Chapter 1

Above the Aurora

Figure 1.1: Aurora seen from the International Space Station (NASA/ESA/ Alexander Gerst https://twitter.com/Astro_Alex/status/505282945272524800).

Earth seems a fantastic place full of magic and wonderment. Alas, as for children growing up, we have, as a species, cast off our notions of magic, and pounded our heads against reality until it gave us deeper knowledge and understanding of the interactions underpinning what once we explained fancifully. So it is with the aurora, both borealis and australis: not for many years have those with any scientific interest been for long able to pass the northern and southern lights off as the work of spirits, ghosts, or gods—excepting, perhaps, if one were to desperately attempt to classify auroral spirits as spirits of gaseous fluorescence.

We have examined the gasses in our atmosphere, and asked why they would ever be so gauche. "Tis not our fault," they declaim, "but that we are so excited by these brutish electron beams."

While it is tempting to simply pass it off as poor taste on the part of these gasses—certainly oxygen is possessed of enough character flaws already, always getting into other elements' business—an expanded examination enlightens everyone, exposing an electric edifice. Elucidating: there exists a grand electric circuit[1], the volumetric bulk of which lives in space, but which exists because Earth and its magnetic field do, and indeed, makes one leg of its journey through Earth's upper atmosphere.

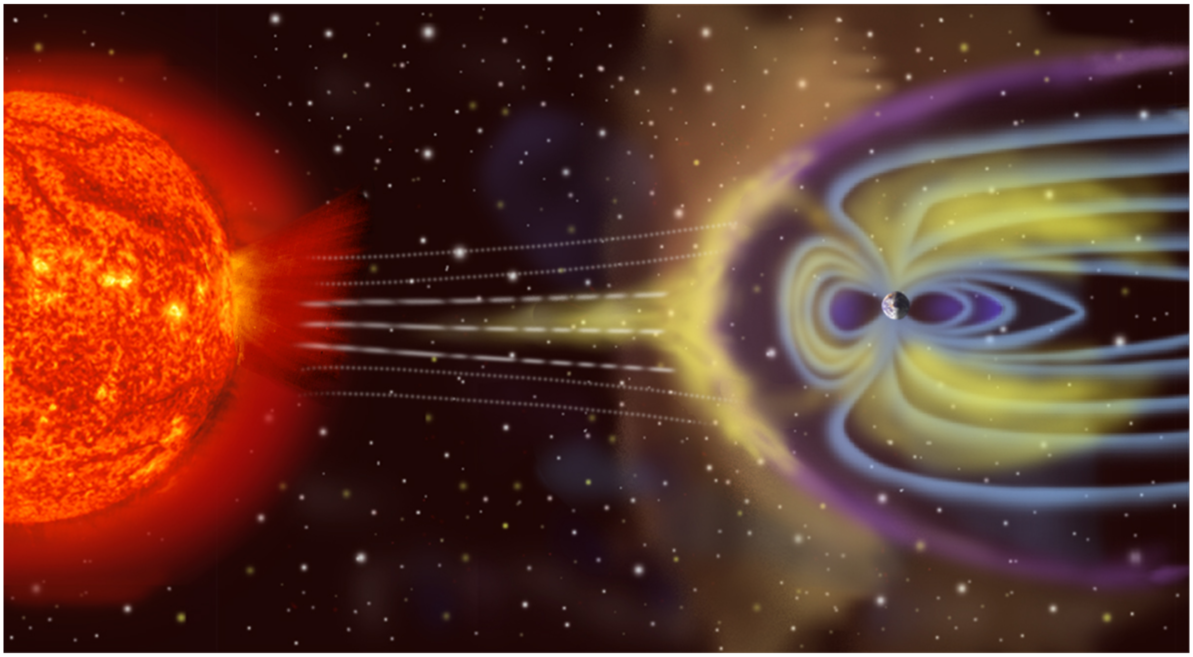

Figure 1.2: An artist's rendition of the solar wind blowing against the Earth's magnetosphere (NASA SDO http://sdo.gsfc.nasa.gov/mission/).

Exists because of, but not solely: as with everything in our general vicinity, our system needs a Sol. As the Sun spins its merry way through the galaxy, it also projects out a panoply of particles both neutral and not, and its very own prodigious magnetic field proceeds along with the plasma part of this play. As far as one can push a comparison of this outflow of solar-wind soup to a river, one then begs leave to similarly portray the Earth and its much more minute magnetic field as a water wheel, capturing a significant fraction of the energy

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[1] Not to be confused with its neighboring circuit, which connects the Earth's surface to the ionosphere via lightning.

that impinges on it, and the power output of which drives a myriad of processes throughout Earth-space.

Here then as in Figure 1.2 we have the origin of our electric circuit of interest: the Sun and Earth's magnetic fields grinding both with and against each other (as mercurial moods mandate), providing both energy and direction to a party of particles from both bodies. This uproarious region, defined in the fore by the balance of solar wind pressure versus Earth's magnetic field, and in the aft by the whimsies of chaotic interactions, and being shaped in a general sense along the lines of a teardrop as shown in Figure 1.3, is classified as the Earth's magnetosphere. Of its associated plasmas, the Ionosphere is merely the most earthward march.

Figure 1.4 forthwith portrays but a small fraction of the bevy of chaotic interactions and phenomena which call these regions home; however, we shall in the wake of our projective expansion choose to limit ourselves closer to our original purview: precisely, processes within the auroral ionosphere, though these are of course affected by more distant realms.

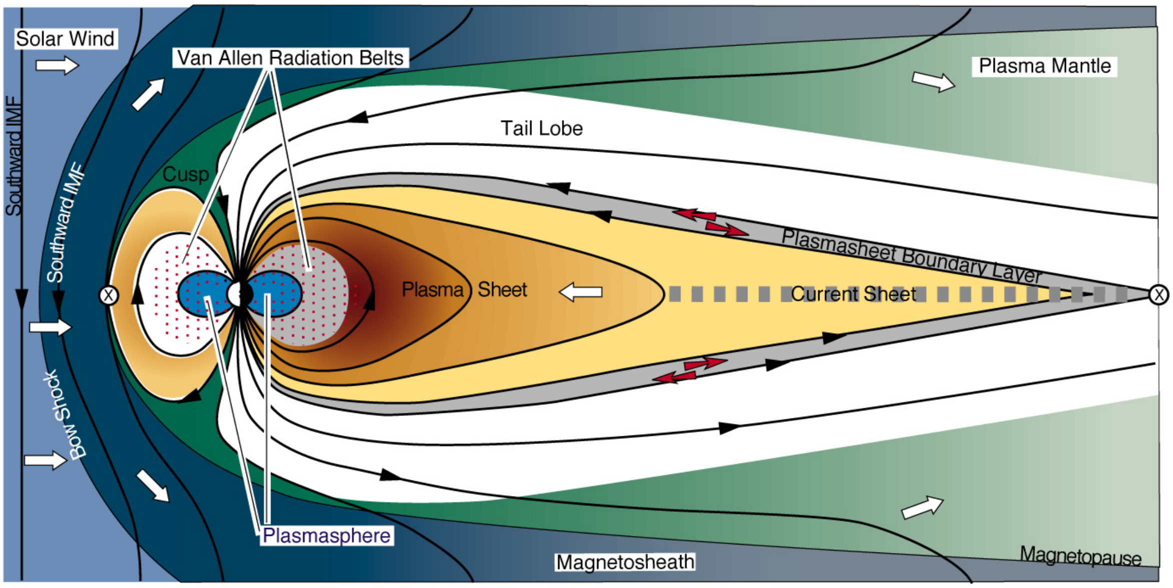

Figure 1.3: A basic diagram of the Earth's magnetosphere, with several features of the field and plasma populations visible (T. W. Hill via http://space.rice.edu/IMAGE/livefrom/sunearth.html).

1.1 PARTICLES!

Far above the the lovely lightshow, we find electrons which move within the confines delineated by Earth's magnetic field, ***B***, forming a multipart current system, parts of which are depicted in Figures 1.3 and 1.4. The electrons most important for our current consideration come from a population trapped in the plasma sheet: a long, thin tail of hot, relatively dense

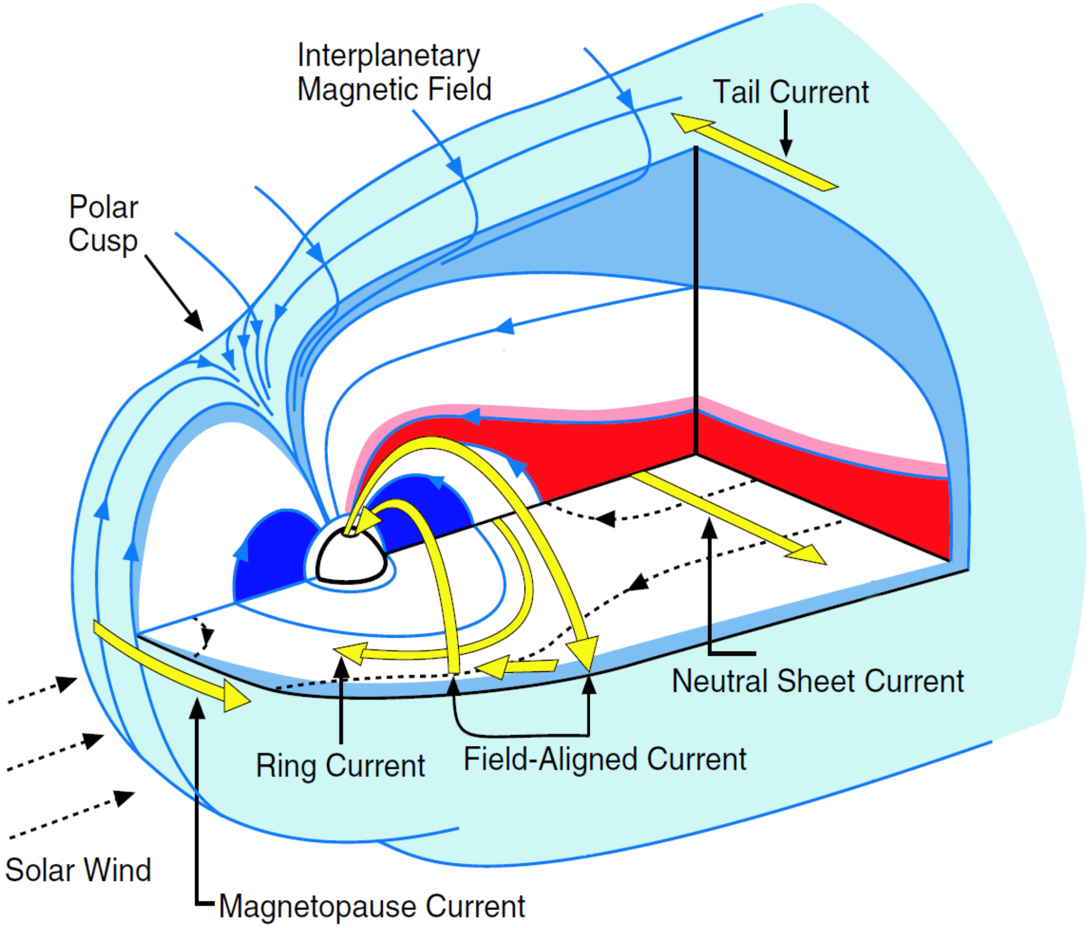

Figure 1.4: A depiction of current systems within the magnetosphere (Adapted from *Keyser et al.* (2005)).

plasma trapped between the two lobes of the tail region of the magnetosphere. Our circuit then travels along the highly conductive magnetic field lines, towards the Earth's magnetic poles—there, as the magnetic field lines continue on into the neutral, insulating lower atmosphere, they first find a nice, lower-resistance region in which to complete the circuit: the higher-density regions of ionosphere. These $\boldsymbol{B}$-parallel or 'field-aligned' currents, also known as Birkeland currents, are the primary source of aurora, though at their end the circuit is completed by the Pederson and Hall currents, which are perpendicular to $\boldsymbol{B}$.

Variations in and interactions between these various currents and fields can create large potential drops along field lines, accelerating electron beams, which pump energy into atmospheric neutrals and plasmas. The subsequent release of some of the energy through photon emission—fluorescence—is what we call aurora. This is, however, only a small part of the story. While the result most obvious to the eye is auroral illumination, improvement of instrumentation and techniques has refined our understanding of these processes from a vague knowledge of the bulk energy transfer, to current knowledge of fluctuations in the electron-beam source regions on smaller and smaller temporal and spatial scales, as well as the presence of small-scale density variations, gradients, and cavities.

From Figure 1.4 it is clear that there are both upward and downward current regions, but it is the lower-latitude, upward currents which are most important for generating the aurora, for it is here that electrons are accelerated downward in order to fulfill those current needs. The activity varies for several reasons, including the direction of the solar wind with respect to the Earth's field and the overall intensity of solar activity. With high levels of solar activity comes increased occurrence of magnetic reconnection, in which field lines in the sun-facing, or 'dayside' magnetosphere open to solar field lines at the bow shock, and then wrap around to the tail/nightside, releasing significant amounts of energy and often injecting both magnetosheath (external solar) and magnetospheric plasma into the current system, increasing auroral activity.

A significant place where reconnection and magnetosheath plasma have effects is in the magnetic cusps (see Figure 1.3), where the closed field lines which lead the bowshock trade off with the open field lines that form the outer fringe of the tail. Here, the field leaves a gap which even at quiet times can offer some amounts of solar plasma direct access to the ionosphere.

The energy being pumped into the ionospheric plasma has many more effects observable by more diverse instrumentation; in particular, radio-wave and charged-particle detectors. While the electron beams travel, already oscillating around their field lines at the cyclotron frequency $f_c = \frac{|q|B}{m_e}$, they may interact with the ionospheric plasma as its density increases to the F-region peak, then falls. The ionosphere is a perfect environment for the generation of various plasma and electromagnetic waves.

1.2 WAVES!

Any plasma with incoming energy is a natural environment for the generation and propagation of a menagerie of waves. The great variety of waves we can detect in-situ via satellites and sounding rockets can, in theory, serve as probes of regions in the plasma; however, a thorough understanding of wave generation, mode conversion, and transit is required. Small-scale frequency-time wave signals are generated by plasma structures and modified in-transit by other structures, and so specific types of wave phenomena can be used to probe their associated small-scale plasma structures.

While both the electrons and ions have a part in plasma dynamics, when studying the electron component of a plasma, it is often convenient to treat the ions as an immobile background (effectively infinite mass). This is a fine approximation to make as long as the frequencies being studied are high enough that the ion motion is negligable.

In an electron plasma, the simplest and most fundamental waves are oft referred to as 'Langmuir waves', after Irving Langmuir, who first detected them in laboratory discharge plasmas (*Langmuir* 1928). This is an oscillation in the electrons which is most easily visualized in a 'cold' plasma, where the thermal velocities are ignored. Then, given a stationary population of electrons with a background of fixed ions, any displacement of the electrons will be restored by the Coulomb force, setting up an oscillation at the 'plasma frequency' $\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$, where n_e is simply the density of electrons in the plasma. In a cold plasma, the Langmuir wave is a standing wave.

In a warm plasma, when we take the electron thermal motion into account, the electron pressure is an additional restoring force, and the frequency is determined by $\omega^2 = \omega_{pe}^2 + 3k^2 v_{e,th}^2 = \omega_{pe}^2 + \frac{3k_B T_e}{m_e} k^2$ with $v_{e,th} = \sqrt{k_B T_e / m_e}$ the electron thermal velocity and $\bar{k}$ the wave vector. This propagating wave can be visualized as a compressional wave along the direction of propagation, or along the magnetic field line in a magnetized plasma.

As Langmuir waves directly interact with both the local plasma and impinging electron beams, they are highly sensitive to the motion and instability of particle populations in the upper atmosphere. Thus, greater understanding of Langmuir wave generation, damping, propagation and interaction is essential to understanding ionospheric plasma and its temporal and spatial variations. A greater understanding of the proportionality and behavior of Langmuir modes through direct measurement can also yield insights into plasma heating and energetic particle sources in such environments.

As the primary instability that occurs in beam-plasma interactions, Langmuir waves are ubiquitous in space physics; thus, any localized study of Langmuir waves may yield insights into processes and interactions in other environments. There are too many examples to cover them all, but we review below four case studies which serve to illustrate the range of phenomena they are involved in, the diversity of locations, and how important they are in space physics.

Langmuir waves exist in diverse regions, sometimes because of subtle interactions. While prior observations of Langmuir waves in Earth's foreshock correctly predicted their presence as arising from the two-stream instability, *Filbert and Kellogg* (1979) examined data from the Imp 6 satellite, and found that the required double-peaked distribution is generated by time-of-flight effects from interactions at the bow shock. Figure 1.5 depicts this process, in which the tip of the bow shock acts as a reflector and source of particles, modifying the distribution enough to yield a second peak in a small region. It was also shown that the resultant growth rates were high enough that some additional mechanism is required to stabilize the distribution in so short a time that the generative unstable distribution was not observable with the Imp 6 instrumentation. They found that a mixture of wave-wave interaction and quasi-linear relaxation in different spatial regions was sufficient.

Lin et al. (1981) examined a particularly strong type III solar radio burst observed 17 February 1979 on the ISEE 3 satellite. They find Langmuir-wave growth consistent with a bump-on-tail distribution generated by dispersion, as in Figure 1.6. They also found that additional mechanisms were required to fit the observations: that wave growth must be limited by nonlinear processes such as wave-wave interaction or the emission and collapse of soliton structures, and also that the distribution did not plateau as expected, implying that waves are being removed from resonance with the positive slope in the distribution. They also note the impulsive character to these Langmuir waves, typical of type III bursts.

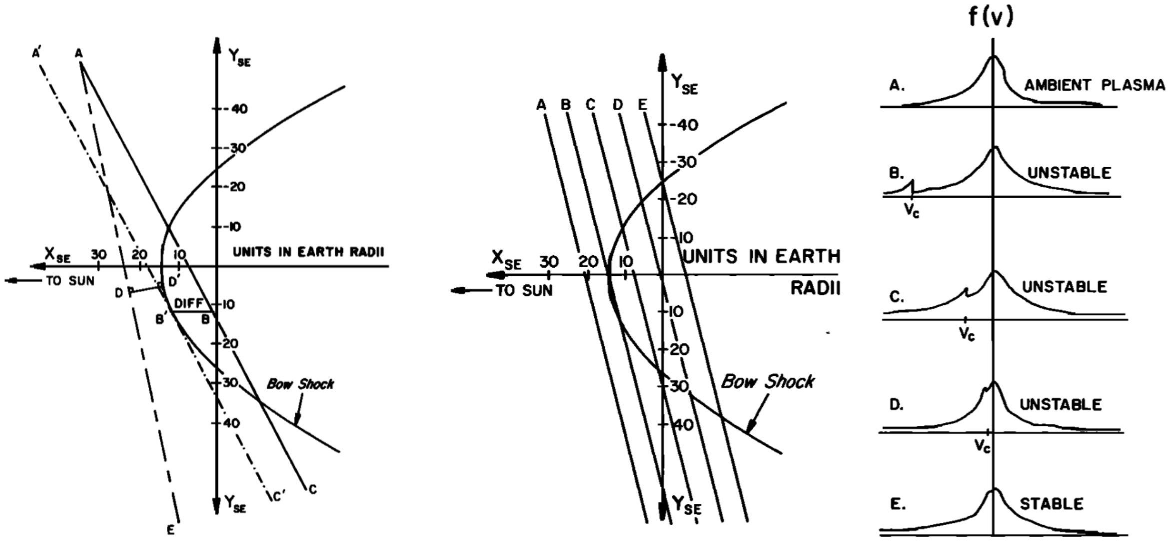

Figure 1.5: The process described by *Filbert and Kellogg* (1979), by which a two-stream instability is produced in the Earth's foreshock. Left, in the narrow region between tangential field line A' and its parallel A, the bow shock acts as a reflector of electrons traveling down solar field lines. Right shows the effect on the distribution, creating a double-peaked distribution in a small region.

As Langmuir waves are a key avenue of energy-release for their generative electron beams, the processes which mediate beam-plasma energy transfer are key to how and why they are able to propagate long distances. Because of this, a thorough understanding of Langmuir wave growth, interaction, and decay processes can aid in understanding electron beam transit and the evolution and relaxation of beam distributions.

Gurnett et al. (1981a) examined data from the 1979 Voyager 1 flyby of Jupiter, finding several examples of intense Langmuir waves upstream of Jupiter's bow shock, generated by the mechanism described by *Filbert and Kellogg* (1979). In addition to allowing an independent measurement of the electron density profile (*Gurnett et al.* 1981b), the high sampling rate of the Voyager wave instrument with respect to the local ω_{pe} allowed for observations of fine structure in the wave data, including the variable amplitude modulation shown in Figure 1.7. This is interpreted as the result of beating between the Langmuir waves and sideband waves created due to parametric interactions, possibly involving background ion-acoustic waves. Further, they found some evidence of soliton-like structures being created and subsequently collapsing, as suggested by *Lin et al.* (1981).

More recent observations, such as by the STEREO spacecraft, find no evidence of soliton collapse in the solar wind (*Graham et al.* 2012). Instead, stochastic growth appears to mediate energy flow to and from relaxed electron beams, with fine and inhomogeneous density structures playing a crucial role in the foreshock (*Malaspina et al.* 2009). The need for three-dimensional instrumentation is also becoming clear, as significant wave power connected to type III solar radio bursts has been observed both parallel and perpendicular to the background magnetic field (*Malaspina and Ergun* 2008; *Graham and Cairns* 2014).

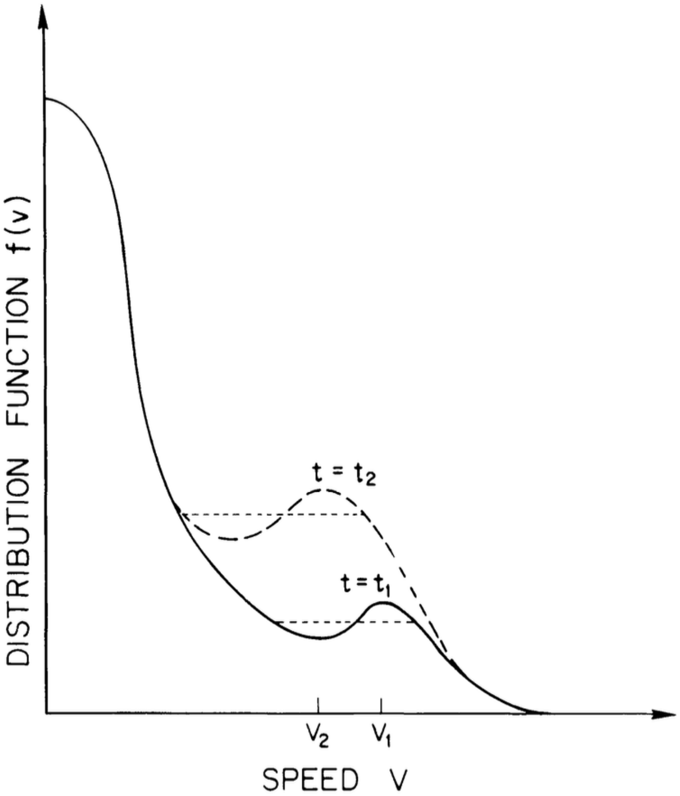

Figure 1.6: A model of a bump-on-tail distribution generated by a dispersive electron beam, presented by (*Lin et al.* 1981). The highest-energy beam electrons arrive first (time t_1), creating the bump and its wave-generating positive slope. The waves should eventually plateau the region, though as slower electrons arrive (t_2) the peak may shift to lower velocities first.

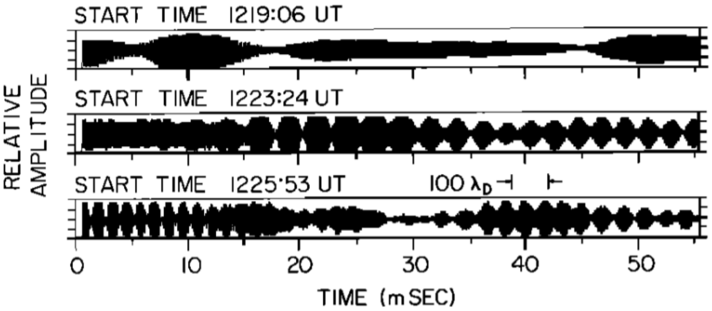

Figure 1.7: The Langmuir wave amplitude modulation observed by Voyager 1 (*Gurnett et al.* 1981a).

As with particle instrumentation, radio wave receivers and data returns have constantly improved. Langmuir waves, as well as other HF waves, have been observed to be, not continuous, but sporadic and at times highly structured. *McAdams* (1999) studied a number of high-frequency phenomena which occur near intense Langmuir-wave activity. 'Bands' are monochromatic, narrow-band emissions seen in underdense ($\omega_{pe} < \omega_{ce}$) regions, and speculated to originate as Langmuir waves generated in regions of highly variable plasma density, and subsequently converted in higher-density regions to long-lived, freely propagating whistler-mode waves. Chirps are impulsive emissions with a time-varying, primarily decreasing frequency, and are consistent with the 'spike' emissions observed via satellite and reported by *Beghin et al.* (1981), as well as with a proposed mechanism wherein Langmuir waves generated in density cavities are converted to Z-mode waves. More interesting still are effects arising from excitation of Langmuir waves in regions characterized by pre-existing electron density fluctuations. *McAdams et al.* (2000) show that the 'bands' observed by *McAdams and LaBelle* (1999) result when the scale size of the density fluctuations is comparable to the Langmuir wavelength. In this case, the Langmuir waves form discrete eigenmodes, and the frequency spacing of these eigenmodes predicted by theory matches that of the Langmuir wave 'bands'. Similar phenomena are reported by *Malaspina et al.* (2012) for Langmuir-wave related solar wind emissions. Doppler shifting due to the high solar-wind speed makes the eigenmodes harder to discern, but their presence is convincingly demonstrated through fitting the theory to the data.

While Langmuir waves have been observed and characterized in many environments, this work seeks to address two particular gaps which still exist. One of these lies in the realm of three-dimensional, high sample-rate measurements, which are nearly unknown, though *Malaspina and Ergun* (2008) have observed some three dimensional structure via the STEREO spacecraft. Such measurements have the potential to speak to questions regarding wave-wave interactions and Langmuir-wave spatial structure. The other gap lies in the area of wave-particle correlation, which aims to directly examine the microphysics of the wave-particle interactions which both generate Langmuir waves and damp them away. Only a few such instruments have been reported on in the literature, and with a very limited number events observed in each case (*Gough et al.* 1990; *Boehm et al.* 1994; *Ergun et al.* 1998; *Kletzing et al.* 2005).

Chapter 2 covers related development efforts to improve a new Receiver/Digital Signal Processor system which has a frequency range appropriate to study ionospheric Langmuir waves, as well as many other space plasma phenomena. An iteration of this system was flown on the CHARM-II sounding rocket mission, and is currently deployed at several sites for ground-based auroral radio studies. Included is a detailed description of an in-situ high time- and frequency- resolution observation of auroral roar.

In Chapter 3 we describe results from the ongoing collaborative Dartmouth College/University of Iowa wave-particle correlation study, an iteration of which was flown on the CHARM-II mission. These results are analyzed and discussed, and then a numerical simulation is implemented to evaluate the plausibility of two related theories explaining what was observed.

Chapter 4 details a three-dimensional study of the bursty nature of Langmuir waves observed on the TRICE mission. A theory explaining these is reviewed and tested, involving wave-wave interaction with oblique electrostatic waves.

Finally, Chapter 5 summarizes our results, and suggests future continuations of this work, while the Appendices shall record the major programmatic codes created for this work, and attempt to document their usage and quirks.

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