Chapter 5

Coda

Waves are pervasive in the auroral ionosphere. Langmuir waves in particular are ubiquitous, and a carrier of energy from their source regions in the magnetosphere, through and into the ionosphere. They can be useful as probes of ionospheric density, and for remote sensing. To fully understand Langmuir waves and make use of them, a thorough understanding of their generation, propagation, damping, and interactions with particles and other waves is necessary, and as Langmuir waves are generated in many other space plasma and laboratory environments, such results can be widely applicable. Several steps have been taken towards improving knowledge of and theories regarding Langmuir waves.

An autonomous, high-speed, digital signal-processing receiver has been developed and refined. The Dartmouth Rx-DSP is a flexible tool, capable of observing fine frequency-time structures, polarization, and source direction, and of onboard data reduction. The features of the Rx-DSP make ARCs built from them ideal for multifaceted studies of Langmuir waves and related phenomena, both remotely and in-situ. ARCs using these receivers have already made new science observations in both ground and sounding rocket deployments, including the first in-situ fine-structure observation of the polarization of auroral roar.

Wave-particle Correlator data from the CHARM-II mission has been presented and analyzed. This constitutes the first statistical observation from a Langmuir-wave Correlator system, and a resistive/reactive fit of the data shows a direct relation between the fit coefficients and electron-beam onset and dissipation. This relation implies that, for a beam which shows an increased Landau-resonance growth rate during onset, beam dissipation will show enhanced damping as the beam dissipates. The data also shows comparable levels of resistive and reactive activity, despite the high electric-field strength which should cause very swift relaxation of resistive electron populations. A flexible, numerical test-particle simulation has been developed to test the plausibility of this conclusion, and simulated results appear to be qualitatively in agreement with theories explaining these observations.

Finally, data from the unique, three-dimensional, high-frequency TAEFWD instrument flown on the TRICE mission has been presented. This data has allowed an unique examination of ionospheric bursty Langmuir waves in the cusp, which are theorized to result from wave-wave interaction. Comparison of the data to simulations of beating waves and results from

J-WHAMP imply that the interacting waves are some mixture of pure, linearly polarized Langmuir waves, and elliptically polarized, partially oblique modes from the upper-hybrid dispersion surface, commonly referred to as whistler-Langmuir hybrid waves.

5.1 Future Work

Future iterations of the Rx-DSP platform may include both hardware and software improvements. The Rx-DSP shows great potential, and has already proven itself as an effective tool, but a number of design flaws are included in the current version of the hardware—see Chapter A—which need to be addressed in future iterations; as well, newer versions of the core processors could increase the platform's basic capabilities, such as digitization bit-depth and DSP RAM. Potential firmware improvements include lossless or lossy data compression, live signal detection and center-frequency tracking, and further enhancements of ARC autonomy.

Concurrent with analysis and publication of the TRICE results, significant three-dimensional wave data from the STEREO spacecraft have been reported on (*Malaspina and Ergun* 2008). These have lead to interpretations of bursty Langmuir-wave structure in the solar wind as eigenmodes of density cavities. Strong perpendicular fields were seen in half of a set of 732 events, implying Langmuir/z-mode waves should generally play a large part in wave decay processes (*Graham and Cairns* 2014).

A significant limiter of the high-frequency, three-dimensional measurements afforded by the TAEFWD receiver as it was flown on the TRICE mission is the single temporospatial observation point. April 2013 discussions with Dr. Konrad Sauer elucidated that the TRICE TAEFWD observations are consistent with the appearance of whistler-Langmuir soliton structures, also known as 'oscillatons' (*Sauer and Sydora* 2001). Confirmation of this and further detangling of the structure of bursty Langmuir waves in both time and space would require multiple simultaneous and synchronous TAEFWD-like observations, with a range of separations from tens to hundreds of meters. Such instrumentation could also yield new data on generative electron-beam cross-sections, and yield new results on wave propagation and the non-Langmuir participants in wave-wave interactions.

While the wave-particle Correlator is an effective system as-is, some improvements towards increasing the high-quality event/mission detection rate are possible. While increased effort was made during CHARM-II mission integration towards reducing the total payload noise as seen by the Dartmouth HFE, even more noise reduction, including through the entire Correlator system, could reduce the interference that led to many manual event screenings. In addition, while the PLL system is generally effective, some form of additional pre-filtering or digital processing of the incoming HFE signal might allow for better tracking of the Langmuir frequency, yielding even more event confidence. An additional study which could be undertaken within the CHARM-II dataset is a search for further relations to the resistive and reactive components; e.g., while CHARM-II did not see large numbers of bursty Langmuir waves, a detailed manual examination of frequency splitting and spacings could prove edifying.

Both the numerical magneto-kinetic test-particle simulation and the growth rate calculation codes developed for comparison with Correlator results are extremely flexible tools. The test-particle simulation is easily expanded to different environments and parameter-spaces, including the potential to add a background electric field, and to vary travel distances, field strengths, field shapes, and particle charges and masses. The distributed, node-independent nature of the test-particle code allows for division of work among as many nodes and cores as are available, optimizing simulation run times given available resources. The distribution builder and growth rate calculator are modular, allowing for easy input of alternate topside distribution functions with angular dependencies, and for arbitrary time-varying beam distributions.

An improvement which is desirable but not immediately attainable is for higher time-resolution growth-rate calculations. The time-overlapping nature of the distribution function data—as well as the requirement $\Delta t_D/\Delta t_S > 10$—swiftly leads to RAM and CPU requirements becoming untenable when attempting to push the simulated detector cadence down towards realistic millisecond values. Further coding effort would be required in order to make a cluster-deployable version of the growth-rate code stack, enabling detailed examinations of the millisecond-scale growth rate reactivity.

Characteristics of bursty Langmuir waves in the solar wind and Earth's foreshock have been quantitatively explained via Stochastic Growth Theory (*Cairns and Robinson* 1997; *Cairns et al.* 2000; *Boshuizen et al.* 2001). Key to this theory is the effects of small-scale density inhomogeneities in the plasma. While the current simulation could theoretically model an inhomogeneous source region, numerical testing which includes density irregularities during electron beam transit would require a simulation such as a Particle-in-Cell code.

There are some quickly accessible future realms of study available, making use these codes with no or minimal revision, even using the existing set of test-particle data. These include highly dynamic scenarios with multiple beams at multiple energies, beams with time-varying source energies or limited angular extents, and even beams with varying azimuthal dependence. When the spatial component of the test particle simulation was discarded towards the end of the test-particle simulation, it equated to an implicit assumption of source-region homogeneity, but this is known not to be unrealistic. As positions are present and accurate in the data, they could be utilized for studies involving the spatial extent of Langmuir-wave generating beams. Augmentations to the growth-rate code stack would allow for examinations of growth rates for obliquely propagating waves. Finally, the test-particle simulation is capable of runs with background electric fields, higher or lower particle launch energies, and higher resolution in both energy and pitch angle.

A more accurate simulation of the situation is possible, and as shown any number of the above factors may contribute to the limiting of any quantitative conclusions. As binning has been shown to affect the small-timescale growth rate behavior, additional particle runs to 'fill in' between the current launch energies may allow for reaching smooth, stable, and more realistic results. Efficiency improvements and cluster capabilities would also allow for more realistic beam lifetimes, and potentially probing of behavior at timescales the Correlators can not yet work at.

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