quite vulnerable to this early form of electronic surveillance. But, Barkhausen notes, sometimes one heard a quite remarkable whistling tone. At the Front, it was said that one could hear "flying grenades," and at times, especially in the forenoon on warm days in May and June, the phenomenon was so strong and so frequent as to make the eavesdropping impossible. Attempting to describe the sound in print, Barkhausen suggests it would be something like "plou." More physically, he sketches in Fig. 2 the descending tone, running down the whole audible scale with the lowest tones fading away, the entire event lasting about a second.

Although the same phenomenon was seen and discussed in the literature over the succeeding years, it was not until 1935 that the correct explanation was offered by Eckersley /2/. In a letter to Nature, Eckersley reproduced, in Fig. 3, some 1933 data taken by Burton and Boardman /3/. On the basis of

Fig. 1. Circuit for monitoring enemy telephone conversations in World War I. V: Audio amplifier; T: Receiver. From Barkhausen (1919).

Fig. 2. Sketch of whistling tone. From Barkhausen (1919).

magneto-ionic theory (which we would now call "cold-plasma wave theory"), Eckersley surmises that the effect is due to the dispersion of a pulse in the ionosphere. Eckersley suggests that the pulse could arise from a flash of lightning, producing waves through the ionosphere which are then reflected at the polar regions. And he states (without proof) that magneto-ionic theory would predict that the observed frequency at time t after the beginning of the pulse is proportional to $1/t^2$.

The details were finally filled in by Storey /4/, in 1953. Storey's simplified dispersion relation describing this whistler mode is just

$$\frac{\omega}{k} = \frac{c}{k} \cdot \frac{\vec{B}_0}{B} \frac{\omega_{ce}}{\omega_{pe}^2}.$$

A little calculation will show that the group velocity is confined to a narrow cone around $\vec{B}_0$, and that it is proportional to $\omega^{1/2}$. The observed frequency, in agreement with Eckersley's statement, then descends just as t^{-2} . Storey's model for the whistlers is shown in Fig. 4, illustrating the ray paths for "short" and "long" whistlers.

Fig. 3. Pair of whistler signals. Frequency versus time. From Eckersley (1935).

Fig. 4. Ray paths for whistler propagation through magnetosphere. From Storey (1953).

Now this 1953 picture of whistler ray paths is a type of plot with which we are all now familiar, but it is interesting to see how long it took for this degree of understanding to come about. The problem with which many excellent radio physicists wrestled during the late 1920's and the early 1930's was the question of propagation paths through the ionosphere. Most attention was paid to the case of vertical incidence, because looking at the echoes of an upward-directed radio pulse was a very popular experiment in the early 1930's. However this case is a special one, and the more general case of oblique incidence upon the ionosphere, taking into account the earth's magnetic field which generally has an inconvenient vector orientation, led to some puzzling results. An analysis in 1930 by the Russian radio-physicist Schekulin /5/, using Snells' Law and the magneto-ionic dispersion relation evaluated at different heights in the ionosphere, gave apparent propagation paths for oblique incidence as in Fig. 5. As noted in 1938 by H. G. Booker /6/, Schekulin "does not, however, offer any convincing interpretation of such a curious result." And it was Booker, eight years after Schekulin's publication, who explained the anomaly. Schekulin's calculations were correct, but the arrows which he had connected together in his diagram were the phase-velocity vectors, not the group-velocity. Putting in the group-velocity vectors and connecting them together then

Fig. 5. Representative propagation paths for radio waves obliquely incident on magnetized ionosphere, as suggested by Schekulin (1930).

produced credible propagation paths such as illustrated in Fig. 6. But even with this impressive advance, the troubles were not over for the ray tracers. The propagation trajectories were now correct, but the methods for calculating them, usually based on $\vec{v}_g = \partial\omega/\partial\vec{k}$, the local dispersion relation, and Snell's Law, were terribly clumsy. Another twenty or more years were evidently to elapse before it was realized that the equation for the location of a wave packet,

$$\frac{d\vec{x}}{dt} = \vec{v}_g = \frac{\partial\omega}{\partial\vec{k}}(\vec{x}, \vec{k}, t),$$

could simply be paired with its Hamiltonian companion

$$\frac{d\vec{k}}{dt} = - \frac{\partial\omega}{\partial\vec{x}}(\vec{x}, \vec{k}, t)$$

in order to advance $\vec{k}$ in the trajectory calculation.

3. Effects of Long Mean Free Paths

Magneto-ionic theory introduces ions and electrons as components of the plasma medium, but omits consideration of the thermal motion of these particles. The resulting theory is then valid only for what we today call the

Fig. 6. Propagation paths based on group velocity (left) and phase velocity (right) for radio waves obliquely incident on magnetized ionosphere. Note that vertical components of group and phase velocity are opposed over the D-A and E-E portions of the trajectory. Group velocity is horizontal at a and b; phase velocity is horizontal at d and e. From Booker (1938).

"cold plasma" model. The ion and electron fluids may each be pictured as crystalline jellies: "free-streaming" is absent and the individual particles merely quiver around their fixed equilibrium positions. But it is the "free-streaming" property which provides all the distinctive kinetic effects which make plasmas so very different from ordinary gases and fluids. The mean free path for 90° like-particle deflection is

$$\lambda_{mfp} = 2.4 \times 10^{13} \frac{T_{ev}^2}{n_{cm^{-3}} Z^4 \ln \Lambda} \text{ cm} , \quad \Lambda = \frac{3}{22e^3} \left(\frac{k^3 T^3}{\pi n_e} \right)^{1/2}$$

and it is the comparison of this length with other lengths characteristic of the plasma environment which determines the importance of free streaming, i.e., which parameterizes the separation between "cold plasmas" and "hot plasmas." For example, the characteristic lengths in a hot plasma will typically be ranked as shown in TABLE I. TABLE I shows several ways that the plasma parameter, Λ , characterizes the plasma state ($\Lambda \gg 1$) and, for this hot-plasma illustration, assigns a larger value to λ_{mfp} than to all λ_{waves} or even to the system size, L .

TABLE I

<u>Quantity</u>	<u>Definition</u>	<u>Ratios</u>	<u>Range</u>
$r_{\min}$	90°-collision impact parameter
$n^{-1/3}$	interparticle distance	$\Lambda^{2/3}$
λ_D	Debye Length	$\Lambda^{1/3}$
ρ_{Le}	electron gyro-radius	$(m_i/m_e)^{1/2}$	λ_{waves}
ρ_{Li}	ion gyro-radius	$\Lambda/\ln \Lambda$	
L	system size
λ_{mfp}	Coulomb mean free path
λ_{DT}	nuclear (DT) mean free path		

In an ordinary gas, two-body collisional relaxation is the dominant and fastest process. $\lambda_{mfp} \ll \lambda_{waves}$ and sound waves are propagated by the imbalance of collisions, due to density gradients. But in a hot plasma, collisional relaxation is subdominant and very slow, and waves are propagated by perturbations in the collective $\vec{E}$ and $\vec{B}$ fields. Where the zero-order distribution in an ordinary gas is a local Maxwellian, the zero-order distribution in a hot magnetized plasma simply follows the unperturbed single-particle trajectories ("ballistic" trajectories) in the background magnetic field. If collisions are sufficiently infrequent, some of the particles have time to become trapped even by the fields of small-amplitude waves, and the trajectory calculations must be corrected for this phenomenon. The collisionality regimes for waves are then:

	Landau	
trapped particle	transit-time,	
(e.g., Bernstein-	cyclotron, and	collisional
Greene-Kruskal)	cyclotron-harmonic	
	damping	

$v_{eff} \approx \omega_{bounce}$	$k_{\perp} \lambda_{mfp} \sim 1$
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$$v_{collisions} \rightarrow$$

Those familiar with neoclassical theory for toroidal confinement will recognize this type of chart. The common element between waves and toroidal confinement is that particles in a tokamak, for instance, could view the

variation of magnetic field strength along a magnetic line of force as a large-amplitude stationary wave.

4. Ion Cyclotron Damping

In the central region of the above figure are listed the most common forms of so-called "collisionfree" damping. Although Landau damping was the first one to be given a theoretical description /7/, the first successful experiments in this general area were those which demonstrated cyclotron damping. In 1958 a 200-kW ICRF experiment /8/ with plasma diagnostics based both on the 50-volt Doppler-broadening of C III impurity lines and on D-D neutron production demonstrated plasma heating through the absorption of ion cyclotron waves. Representative data from this experiment are shown in Fig. 7.

The evidence for generation and damping in the 1958 experiment was indirect, but in 1961 a group led by W. M. Hooke /9/ demonstrated ion

Fig. 7. Plasma heating near the ion cyclotron frequency. From top to bottom: Antenna radiation resistance; intensity of D β spectral line; intensity of λ 4647 C⁺⁺ spectral line; detected neutrons. Ion cyclotron resonance at 15090 gauss. The peaks around 16,600 gauss are attributed to the generation of electromagnetic ion cyclotron waves. From Stix and Palladino (1958).

Fig. 8. Sketch of B-65 apparatus at PPPL. Note irregularly decreasing magnetic field ("magnetic beach") to left and right of rf coil. From Hooke et al. (1961).

cyclotron wave damping directly by magnetic probes placed in the plasma. Figure 8 gives a sketch of the apparatus, showing the profile of the magnetic field which decreased in magnitude on each side of the ICRH coil. Electromagnetic ion cyclotron waves generated under the coil, where $\omega < \omega_{ci}$, propagated into these two "magnetic beach" regions to be absorbed in the vicinity of the point where locally $\omega = \omega_{ci}(z)$. Figure 9 shows magnetic probe data giving the wave amplitude in the beach region for three values of $\omega/\omega_{ci}(0)$, and confirms the strong attenuation of the wave near the $\omega = \omega_{ci}(z)$ point.

But an unexpected and fascinating thing happened when the machine field was set high enough so that the $\omega = \omega_{ci}(z)$ condition was not satisfied anywhere between the mirrors. The wave amplitude increased going away from the coil. Actually, as seen in Fig. 10, it went through a maximum, then a

Fig. 9. Magnetic probe signals in magnetic beach region of B-65, for three different machine magnetic fields. $\Omega = 1$ designates point where $\omega = \omega_{ci}(z)$ locally. From Hooke et al. (1961).

Fig. 10. Magnetic probe signals from magnetic beach region of B-65. Machine magnetic field set so that $\omega < \omega_{ci}(z)$ everywhere between mirrors. From Hooke et al. (1961).

minimum, then a second maximum. Hooke's team was able to identify these wave-amplitude extrema with extrema in the local values of $\omega_{ci}(z)$, the maximum wave amplitude appearing at the point of minimum $\omega_{ci}(z)$. WKB theory shows that $k_{\parallel}(z)$ would also be a maximum where $\omega_{ci}(z)$ is a minimum, so even though the wave is not yet damped, it is slowed down, and conservation of the flux of wave energy then requires the undamped wave amplitude to increase. By analogy to wave behavior near a cutoff ($k_{\parallel} \rightarrow 0$), the process found here now is given the generic title of "Airy swelling."

5. Proton Whistlers

To now, the two waves which I have talked about are the whistler mode, which belongs to the fast-Alfvén-wave branch of the dispersion curve, and ion cyclotron waves, which belong to the slow-Alfvén-wave branch. In 1964, another totally unexpected event was observed -- this time in satellite data from the ionosphere. The team of Gurnett, Shawhan, Brice, and Smith /10/ identified spectrogram traces showing the coupling of these two branches, the conventional whistler triggering -- at a location in the ionosphere where a certain critical condition is satisfied -- the

Fig. 11. Proton whistler signals observed in satellite data. Excited at a remote location by an electron whistler, the received proton whistler tone rises in frequency and asymptotically approaches the local proton cyclotron frequency. From Gurnett et al. (1965).

generation of an electromagnetic ion cyclotron wave, Fig. 11. Dispersion of the ion cyclotron wave as it traveled from its generation point to the satellite gave a whistling character also to its received signal. In this circumstance, the tone rises with time and asymptotically approaches the local ion cyclotron frequency. In their classic 1965 paper, the authors note that the proton whistler was never observed without an electron whistler present, that the asymptotic proton whistler frequency was experimentally within 3.5% of the local proton gyrofrequency, and that the point of generation for the proton whistler could be identified with a critical plasma-parameter condition under which equations describing the two modes of propagation become strongly coupled. Moreover, the critical condition itself is unusual: the condition is that the plasma dielectric tensor element $\epsilon_{xy} = 0$, a condition which is never satisfied in a proton-electron plasma, but can only be satisfied if another ion species (e.g., He^+ in the ionosphere) is also present.

6. Landau Damping

1964, the year of the proton whistler experiment, was also the year that Landau damping itself was given quantitative verification in laboratory experiments. Precise experiments were performed by Malmberg and Wharton /11/ on electrostatic electron plasma waves in a laboratory plasma with mean free paths about twenty times (4000 cm) the length of the apparatus. Accurate exponential decay in agreement with Landau theory was observed over two orders of magnitude of wave power, and quantitative agreement was also found for the Langmuir-Tonks dispersion formula with the warm-plasma Bohm-Gross correction. Figs. 12 and 13.

Fig. 12. Experimental observation of Landau damping of electrostatic electron plasma wave. Interferometer and amplitude signals versus distance. From Malmberg and Wharton (1964).

Fig. 13. Dispersion relation for electron plasma waves, from experimental observations. From Malmberg and Wharton (1966).

7. Nonlocal Response

Up to this point, we have been discussing just one property of long mean-free-path plasmas -- collisionfree damping. Let us now look at another property: nonlocal response. By this one means that the response to a perturbing impulse can appear at a later time and at a different place from the original impulse. A long mean-free-path medium has this property, and its current local behavior can be influenced by the whole history of the plasma from earlier times and from other places. To understand the formal treatment of nonlocal phenomena, let us for a moment consider a long mean-free-path ordinary gas. One could formulate a complete set of normal modes for such a gas by writing

$$n(\vec{x}, t) = \int_{\vec{k}, \omega} n(\vec{k}, \omega) \exp[i(\vec{k} \cdot \vec{x} - i\omega t)]$$

and it would be possible in a collisionfree gas to construct a single mode out of a modulated beam of gas atoms all moving with the same velocity, $\vec{v}_0$. The mode can be written in the form of a "ballistic" perturbation, $f(\vec{x} - \vec{v}_0 t)$,

$$f(\vec{x}, \vec{v}, t) \sim \delta(\vec{v} - \vec{v}_0) \exp[i(\vec{k} \cdot \vec{x} - \vec{k} \cdot \vec{v}_0 t)]$$

which clearly satisfies the Boltzmann equation for the collisionless gas,

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} = 0.$$

The frequency associated with each such normal mode is just $\omega = \vec{k} \cdot \vec{v}_0$.

Now the normal modes for a collisionfree plasma are almost of the same form. They are the well-known Van Kampen modes /12/, and at the heart of each

Van Kampen mode is such a modulated beam of electrons or ions moving with a single velocity. The velocity distribution for the mode is therefore singular [containing a portion $\sim \delta(\vec{v} - \vec{v}_0)$] and the mode is -- as it should be -- undamped. Recall that Landau damping applies only to initial perturbations which are very well behaved functions of velocity. If one wishes to describe a perturbation which initially is a smooth function of velocity in terms of these normal modes, it is necessary to put together a band of them in $(\omega, \vec{k})$ space in order to smooth out their singularities in $\vec{v}$ -space. But as time passes, the individual modes, with different frequencies and wavelengths, get out of phase with each other and the macroscopic manifestations of the perturbation disappear by destructive interference. This is the well-known process of "phase-mixing," and it provides the explanation of Landau damping from the point of view of normal modes. However, even after macroscopic effects have phase-mixed away, all these microscopic normal modes are still present. In an elegant experiment, performed in 1968 on the same apparatus used for the Landau damping work, it was shown by Malmberg, Wharton, Gould, and O'Neil /13/ that -- long after the disturbance had ostensibly disappeared by Landau damping -- coherence could be reestablished. The reappearance, called a plasma wave "echo," can be explained qualitatively in a simple way. Consider that a grid, at $x = 0$, is electrically modulated at frequency ω_a . The modulations will produce perturbations to the plasma of the ballistic form, $f(x - vt)$, which might be written for this case

$$f_a^{(1)}(x, v, t) \sim f_a(v) \exp[-i\omega_a(t - \frac{x}{v})] .$$

Now a second grid, placed a distance l away, is excited at frequency ω_b . It also will produce first-order perturbations, $f_b^{(1)}(x, v, t) \sim$

$f_b(v)\exp(-i\omega_b[t - (x-l)/v])$ but there will be a second-order effect due to the modulation of the first group of electrons by the second grid,

$$f^{(2)}(x, v, t) \sim \left(\frac{f_b^{(1)}(x, v, t)}{f_b(v)} \right) f_a^{(1)}(v) \\ \sim f(v) \exp[-i((\omega_a - \omega_b)t - \frac{\omega_a x - \omega_b x}{v} - \frac{\omega_b^2}{v})].$$

Integrating over all velocities, the velocity-dependent terms phase-mix the contributions to zero except where the velocity dependence in the exponent disappears, namely, where

$$x = \frac{\omega_b l}{\omega_b - \omega_a}.$$

At this value of x , which can be far away from both grids, the phase mixing or Landau damping for the second-order perturbations is unscrambled, these perturbations all become coherent again and a macroscopic signal reappears. A plot of experimental data is given in Fig. 14.

Fig. 14. Power at echo frequency, 160 MHz, versus distance. First grid, at $x = 0$, is excited at 120 MHz, second grid, at $x = 40$ cm, at 280 cm. Calculated position for center of echo is $x = 70$ cm. From Malmberg et al. (1968).

8. Randomization Without Collisions

For the long-mean-free-path processes we have discussed, namely cyclotron and Landau damping, Van Kampen modes and plasma-wave echoes, the limitation on the mean-free-path has been described due only to collisions. There are,

however, other processes which can play the same randomizing role: noise, interference, turbulence, etc. But randomness or stochasticity can also be present even in an absolutely ideal, quiescent and collisionfree situation. This type of randomization can occur when there is a loss of symmetry, such as for a charged particle moving in the field of two incommensurate waves, or when a helical magnetic perturbation is imposed on the otherwise axisymmetric magnetic lines of force in a tokamak. There are abundant examples in plasma physics: such stochasticity is often the mechanism through which adiabatic invariance breaks down, and the process can play important roles both in plasma heating and in plasma transport. But let me draw an example from outside plasma physics.

The gravitational attraction between stars follows the same $1/r^2$ force law as Coulomb interactions, and galaxies can furnish prime examples of very long-mean-free-path systems: collision times are typically many times the life of the galaxy. A question receiving current attention in astrophysics is the construction of self-consistent collisionless equilibrium velocity distributions which will reproduce the desired $n(\vec{r})$. The most general stable configuration is thought to be the triaxial shape, i.e., an ellipsoid with $a \neq b \neq c$, Figs. 15 and 16. M. Schwarzschild /14/, together with his students, have used computers to follow thousands of single-star orbits through very smooth model triaxial potentials. For such potentials, there is only one classical constant of motion, namely, the energy, yet nonclassical (typically two more) invariants of motion frequently show up in the orbit integrations, as in Fig. 17 due to de Zeeuw and Merritt /15/. And Schwarzschild believes that self-consistent triaxial solutions almost always require that most of the orbits possess (at least for a galactic lifetime) such additional two nonclassical invariants -- because (a) enough randomness would allow the

Fig. 15. Galaxy in the Andromeda nebula. Measured dispersion of star velocities indicate extremely low degree of collisionality.

Fig. 16. Great Galaxy in Andromeda. Bulge is collisionfree, but stars in disc at edge have probably been formed through condensation there of cold gas and show much lower random velocities.

orbits to reach all points within the potential energy surface in phase space; and (b) the gravitational potential, found from Poisson's equation, will always be smoother in space than the density distribution. But the computer analysis confirms that not all orbits even in highly idealized potentials will have three invariants as in Fig. 17: resonances, island structures, and collisionless stochasticity may also appear. Sufficient such stochasticity then appears to inhibit the creation of self-consistent triaxial phase-space distributions. Surface of section plots showing collisionless stochasticity in some triaxial orbit calculations are shown in Fig. 18.

Fig. 17. Representative "box" and "tube" orbits confined to the plane of rotation, calculated for Schwarzschild triaxial potential. From de Zeeuw and Merritt (1983).

Fig. 18. Surface of section plots for stellar orbits in the plane of rotation, for galaxy with Schwarzschild triaxial potential. v_x versus x . Note stochastic region. From de Zeeuw and Merritt (1983).

9. Finite Larmor Radius Effects

As final topics within the general area of long-mean-free-path phenomena, let me talk about finite-Larmor-radius and cyclotron-harmonic effects. These two topics are related because strong cyclotron-harmonic wave-particle

interaction requires that the resonance condition, $\omega - \vec{k} \cdot \vec{v} = 0$, be satisfied somewhere on the circular orbit. For harmonic resonance at $\omega = n\omega_c$, one then needs $k_{\perp} v_{\perp} \gtrsim n\omega_c$, or $k_{\perp} \rho_L \gtrsim n$.

While both ion and electron cyclotron harmonic radiation had been observed in several experiments a few years earlier, by far the most dramatic and most influential experiment in this area was that done by G. Landauer /16/ in 1961, observing the noise emission from a simple Penning discharge. The receiver frequency was 34.4 GHz, the magnetic field was varied between 2500 and 500 gauss, and all the harmonics between $n = 5$ and $n = 25$ appeared, nicely separated, at his receiving antenna, Fig. 19. It was Canobbio and Croci /17/, in 1963, who recognized the kinetic implications of this experiment, namely, that the origin of the harmonic structure must be the excitation of electrostatic waves with extremely short wavelength, i.e., electron Bernstein waves with $k_{\perp} \rho_{Le} \gtrsim n$. Then, in a related experiment in 1964, Buchsbaum and Hasegawa /18/ found that electron Bernstein modes could be established as radial standing waves inside a plasma column. And it was to explain Landauer's original observation, in which rf energy presumably in electron Bernstein running waves deep inside the plasma managed to propagate out to an external receiving antenna, that led to the development of mode-conversion theory /19/.

Fig. 19. Noise at 34.4 GHz from Penning discharge. Horizontal axis is magnetic field; ticks at 500, 1000, 1500, 2000, 2500, and 3000 gauss. From Landauer (1962).

Recent experiments by Ono, Wong, and Wurden /20/, have focused on ion Bernstein waves. Mode conversion is again involved -- these waves are launched as electrostatic electron plasma waves $[k_{\perp}^2(1 + \dots) + k_{\parallel}^2(-\omega_{pe}^2/\omega^2) \approx 0]$ at the plasma edge, and mode-convert to $\tilde{E} \perp \tilde{B}_0$ ion-Bernstein waves beyond the lower-hybrid resonance layer ($\epsilon_{xx} = 0$) inside the plasma. Some results from the ACT-I apparatus at Princeton are shown in Fig. 20.

Ion cyclotron harmonics have also been observed in satellite experiments. Figure 21, taken from the paper of Gurnett, Pfeiffer, Anderson, Mosler, and Cauffman /21/ (1969), shows a clear periodic structure for at least the first six proton cyclotron harmonics in the observed electric and magnetic field spectra.

10. Conclusion

In conclusion, what has been presented has been a limited selection of experiments and their interpretation in the field of plasma waves. I have used the concept of long mean-free-path to tie the selections together, but beyond that, I would hope that this quasihistorical review highlights the essential interplay not only between observation and theory and experiment, but also between the many disciplines that invoke plasma physics as a tool, including radio communication, astrophysics, controlled fusion, space physics, and basic research.

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Fig. 20. Ion Bernstein wave data from ACT I at PPPL. Upper left: downstream interferometer traces for different values of ω/ω_{ci} , measured at $x = 2$ cm, versus distance into the plasma. $B_0 = 4.3$ kG at $x = 2$ cm. Electron plasma wave, at left, mode-converts to ion Bernstein wave at higher densities. Upper right: interferometer traces, downstream from the antenna, for five values of time delay as fractions of a wave period. Radial propagation has the character of a backward wave. Lower figure: Theoretical ion-Bernstein-wave dispersion relations for three different ion temperatures, with experimental points. From Ono, Wong, and Wurden (1983).

Fig. 21. Satellite data showing ion cyclotron harmonic structure on the electric and magnetic components of the received signals. From Gurnett et al. (1969).

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