Comment on “Properties of lower hybrid solitary structures: A comparison between space observations, a laboratory experiment, and the cold homogeneous plasma dispersion relation” by Schuck et al.

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[1] Laboratory experiments involving the interaction of lower hybrid waves and density cavities with full width at half maximums ranging from $1 \equiv k_{\perp} \delta \leq 4$, where $\delta = \frac{\omega_p}{\omega}$ is the collisionless skin depth, were performed several years ago at the University of California, Los Angeles. The results were published in the Journal of Geophysical Research in December 2001 [Rosenberg and Gekelman, 2001]. These experiments are relevant to scaled parameters in the auroral ionosphere. This is a comment to the paper of Schuck et al. [2003], regarding the laboratory experiment on lower hybrid (LH) waves in the presence of a density striation. The main point Schuck et al. [2003] wish to make is that density striations in the auroral ionosphere are narrower than $\delta$ and that $k_{\perp} \delta \approx 10$ there. They argue that if this condition is not strictly satisfied in laboratory experiment then they are inappropriate to model the physics occurring in the ionosphere. In our experiments an incoming short perpendicular wavelength lower hybrid wave impinges upon a density striation which is many parallel (to B0) LH wavelengths long. A striking transformation occurs in which a cavity mode confined to the density gradient of the striation is excited. The mode localization does not depend on the ratio of the cavity diameter with respect to $\delta$. We discuss the properties of lower hybrid waves, the experimental results as well as differences in the rocket and laboratory experiments. INDEX TERMS: 0624 Electromagnetics: Guided waves; 2447 Ionosphere: Modeling and forecasting; 2471 Ionosphere: Plasma waves and instabilities; 2487 Ionosphere: Wave propagation (6934); KEYWORDS: density cavities, lower hybrid waves, striation eigenmodes, lower hybrid solitary structures, experiments on LHSS


1. Introduction

[2] Two experiments involving the interaction of waves in the whistler frequency range and density striations have been performed in the University of California, Los Angeles (UCLA) large plasma device (LAPD) in the past 10 years. The first experiment involved the interaction of a long wavelength whistler wave with a magnetic field-aligned density cavity [Bamber et al., 1995]. The wave was launched with a small loop antenna and propagated across the background magnetic field until it struck a field aligned density cavity. The whistler waves directly converted to lower hybrid (LH) waves at the boundary of the striation but did not propagate deeply into it. The LH wavelength perpendicular to B0 was a fraction (\~{}1/10) of the cavity diameter. The reflection of the whistler wave as well as the conversion efficiency into lower hybrid waves was carefully measured. The LH waves did not become a mode, which filled the cavity. In the second experiment, LH waves were launched from a slow wave structure. In a uniform plasma the wave exhibited the expected spatial structure [Rosenberg and Gekelman, 1998]. In the presence of the striation the results are remarkably different [Rosenberg and Gekelman, 2001, hereinafter referred to as RG]. The waves generate a cavity mode with an electric field that is confined to the steep density gradient, an interval smaller than $\delta$, in the striation. Cavities of various diameters and shapes were used and the result was invariant. This mode “lives” on the density gradient. The parallel wavelength of the waves in the cavity was measured and agreed well with the cold plasma dispersion relation for LH waves. Experimental data of the cavity mode behavior during one half period is shown in Figure 1. (Journal of Geophysical Research made an error and printed Plate 6 twice in RG, and Figure 1 corresponds to what Plate 3 should be in RG). Inspection of the figure shows that the wave energy forms a ring distribution, which is localized on the density gradient (also see RG).

[3] In another erratum in RG, there is a mistake in the figure caption and description of Figure 6. The frequency was 90 MHz, which is 6.5 times the lower hybrid frequency in the background plasma. Schuck et al. [2003, hereinafter referred to as SBP] point this out and we thank them as there was an error in proofing the manuscript on our part. Finally, the RG article had an incorrect reference as pointed
Figure 1. Temporal evolution of the electric field in a density striation which is deep \( n_{\text{center}} = 0.20 n_{\text{exterior}} \). This pattern is for \( f/f_{\text{LH}} = 6 \); however, another measurement at \( f/f_{\text{LH}} = 2 \) gives essentially the same pattern. The striation diameter is \( D = 2.55 \) cm which is 6.54 ion gyroradii across, but the density gradient is about one ion gyroradius wide. The skin depth in the cavity is 1.87 cm \( (D/\delta = 1.36) \) and outside the cavity is 0.75 cm \( (D/\delta = 3.4) \). The wave activity is localized to a region \( \Delta \), which is 0.39 cm in diameter \( (D/\Delta = 0.2) \). In this figure, time evolves down the left column and then down the right column. When the field is maximum in panel 1 the sense of rotation points into the page (the background magnetic field points into the page as well). The field progresses through a minimum in panels 3 and 4. Finally, the field reaches another maximum in panel 6 with the sense of rotation out of the page \( (180^\circ \text{ out of phase}) \). The wave frequency is 90 MHz. The LH wave frequency is 15 MHz. The time interval between time 1 and time 6 is 5.56 ns.
out instead of Ergun et al. [1998] (a paper about electron holes and Langmuir turbulence) it should have been Ergun et al. [1995], which discusses VLF wave localization in density depletions.

2. Wave Behavior at the Electron Inertial Scale

[4] One of the main points in SBP is their assertion that the magnetic field of the waves to the left of the minimum in the $k_c - k_{L}$ dispersion plot (RG, Figure 2, or SBP, Figure 3) is vanishingly small and the waves are strictly electrostatic. It is certainly true that this minimum separates whistler waves, which lie to the right of it, and lower hybrid waves. For the purpose of calculating a LH dispersion relation the electrostatic approximation can assume $\vec{E} = -\nabla \phi$ and $\vec{k} \parallel \vec{E}$ and good wavelength predictions for a given frequency. They quote Stix [1992, p. 54] on this point. We point out that reading ahead in the work of Stix to p. 57, 

"it may be mentioned that the evaluation of the electrostatic validity criteria, ..., may not be as simple as would appear at first glance." To determine the transverse (to $B_0$) component of $E$ "...one must go beyond the electrostatic approximation evaluating $E$ and include at least the leading electromagnetic correction".

[5] In section 2, SBP discuss their measurements from which they conclude that the LHSS are rotating structures. They cite Høyomørk et al. [2000], who observed very small magnetic fields in the density striations, which were poorly correlated to electric fields. SBP then argue that since $D/\delta$ (ratio of the striation diameter to the skin depth) is 0.2–0.4 in the laboratory and 1.3–4 in the laboratory (see Table 1 in RG), the laboratory experiments must have nothing to do with the phenomena in space. They then make the incorrect argument that only electrostatic waves can exist at scale lengths less than $\delta$. Based on this, Schuck et al. [1998] did a purely electrostatic theory which agreed with the electric field measurements (which included phase information) on their rocket experiment.

[6] There is nothing mysterious about the skin depth $\delta$. For LH waves there is no abrupt transition from electromagnetic to electrostatic waves at wavenumbers, $k \approx \frac{1}{\delta}$. This is not difficult to show. We start with the Appleton-Hartree equation

$$n^2 = 1 - \frac{2\Pi \omega^2 (1 - \Pi)}{2\omega^2 (1 - \Pi) - \omega_c^2 \sin^2 \theta - \omega_c \Delta}$$

$$\Delta = [\omega_c^2 \sin^2 \theta + 4\omega^2 (1 - \Pi) \cos^2 \theta]^{\frac{1}{2}}$$

$$\Pi = 1 - \frac{\omega_c^2 + \omega^2}{\omega^2} \approx 1 - \frac{\omega_c^2}{\omega^2}$$

Here $n$ is the index of refraction ($n = kc/\omega$), $k$ is the wavenumber, and $\theta$ is the angle of propagation of the wave with respect to the magnetic field. The leading term, 1, in the index of refraction can be neglected and the equation rewritten as:

$$f(\omega, \theta) = \frac{1}{k^2 \delta^2}$$

Here $\delta$ is the electron inertial length or collisionless skin depth. The term $f(\omega, \theta)$ goes to zero along the resonance cone angle. This is the point where the wave no longer propagates. From equation (2) we see no abrupt transition at $k\delta = 1$. Let us now examine the magnetic field of the wave. If we take the dot product of $\vec{B} = \vec{n} \times \vec{E}$ we can easily show:

$$B^2 = k^2 \delta^2 \frac{\omega_c^2}{\omega^2} [1 - (\vec{n} \cdot \vec{E})] \epsilon^2$$

Here $\vec{n}$ is a unit vector in the direction of the wave propagation and $\vec{E}$ is a unit vector along the wave electric field. The product $\vec{n} \cdot \vec{E}$ is 1.0 on the resonance cone. That is the only propagation angle where the wave has no magnetic field. In this situation, $k_c \ll k_{L}$, therefore $k_{L} \approx k$. Once again if we are not propagating along the cone angle there is no abrupt transition at $k \delta \approx 1$. SBP in section 5 argue that one component of the ratio of the longitudinal to transverse electric fields depends upon the skin depth but this argument is nonintuitive. What matters is the ratio of the wave magnetic field energy divided by the total wave energy as a function of $k \delta$. This is shown in Figure 2.

[7] In our experiment for propagation angles within 3 degrees of the resonance cone 40% of the wave energy is in the magnetic field. SBP are correct in stating what the electrostatic approximation is, but this approximation is strictly true only in the limit in which $k_{L} \rightarrow \infty$.

[8] The lower hybrid wave magnetic fields are easily detected in the laboratory. This is very clearly seen for the lower hybrid phase fronts shown in Figure 4c in the work of Rosenberg and Gekelman [1998]. The LH waves have a short wavelength across $B_0$ and a long wavelength along $B_{0b}$ and their phase fronts are inclined with respect to the background magnetic field. The experiments of Bamher et al. [1995] used a magnetic probe to measure the properties of whistler waves as well as their mode conversion to lower hybrid waves. This would not be possible if LH waves had no magnetic field. Subsequently a measurement of the electric field of the LH waves under the same experimental conditions. (Rosenberg and Gekelman [1998] verified this.) It has long been recognized [e.g., Taylor and Shawan, 1974] that LH waves have a magnetic field and its magnitude is highly dependent on the wave normal direction. The transition to an electrostatic wave occurs gradually, and the wave is only purely electrostatic at exactly the lower hybrid frequency, where it does not propagate. What we mean by stating that lower hybrid waves are well described by electrostatic theory is that the dispersion relation will give you a good prediction for the wave-length and propagation direction at a given frequency.

[9] One would expect that close to the LH frequency the wave magnetic field is small, but it is still measurable in the laboratory and should be measurable in space with sensitive detectors. At the American Geophysical Union Spring Meeting 2001, it was reported [Knudsen, 2001] that the GEODESIC sounding rocket detected wave magnetic fields in density cavities with a range in the ratio $\frac{B}{E}$. There was an instrumental problem which is in the processes of being sorted out, but the experimental group is confident that the magnetic signal in the case for $\frac{B}{E} \approx 0.4$ which they analyzed is real (D. J. Knudsen, private communication, 2003); they will submit results for publication this year.

[10] The mode observed in the laboratory experiment is an eigenmode of the cavity excited by the incoming LH wave. It is not a plane wave. We use the cold plasma
Figure 2. (a) The ratio of the wave magnetic field to total wave energy and (b) the ratio of the electric energy to total energy as a function of $k_{\perp} \delta$. Note that at $k_{\perp} \delta = 1$, half the wave energy is in the magnetic field. This is therefore not the point where one can declare the wave to be electrostatic. It is obvious from the energy curve that there is no dividing point between whistler and lower hybrid waves. From a magnetic energy content standpoint the wave becomes electrostatic when $k_{\perp} \delta \gg 1$. From the perpendicular phase velocity perspective it is at the dispersion curve minimum where $k_{\perp} \delta \approx 1$ (RG, Figure 2). Curve for the lab experiment in Argon plasma, $B_0 = 1650$ gauss, $n = 5 \times 10^{11}$ cm$^{-3}$.

dispersion relation (Appelton-Hartree) for plane waves only as a point of reference. In section 2 of RG we point out that the dispersion along the background magnetic field is, to first order, unaffected by the presence of the density striation whereas the perpendicular wavenumbers certainly are. We measure $k_\parallel$, and in Figures 5 and 6 plot it and the cold plasma dispersion relation. The measured spatial field pattern is used to given a spectrum of perpendicular wavenumbers. What these figures show is that the wave in the cavity is consistent with lower hybrid waves. A theory, which is not purely electrostatic, is necessary for comparison with this experiment. Doing this is nontrivial (see, for example, calculations by Kondrat’ev et al. [1999]). Such a theory would include scattering/diffraction of the incoming waves and an eigenmode calculation for the cavity. In this light, the points SBP make about the failure of the AHDR to predict the experimental measurements of $k_\perp$ are meaningless. What is needed is a better theoretical model to explain the laboratory experiments as well as spacecraft data.

3. Comparison of the Laboratory Experiment With Rocket Data and Models

[11] In the experiment we measured the electric field $\vec{E}_\perp$ everywhere in the plane of the striation. In the experiment the field was measured with an electric dipole probe. There were two sets of small balls, one on each tip on this probe. The probe in its entirety consisted of two dipole probes at right angles to each other. The potential difference between the tips gives a signal proportional to the electric field. We could plot the phase shift as a function of position for any trajectory across the cavity. We chose to display the azimuthal and radial phase, since the striations we did this for had cylindrical symmetry.

[12] Depending upon the trajectory one takes in traversing the striation, one can get a large variety of phase relations. The wave phase as a function of time on a rocket flight is only meaningful if you know exactly how the fly-through occurred and can compare it with three-dimensional theoretical model. SBP claim that the phase relations measured in the laboratory is due to density inhomogeneity in the cavity but trajectories through chords, which have symmetric $n(r)$ (RG, Plate 9), were used in the analysis as well. It is not clear that all striations in the ionosphere are Gaussian and highly symmetric. In space one cannot accumulate contour plots of density in a plane and symmetry is assumed. In fact, the density on the AMCIST mission [Pinçon et al., 1997] was not measured at all! The density profile was inferred from background waves received by the dipole probes. Conclusions about LHSS from the PHASE2 rocket flight [Bonnel et al., 1998] are similar to those of AMCIST, and density was not measured there either. The density was inferred again from frequency. A third rocket flight, which included a study of LHSS as rotating eigenmodes, was TOPAZ III. There was a Langmuir probe on board. The raw data [Schunk et al., 1998, Figure 6] show an asymmetric density depression, which is nearly all gradient. The signal to noise in the electric field data shown in Figure 6 is about 2; by inspection one sees a field enhancement, which seems large on the steeper side of the gradient. The orientation of the beams in the TOPAZ III experiment was such that the radial component of the electric field in the striation was measured [Schunk et al., 1997]. The theory predicts that the radial phase velocity component would point to the right (Figure 7) for a right hand rotating mode. This was observed using the same analysis techniques for AMCIST. In the laboratory the radial phase velocity changed sign when the center of a cavity with symmetrical density gradient on either side was traversed. If a chord in a nonsymmetric path were taken, the reverse could occur. In short, without knowledge of the striation morphology, definitive conclusions drawn from phase data are suspect.

[13] We are in no position to comment on the techniques used to analyze the rocket data, which are in fact not the observation of a monochromatic wave (cross-spectral analysis is necessary) and are complicated by the rocket motion and short “encounter” time. Let us assume that everything they did was correct. Pinçon et al. [1997] show that as they move through a radial chord the derived phase velocity reverses sign (see Figure 8) from which they infer there is a rotating mode.

[14] In RG, as was pointed out, a different coordinate system was used, but the laboratory measurement shows the azimuthal component of the vector does not change phase when the diameter of the striation is traversed, but the radial component does change sign. If we switch to the coordinates in the work of Pinçon et al. [1997], there is no change in the “vertical” phase velocity in our data. The lab
experiment is π out of phase with the AMCIST rocket flight for a trajectory through the center of the cavity. If we choose trajectories along chords we can get the vertical phase velocity to change sign across the striation as in the rocket experiment.

[15] In the laboratory experiment, the LH wave is radially localized to the density gradient. If an imaginary spacecraft were to fly through the pattern shown in Figure 1, it would record a double humped distribution of wavefield. In spacecraft measurements the trajectory through the cavity is not precisely known (there can be a component of the motion along the cavity and the chance of going through the diameter is smaller than that of cutting through a chord). However, some data as in the work of Kjus et al. [1998, Figures 7a and 7b] shows that the most intense wave activity occurs on the gradient. This is not the case for the cavity in Figure 7d, however. That cavity was narrow enough that the probes, which measured density, gave profiles which, in our opinion, were different enough to make the gradient location unclear. Kjus et al. reach the following conclusion (p. 26,644): “The wave packets observed in the MF band have a double humped appearance similar to that of Figure 7a for approximately 10% of all cases. The observational material is for the time being too sparse to allow a statistical analysis of this particular question, but it might be that most of the cavities are actually associated with a ring distribution of wave energy and that observations without any bifurcation are merely a consequence of the satellite glancing the cavity along a trajectory, avoiding the central wave energy depletion.” The rocket data shown in Figure 6 of Schuck et al. [1998] is far less clear and, to the unpracticed eye, it appears that the wave activity changes during the traversal of the density cavity, but the spatial detail is not there.

[16] In the lab experiment, the smallest striation studied is 1 cm in diameter, which is about 1.4 times the skin depth in the background plasma. There is no difference in the laboratory in phenomena observed at this small scale and those for much larger striations (D = 3λ). There is a mode which is localized to the density gradient in every case. The transverse distance over which this mode is localized is less than a skin depth (D/δ = 0.2) across. From Figure 1 it is clear that the pattern is not purely electrostatic, ∇ × E ≠ 0, A ≠ 0.

4. Conclusion

[17] A laboratory experiment at UCLA has been conducted to investigate the interaction between lower hybrid waves and a field-aligned density cavity. This experiment was scaled to be relevant to the auroral ionosphere. In this study a wave launched from an antenna at a fixed frequency gave rise to a cavity mode, which was localized on the steep density gradient of the cavity. The measured wave fields in the cavity show it was not purely electrostatic and there is a wave magnetic field along the striation. This was a surprising result and we believe must be considered by those instrumenting future rocket flights. The laboratory experiment does not claim to reproduce the aurora. In the auroral ionosphere, LH waves and whistler waves at a variety of frequencies bombard the naturally occurring cavities from all directions. The laboratory cavity (unlike striations in the aurora) was not Gaussian in shape. The laboratory striation was many parallel LH wavelengths along the magnetic field. The morphology of auroral striations along the magnetic field is unknown, and the perpendicular morphology is surmised from the statistics of many chord traversals of different striations. The results of the laboratory experiment differ from the electrostatic model for the rocket flights.

[18] SBP comment that this experiment is not relevant to LHSSs. They argue that the difference, which makes the laboratory scaling invalid, is that the lab striation was not smaller than an electron inertial length in diameter. The basis for this is an argument about electrostatics we show to be invalid. Our claim is that it is relevant, although it does not agree with their electrostatic model. There is a range of striation diameters in the ionosphere spanning a range of D/δ smaller and larger than unity. The laboratory experiments are certainly relevant to the range D/δ ≥ 1 and show no indication that a drastic change occurs at D/δ = 1. To be fair, their model agrees with the analysis of their rocket data; however, the data may be incomplete because they do not know the morphology of the density striation through which their rocket flies and they did not measure magnetic fields. The resolution will come about when differently instrumented rockets are flown, more laboratory experiments are performed, and hopefully space experimentalists and laboratory experimentalists work together.

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