Press Kit for

“Laboratory measurements of the physics of auroral electron acceleration by Alfvén waves”

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1 Media "Sound bite"

The shimmering displays of the aurora borealis have always fascinated humankind, but a demonstration of how auroral electrons are accelerated down towards the Earth—where collisions with molecules in the thin upper atmosphere cause the emission of auroral light—has remained elusive. Using laboratory experiments on the Large Plasma Device (LAPD) at UCLA's Basic Plasma Science Facility, researchers from the University of Iowa, Wheaton College (IL), and UCLA have demonstrated the acceleration of electrons by Alfvén waves under conditions corresponding to Earth's auroral magnetosphere. The electrons were shown to "surf" on the electric field of the Alfvén wave, a phenomenon known as Landau damping, in which the energy of the wave is transferred to the accelerated electrons, analogous to a surfer catching a wave and being continually accelerated as the surfer moves along with the wave. Numerical simulations and mathematical modeling showed clear agreement with the signature of electron acceleration measured in the laboratory, confirming the first direct experimental demonstration showing that Alfvén waves can produce accelerated electrons that cause the aurora.

2 Single Paragraph Description

The shimmering displays of the aurora borealis have always fascinated humankind since the dawn of civilization, first inspiring both awe and fear for their seemingly mysterious origin, but more recently capturing the attention of scientists curious to explain what causes this natural phenomenon. It is known that electrons from space precipitate into the rarefied upper atmosphere and collide with atoms and molecules to produce auroral light; however, the cause of electron precipitation has remained an area of ongoing research. One theory is supported by the fact that spacecraft missions and sounding rockets regularly find powerful electromagnetic waves called Alfvén waves traveling Earthward above auroras. According to this theory, Alfvén waves accelerate electrons toward Earth, causing them to precipitate and produce auroras. Although space-based measurements provide strong support of this theory, limitations inherent to spacecraft and rocket measurements have prevented a definitive test. To overcome these limitations, a group of researchers from the University of Iowa, Wheaton College (IL), and UCLA performed laboratory experiments on the Large Plasma Device (LAPD) at UCLA's Basic Plasma Science Facility, a national collaborative research facility supported jointly by the US Department of Energy and National Science Foundation. By performing a scaled laboratory experiment, in which conditions corresponding to those of Earth's auroral magnetosphere can be reproduced in the laboratory, the team used specially designed instruments to launch Alfvén waves down the 20 meter long LAPD chamber and then to measure the electrons accelerated by the electric field of the Alfvén waves. This challenging experiment required a measurement of the very small population of electrons moving down the LAPD chamber at nearly the same speed as the Alfvén waves, numbering less than one in a thousand of the electrons in the plasma. Measurements revealed these particular electrons undergo *resonant* acceleration by the wave's electric field, similar to a surfer catching a wave and being continually accelerated as the surfer moves along with the wave. The physics of electrons "surfing" on the electric field of a wave is a phenomenon known as Landau damping, in which the energy of the wave is transferred to the accelerated electrons. The research team used an innovative analysis technique that combines the measurements of the wave's electric field and the electrons to generate a unique signature of the electron acceleration by Landau damping. Through numerical simulations and mathematical modeling, they showed that the signature of acceleration measured in the experiment agreed with the predicted signature for Landau damping. The agreement of experiment, simulation, and modeling provides the first direct test showing that Alfvén waves can produce accelerated electrons that cause the aurora.

3 One Page Description

The shimmering displays of the aurora borealis have always fascinated humankind since the dawn of civilization, first inspiring both awe and fear for their seemingly mysterious origin, but more recently capturing the attention of scientists curious to explain what causes this natural phenomenon. One of the proposed theories to explain the discrete auroral arcs—the most widely known type of the aurora, which appears as bright and undulating curtains of light—involves the acceleration of electrons by Earthward traveling Alfvén waves, with a progression of events as follows.

Violent events on the Sun, such as solar flares and coronal mass ejections, strongly disturb the flow of the solar wind through the solar system and sometimes trigger severe geomagnetic storms at the Earth, accompanied by some of the most intense auroral displays. The dynamics of the geomagnetic storm drives a process called magnetic reconnection in the Earth's distant magnetotail, in which magnetic field lines break and reform, eventually snapping back towards the Earth due to magnetic tension, like a stretched rubber band that is suddenly released. This rebounding of the magnetic field launches Alfvén waves that travel Earthward along the magnetic field. At altitudes below about three Earth radii (20,000 km, or 12,000 mi), where Alfvén wave speed exceeds the electron thermal velocity, electrons moving in the same direction as the Alfvén wave can be efficiently accelerated by the wave to higher speeds. These electrons effectively surf on the electric field of the Alfvén wave, gaining speed through a mechanism known as Landau damping, in which the energy of the wave is transferred to the accelerated electrons, a process first discovered in 1946. The accelerated electrons, traveling at speeds up to 20,000 km/s (or 45 million mph), stream down along the Earth's magnetic field, eventually colliding with the oxygen and nitrogen molecules in the thin air of the upper atmosphere. The impact causes these molecules to emit light, resulting in the glow of the shimmering curtains of light in discrete auroral arcs.

Although observations from a number of sounding rocket flights and spacecraft missions have provided strong evidence in support of the theory that Alfvén waves accelerate auroral electrons, limitations inherent to spacecraft measurements have prevented definitive measurements of the accelerated electrons *and* the Alfvén wave that accelerated those electrons in space. To overcome these limitations, a group of researchers from the University of Iowa, Wheaton College (IL), and UCLA performed laboratory experiments on the Large Plasma Device (LAPD) at UCLA's Basic Plasma Science Facility, a national collaborative research facility supported jointly by the US Department of Energy and National Science Foundation. By performing a scaled laboratory experiment, conditions corresponding to those of Earth's auroral magnetosphere can be reproduced in the laboratory.

In the experiment, the team used specially designed instruments to launch Alfvén waves down the 20 meter long LAPD chamber and then to measure the electrons accelerated by the electric field of the Alfvén waves. This challenging experiment required a measurement of the very small population of electrons moving down the LAPD chamber at nearly the same speed as the Alfvén waves, numbering less than one in a thousand of the electrons in the plasma. These particular electrons undergo *resonant* acceleration by the wave's electric field, similar to a surfer catching a wave and being continually accelerated as the surfer moves along with the wave. The physics of electrons "surfing" on the electric field of a wave is a phenomenon known as Landau damping, in which the energy of the wave is transferred to the accelerated electrons. The research team used an innovative analysis technique that combines the measurements of the wave's electric field and the electrons to generate a unique signature of the electron acceleration by Landau damping. Through numerical simulations and mathematical modeling, they showed that the signature of acceleration measured in the experiment agreed with the predicted signature for Landau damping. The agreement of experiment, simulation, and modeling provides the first direct test showing that Alfvén waves produce accelerated electrons that cause auroras.

4 Detailed Scientific Background: Physics of the Aurora

The shimmering displays of the aurora borealis have always fascinated humankind, with descriptions of the aurora first appearing thousands of years ago in ancient Greek and Chinese texts. The mystery of these shimmering auroral curtains spawned fear and superstition until early scientists began to discover evidence suggesting a connection between solar flares, the Earth's magnetic field, and the appearance of the aurora. At the turn of the 20th century, the Norwegian physicist Kristian Birkeland first concluded, after a several scientific expeditions to northern Norway, that there was a direct connection between electrical currents flowing along the Earth's magnetic field and aurora events.

Today, we know that energetic particles (for example, electrons moving at around 20,000 km/s, or 45 million mph) precipitate down along Earth's magnetic field lines into the upper atmosphere and collide with oxygen and nitrogen molecules, kicking them into an excited state. These collisionally excited molecules relax by emitting light, leading to the beautiful green and red hues of the aurora. What is not fully understood is exactly how these precipitating particles are accelerated from space down towards the Earth. It is suggested that the various manifestations of the aurora—from a diffuse glow, to faint arcs, to bright shimmering arcs—are caused by precipitating particles which originate from different regions and are accelerated by different mechanisms. The chain of events leading to discrete auroral arcs—the most widely known type of the aurora, which appears as bright and undulating curtains of light—begins with violent events on the Sun that strongly disturb the flow of the solar wind through the solar system and trigger geomagnetic storms at the Earth. Such geomagnetic storms are accompanied by some of the most intense auroral displays. Scientists have suggested that these discrete auroral arcs are primarily caused by the acceleration of electrons Earthward by Alfvén waves.

The Earth's intrinsically dipolar magnetic field is stretched out by the supersonically flowing solar wind, distorting it from a toriod (or donut shape) into a long, tear-drop shaped magnetic field with an elongated magnetotail stretching nearly two hundred Earth radii (1.2 million kilometers, or 800,000 miles) away from the Sun. During geomagnetic storms, oppositely directed magnetic field lines emerging from Earth's southern and northern hemispheres can be pushed together in the distant magnetotail, breaking and reforming in a process called magnetic reconnection. The tension in the loops of reconnected magnetic field leads to those field lines snapping back toward the Earth, like a stretched rubber band that is suddenly released. This rebounding of the magnetic field launches Alfvén waves that travel along the Earth's magnetic field. The field lines that pass through the region of reconnection, typically about 20 Earth radii (120,000 km, or 80,000 mi) away from the Earth, connect to the polar regions, over the range from 60 to 75 degrees northern and southern latitude.

As the Alfvén waves travel from the distant magnetotail toward the Earth, the increasing strength of the Earth's magnetic field causes those waves to accelerate from typical speeds of 5,000 km/s (or about 10 million mph) up to nearly 35,000 km/s (nearly 80 million mph). Over the same distances, the temperature of the electrons trapped within the Earth's magnetosphere decreases from the hot electrons with 2000 electron-Volt (eV) energies (around 23 million degrees Celsius) in the distant magnetotail to the cool 1 eV (around 11 thousand degrees Celsius) electrons in the ionosphere. The corresponding typical thermal speeds of those electrons decreases from the hot electron thermal speeds of around 28,000 km/s (around 60 million mph) down to the cool electron thermal speeds of around 600 km/s (or around 1 million mph). At altitudes below about three Earth radii (20,000 km, or 12,000 mi), where Alfvén wave speed exceeds the electron thermal velocity, electrons moving in the same direction as the Alfvén wave can be efficiently accelerated by the wave to higher speeds. These electrons effectively surf on the electric field of the Alfvén wave, gaining speed through a mechanism known as Landau damping, in which the energy of the wave is transferred to the accelerated electrons, a process first discovered theoretically by the brilliant Soviet physicist Lev Landau in 1946.

Ultimately, the electrons surfing on the Alfvén waves can be accelerated up to speeds of 20,000 km/s (or 45 million mph). As these accelerated electrons stream down along the Earth's magnetic field, they eventually encounter the thin air of the upper atmosphere, where they collide primarily with oxygen and nitrogen molecules. The impact on those molecules kicks some of the electrons in those molecules into an excited state. Those excited molecules eventually relax by falling into their usual ground state, emitting a photon of light in the process. From excited molecules at 100 to 200 km in altitude (60 to 120 mi), the light emitted is typically green or yellow, whereas at altitudes above 200 km (120 mi) the emitted light is more often red.

In summary, the dynamics of geomagnetic storms drive magnetic reconnection in the distant magnetotail, around 120,000 km (or 80,000 mi) away from the Earth. The resulting shifting of the Earth's magnetic field lines launches Alfvén waves towards the Earth. Electrons surfing along those Alfvén waves accelerate towards the Earth, up to speeds of 20,000 km/s (or 45 million mph), ultimately colliding with the Earth's atmosphere. These collisions cause the air molecules to emit light, resulting in the glowing of the aurora. Because the regions of magnetic reconnection shift over time during the geomagnetic storm, the Alfvén waves are launched on different field lines over time, ultimately leading to the unparalleled beauty of the undulating curtains of light observed in discrete auroral arcs.

5 What Did We Actually Do? Measuring the Physics of Auroral Electron Acceleration in the Laboratory

Although observations from a number of sounding rocket flights and spacecraft missions have provided strong evidence in support of the theory of the acceleration of auroral electrons by Alfvén waves, spacecraft measurements alone have not been able to provide definitive measurements of the accelerated electrons *and* the Alfvén wave that accelerated those electrons. Such inherent limitations of spacecraft measurements can be overcome by performing experiments in the laboratory. In the Large Plasma Device (LAPD) at UCLA's Basic Plasma Science Facility, a national collaborative research facility supported jointly by the US Department of Energy (DOE) and National Science Foundation (NSF), a group of researchers from the University of Iowa, Wheaton College (IL), and UCLA launched Alfvén waves under conditions corresponding to the Earth's auroral magnetosphere and directly measured the acceleration of electrons, in agreement with the proposed physics of auroral electron acceleration.

Although the length and time scales of the laboratory experiment are vastly different from those in Earth's magnetosphere (tens of meters and a few microseconds in the laboratory compared to tens of thousands of kilometers and a couple of minutes in the magnetosphere), the research team exploited a powerful approach known as *similarity analysis* to accomplish this verification of the physics of the auroral electron acceleration. In this approach, an appropriate combination of these different dimensional scales yields a small set of dimensionless numbers that are the same in both the experiment and the magnetosphere. The physical behavior can be shown to depend *only* on the values of these dimensionless numbers, independent of the absolute length and time scales of the system, and so with appropriate scaling the LAPD experiment can probe the physics of electron acceleration in space. The most important dimensionless number for the physics of Alfvénic electron acceleration is the ratio of the Alfvén wave speed to the thermal speed of the electrons, having a value of about 3 at an altitude of 16,000 km (or 10,000 miles) in the Earth's auroral magnetosphere. The LAPD is a 20 meter long, 1 meter diameter cylindrical vacuum chamber wrapped in water cooled electrical coils that generate a sufficiently powerful magnetic field to achieve the very high Alfvén speeds needed to achieve that desired ratio of 3.

In addition to the unique experimental conditions made possible by using the LAPD, the research team developed a number of cutting-edge instruments and techniques needed to measure the Alfvén-wave-accelerated electrons successfully. First, the University of Iowa team developed and constructed a Whistler Wave Absorption Diagnostic capable of measuring the very small population of accelerated electrons at a sensitivity of better than one in a thousand. Second, the team devised and built a new type of electromagnetic probe, the Elsasser probe, capable of measuring both the electric and magnetic fields at the same position. Third, the team designed a high-power antenna for launching Alfvén waves with a sufficiently small waveform across the magnetic field to yield effective electron acceleration. Finally, the team exploited the recently developed field-particle correlation technique to combine the electric field and electron measurements into a unique velocity-space signature that can be used to verify definitively the sought-after physics of electron acceleration. The invention, development, testing, and refinement of these critical instruments essential to the experiment was supported by the NSF/DOE Partnership in Basic Plasma Science and Engineering program and involved the training more than five graduate students and postdoctoral researchers who have gone on to permanent positions as faculty members or research scientists at universities and research institutes around the United States.

With all of these critical elements in place, the research team prepared the LAPD facility to reproduce the plasma conditions of strong magnetic field and low electron temperature that are relevant to the auroral magnetosphere. The magnetic field coils were tuned to generate a strong magnetic field of 0.17 Teslas (about 3500 times stronger than the Earth's magnetic field in Los Angeles) down the axis of the cylindrical

LAPD chamber. Once per second, a high-power capacitor bank is fired to fill the LAPD chamber with a plasma having an electron temperature of 4 electron Volts (eV), or approximately 45,000 degrees Celsius, a relatively low temperature compared to that typical of space plasmas. With this experimental set up, the key ratio of the Alfvén wave speed to the electron thermal speed achieved in the experiment was 2.9, corresponding to the conditions at an altitude above the Earth's surface of about 16,000 km, or 10,000 miles.

Using the specially designed high-power Sigma antenna, the team launched Alfvén waves down the axis of the LAPD chamber, along the strong magnetic field. As those Alfvén waves traveled down the length of the LAPD chamber, the electric field of the wave interacted with the electrons in the plasma. How that wave electric field affects the electrons depends strongly on each electron's velocity. The full population of electrons in the plasma move up and down the magnetic field with a range of speeds, characterized by the plasma temperature. A very small fraction of those electrons (less than one in a thousand) are moving down the chamber at nearly the same speed as the wave. Such electrons can undergo a *resonant* interaction, continually being accelerated by the electric field of the Alfvén wave as they move down the experimental chamber with the wave. The physics of resonant acceleration is essentially the same as a surfer paddling quickly to catch a wave. If the surfer can paddle at nearly the speed of the wave, the surfer can catch the wave. The wave will accelerate the surfer, allowing to surfer to stay with the wave and continue to be accelerated, also a resonant interaction. In physics, the resonant acceleration of electrons by the electric field of a traveling wave is a phenomenon discovered in 1946, known as Landau damping. Thus, the primary aim of the LAPD experiment was to measure directly the acceleration of the electrons by the Alfvén wave.

Five meters down the LAPD chamber from the antenna, the research team measured the electric and magnetic field variations using the Elssaser probe on a plane across the cylindrical chamber. Nearby, the Whistler Wave Absorption Diagnostic measured the number of electrons over the expected range of velocities for the resonant acceleration by the Alfvén waves. The newly developed field-particle technique was used to combine these measurements of the electric field and the electrons to generate a characteristic signature of the acceleration of the electrons versus their velocity. Using numerical simulations and analytical modeling, the researchers showed that this measured experimental signature of the electron acceleration agreed with the predictions from kinetic plasma theory, confirming that they had succeeded in measuring the proposed acceleration of electrons by Alfvén waves under conditions corresponding to Earth's auroral magnetosphere.

6 List of Graduate Students and Postdoctoral Researchers Trained

Over the years, a number of young scientists have been trained through efforts to devise, construct, test, and refine the critical specialized instrumentation and techniques needed to achieve the ultimate goal of this project—to measure the acceleration of electrons by Alfvén waves under conditions corresponding to Earth's auroral magnetosphere. All of these former graduate students and postdoctoral researchers have gone on to permanent career positions in academia or the research community. Thus, this project has significantly advanced one of the National Science Foundation's strategic objectives—to foster the integration of research and education, with the goal to recruit, train, and prepare a diverse STEM workforce to advance the frontiers of science and participate in the U.S. technology-based economy.

Here we briefly list these students, highlighting their contribution to this project and their current positions:

1. As a postdoctoral researcher for Professor Craig Kletzing, **Scott Bounds** worked on early designs for Alfvén wave antennas for the LAPD experiments, and helped to design, develop, and test the Arbitrary Spatial Waveform (ASW) antenna for launching Alfvén waves with careful control of the waveform in the plane perpendicular to the LAPD's axial magnetic field, enabling the wavevector content of these Alfvén waves to be determined. This enabled the creation of kinetic or inertial Alfvén waves that have a parallel component of the electric field capable of accelerating electrons. Scott Bounds currently holds the position of Associate Research Scientist at the University of Iowa and is involved in building spacecraft hardware and analyzing data collected by rockets and satellites, in particular working on development and construction of the new NASA Small Explorer mission TRACERS.

2. As a graduate student for Professor Craig Kletzing, **Derek Thuecks** worked on testing the Arbitrary Spatial Waveform (ASW) antenna for launching Alfvén waves in the LAPD in the kinetic Alfvén wave and inertial Alfvén wave regimes. Furthermore, he worked on the design, construction, and original testing of the Whistler Wave Absorption Diagnostic. Derek Thuecks currently holds the position of Associate Professor of Physics at Washington College in Chestertown, Maryland.

3. As a graduate student for Professor Gregory Howes, **Kevin Nielson** used the Astrophysical Gyrokinetics code, `AstroGK`, to simulate numerically LAPD experiments using the ASW antenna to launch Alfvén waves in the kinetic Alfvén wave and inertial Alfvén wave regimes. Furthermore, he used `AstroGK` simulations to understand Alfvén wave collisions—nonlinear interactions between counterpropagating Alfvén waves–which serve as a fundamental block of astrophysical plasma turbulence. The properties of these Alfvén wave collisions were first verified by our collaboration using a combination of mathematical modeling, `AstroGK` numerical simulations, and LAPD experiments. Kevin Nielson is currently a Senior Research Scientist at the Georgia Tech Research Institute. Dr. Nielson's expertise is in applied modeling, simulation, and concept development of electro-optical systems. He principally supports developmental Department of Defense projects in remote sensing and aircraft survivability systems.

4. As a postdoctoral researcher working with our LAPD collaboration, **Jan Drake** helped to design, construct, test, and characterize the Elsässer probes used to measure the perpendicular components of the electric and magnetic fields at the same position in the LAPD experiments. She used these probes to conduct the Alfvén wave collision experiments on the LAPD that confirmed the nonlinear transfer of energy caused by the interaction between two counterpropagating Alfvén waves, confirming that the physics of these Alfvén wave collisions served as a fundamental block of astrophysical plasma turbulence. Jan Drake currently holds the position of Associate Professor of Physics at Valdosta State University in Georgia.

5. As a graduate student for Professor Fred Skiff, supported by an NSF Graduate Research Fellowship, **Jim Schroeder** ran initial tests of the Whistler Wave Absorption Diagnostic for inertial Alfvén waves launched by the ASW antenna and verified that the measured fluctuations in the electron velocity distribution agreed with theoretical predictions, a critical milestone on the way to this final experiment. Later, as a postdoctoral researcher for Professor Gregory Howes, Jim designed, constructed, and tested the high-power sigma antenna, making it possible to launch much larger amplitude Alfvén waves so that it was possible to measure the energization rate of the accelerated electrons by applying the field-particle correlation method to the combination of the Elsasser probe measurements and the Whistler Wave Absorption Diagnostic measurements. Jim Schroeder currently holds the position of Assistant Professor of Physics at Wheaton College in Illinois.

6. As a postdoctoral researcher for Professor Troy Carter at UCLA, supported first by a Department of Energy Fusion Energy Sciences Postdoctoral Fellowship and later by a NASA Jack Eddy Postdoctoral Fellowship, **Seth Dorfman** helped to perform the auroral electron acceleration experiments on the LAPD. Seth Dorfman is currently a Research Scientist for the Space Science Institute and is based in Los Angeles, California. His current research focuses on the use of laboratory experiments and satellite observations to explore the fundamental plasma physics of our Sun-Earth system, including unstable waves generated by ion and electron beams as well as the interactions between and instabilities arising from large amplitude Alfvén waves.

7 Funding

The primary source of funding supporting this research program over the years is the US National Science Foundation's and Department of Energy's (NSF/DOE) Partnership in Basic Plasma Science and Engineering program (through grants ATM 98-06868, ATM 03-17310, DE-FG02-06ER54890, PHY-10033446, and DE-SC0014599). The goal of the Partnership is to enhance basic plasma science research and education in the broad, multidisciplinary field of plasma physics by coordinating efforts and combining resources of the two agencies. In particular, the program supports cutting-edge research projects that aim to perform basic plasma experiments at DOE and NSF supported collaborative research facilities, such as the Basic Plasma Science Facility (BAPSF) at the University of California at Los Angeles (UCLA), where these experiments were performed.

The Basic Plasma Science Facility (BAPSF) is supported by grants through the National Science Foundation (PHY-1561912) and the Department of Energy (DE-FC02-07ER54918). Additional local support for this project from the BAPSF was provided through the *Physics of the Solar Wind Campaign*, for which PI Gregory Howes is the Campaign Lead. Addressing not only the solar wind, but heliospheric plasma physics more broadly (including solar, interplanetary, magnetospheric, and ionospheric plasmas), this campaign aims to initiate a community-wide effort to address important questions at the frontier of space physics through the use of targeted laboratory experiments. The Bringing Space Down to Earth workshop, held at UCLA during April 10-12, 2017, brought together a critical mass of experts from the laboratory plasma physics, space plasma physics, and astrophysics communities, with one goal being to identify specific experimental projects that can be tackled in the near term through collaborative efforts among plasma theorists, laboratory plasma experimentalists, and space plasma experimentalists.

Further support for the program was provided to graduate student James Schroeder through the NSF's Graduate Research Fellowship program (DGE-1048957), to postdoctoral researcher Seth Dorfman first through a Department of Energy Fusion Energy Sciences Postdoctoral Fellowship and later through a NASA Jack Eddy Postdoctoral Fellowship, and by the NSF CAREER Award (AGS-1054061) and NASA Heliophysics Supporting Research grant (80NSSC18K1217) to Professor Gregory Howes which supported the development of the field-particle correlation technique used to identify uniquely the acceleration of the electrons through the process of Landau damping.

Together, these sources of funding from the NSF and DOE supported our work that achieved three major broader impacts that are central to the strategic interests of both agencies: (1) the education and training of graduate students and postdoctoral researchers, (2) fostering communication between the space plasma and laboratory plasma experimentalists, and (3) establishing direct collaboration between plasma theorists and experimentalists on a cross-cutting program of research on the fundamental physics of auroral electron acceleration. Our active collaboration between plasma theorists, space plasma experimentalists, laboratory plasma experimentalists at the University of Iowa, a laboratory plasma experimentalist at Wheaton College (IL) and laboratory plasma experimentalists at UCLA enabled us to achieve the first definitive measurements of the acceleration of electrons by Alfvén waves under conditions appropriate to Earth's auroral magnetosphere. Furthermore, six graduate students and postdoctoral researchers received training that has lead to their permanent employment as part of the next generation of educators and researchers at universities and research institutes.

8 Technological and Scientific Advancements

In addition to the unique experimental conditions made possible by using the Large Plasma Device (LAPD) at UCLA's Basic Plasma Science Facility, the research team developed a number of cutting-edge instruments and techniques needed to perform this challenging experiment. Below, we enumerate each of these advancements, providing details about their capabilities:

1. **Arbitrary Spatial Waveform Antenna** (Thuecks et al., 2009): Early work involved postdoctoral researcher Scott Bounds' and graduate student Derek Theucks' contributions to the design of the unique Arbitrary Spatial Waveform (ASW) antenna, in which each of 48 elements can be driven independently to tune the spatial pattern of the wave. This powerful tool for exploring the physics of Alfvén waves in the experiments allowed control of the power of the Alfvén waves in wavevector space in both the kinetic and inertial regimes, providing the critical control needed to test the Whistler Wave Absorption Diagnostic. Ultimately, the flexible design limited the peak antenna power, making it difficult to measure the very small, desired signal of accelerated electrons, and so the new Sigma antenna was designed for the final electron acceleration experiment.

2. **Wave Absorption Techniques** (Skiff et al., 1993): The single most challenging aspect of the project to demonstrate experimentally the acceleration of electrons by Alfvén waves is to measure the small population of electrons in the tail of the electron velocity distribution. A very sensitive technique is needed to detect this small population of electrons moving within a narrow range of velocities, requiring a sensitivity often greater than one in a thousand. Wave absorption techniques, in which a wave passing through the plasma of ions and electrons is partly absorbed, can be used to connect the fraction of the wave transmitted through the plasma to the population of electrons with a particular speed. Professor Fred Skiff brought his expertise on sophisticated wave absorption techniques to the design and construction of a new diagnostic, the Whistler Wave Absorption Diagnostic, needed to measure the accelerated electrons under the particular plasma conditions relevant to the physics of the auroral magnetosphere.

3. **Whistler Wave Absorption Diagnostic** (Thuecks et al., 2012): Graduate student Derek Theucks worked on the first implementation of wave absorption techniques relevant to the overdense plasma conditions corresponding to the auroral magnetosphere, in which whistler waves serve as an appropriate probe of the electrons in the tail of the velocity distribution. The resulting Whistler Wave Absorption Diagnostic was constructed and tested, demonstrating the critical capability of measuring the small population of electrons that will experience resonant acceleration by the inertial Alfvén waves launched in this experiment.

4. **Elsasser probes** (Drake et al., 2011): In addition to measuring the accelerated electrons, the successful demonstration of auroral electron acceleration in the laboratory requires the careful measurement of the electric and magnetic fields associated with the Alfvén wave at the same point in the experiment. Postdoctoral researcher Jan Drake lead the development and testing of a new "Elsasser" probe that can measure both fields simultaneously, named after a scientist that created a method to determine the direction of Alfvén waves by combining electric and magnetic field measurements.

5. **Sigma Antenna** (Schroeder et al., 2021): In the final experiment, graduate student Jim Schroeder designed and constructed the "Sigma" antenna (named because its design looks like the capital Greek letter Sigma) to generate high-power Alfvén waves with a sufficiently small wavelength across the magnetic field to efficiently accelerate electrons.

6. **Field-Particle Correlation Technique** (Klein and Howes, 2016; Howes et al., 2017; Klein et al., 2017): The final piece of the puzzle to demonstrate the acceleration of electrons—showing that the variation of the acceleration as a function of the electron velocity agrees with predictions for Landau damping—was the use of the field-particle correlation technique, a new analysis method that can be used to determine the energization of particles using spatially coincident particle and electric field measurements. Although this innovative technique had been used successfully to determine rates of particle energization in numerical simulations of plasma turbulence (Klein et al., 2017, 2020) and *Magnetospheric Multiscale* (*MMS*) spacecraft measurements of Earth's turbulent magnetosheath (Chen et al., 2019), this project is the first application of the technique to explore particle acceleration in a laboratory plasma.

9 Space Physics in the Lab

In the effort to demonstrate the physics of auroral electron acceleration by Alfvén waves in the laboratory, an obvious question arises: how can one reconcile the enormous difference in the length and time scales found in Earth's magnetosphere with what can be achieved in a terrestrial laboratory? For example, the electron acceleration in our experiment occurs over distances of tens of meters and times of a few microseconds, whereas the same acceleration occurs over tens of thousands of kilometers and a couple of minutes in the magnetosphere. The answer is that the physical equations governing the evolution of the system remain invariant through a careful scaling of the length scales, time scales, and other dimensional parameters of the system. This powerful approach, known as *similarity analysis* (Barenblatt, 1996), was exploited to create conditions in the laboratory to correspond appropriately to the conditions found in space. Through dimensional analysis, the physical behavior of a given system can be found to depend on a minimal number of dimensionless parameters, as shown by Buckingham in 1914, commonly known as the Buckingham "Pi Theorem" (Buckingham, 1914).

One of the most famous applications of similarity analysis occurred in 1950 when British physicist G. I. Taylor used declassified photos of the first atomic explosion in New Mexico, which had been published in Life magazine, to estimate accurately the yield of that atomic weapon test (Taylor, 1950a,b), information that remained highly classified at that time.

The use of similarity analysis to create experimental conditions that probe the physics of nuclear weapons is central to the US government's efforts to maintain and ensure the safety of our nuclear stockpile. In fact, the high-energy density physics community has taken full advantage of similarity analysis to design laboratory experiments using some of the most powerful lasers ever built to explore the physics of supernova explosions and the nonlinear evolution of their remnants (Ryutov et al., 1999; Drake, 2000; Remington et al., 2006). Such scientific efforts to exploit similarity analysis to investigate the physics of extreme astrophysical environments has been dubbed "laboratory astrophysics." Although the high-energy density environments relevant to supernova explosions require the use of international laser facilities, scaled laboratory experiments are also ideal to explore the physics at the lower energy densities that are typical of many heliospheric and less extreme astrophysical environments (Howes, 2018). The value of such an approach to investigate experimentally the physics of space and astrophysical plasmas led to the creation in 2012 of the Laboratory Astrophysics Division (LAD) of the American Astronomical Society (AAS).

The particular capabilities of the Large Plasma Device (LAPD) at UCLA's Basic Plasma Science Facility (BAPSF), a Department of Energy and National Science Foundation collaborative research facility, enable scaled laboratory experiments to explore the physics of space plasmas, here the acceleration of auroral electrons by Alfvén waves under conditions relevant to the Earth's magnetosphere above the polar regions. The most important dimensionless number for the physics of Alfvénic electron acceleration is the ratio of the Alfvén wave speed to the thermal speed of the electrons, having a value of about 3 at an altitude of 16,000 km (or 10,000 miles) in the Earth's auroral magnetosphere. The LAPD is a 20 meter long, 1 meter diameter cylindrical vacuum chamber wrapped in water cooled electrical coils that generate a sufficiently powerful magnetic field (0.17 Teslas, or about 3500 times stronger than the Earth's magnetic field in Los Angeles) to achieve the very high Alfvén speeds. Next, the team fires a capacitor bank once per second to fill the LAPD chamber with a plasma having an electron temperature of 4 electron Volts (eV), or approximately 45,000 degrees Celsius, a relatively low temperature compared to that typical of space plasmas. With this experimental set up, the key ratio of the Alfvén wave speed to the electron thermal speed achieved in the experiment was 2.9, corresponding to the conditions at an altitude above the Earth's surface of about 16,000 km, or 10,000 miles. By launching an Alfvén wave into the LAPD plasma under these conditions, the team was able to measure the acceleration of a small population of electrons in the plasma that correspond to those electrons accelerated toward the Earth that ultimately lead to the glowing of the aurora.

10 Quotes about this Project and Contact Information

1. **Vyacheslav (Slava) Lukin, Program Director for Plasma Physics at the National Science Foundation**:
   "This experimental confirmation of the physics behind the aurora is due to persistent ingenuity of research groups at the University of Iowa and UCLA," said Vyacheslav (Slava) Lukin, Program Director for Plasma Physics at the National Science Foundation. "From student support via an NSF Graduate Research Fellowship, to the NSF CAREER program for early career faculty, to the 25-year partnership between NSF and the Department of Energy that has enabled the unique capabilities of the Basic Plasma Science Facility, this is a success story of a discovery made possible by consistent support of the university research community."

2. **Nirmol Podder, Program Manager for General Plasma Science in the Office of Fusion Energy Sciences at the Department of Energy (DOE) Office of Science**:
   "This definitive test illuminates the mechanism responsible for the spectacular display of auroras in the Northern and Southern skies," said Nirmol Podder, Program Manager for General Plasma Science in the Office of Fusion Energy Sciences at the Department of Energy (DOE) Office of Science. "For the first time through laboratory measurements, the University of Iowa, Wheaton College, and UCLA researchers have discovered a direct link of energy transfer from Alfvén waves to electrons that causes auroras. We are pleased to support members of this innovative collaboration as well as the Large Plasma Device at the Basic Plasma Science Facility, which made this discovery possible through a long-term, fruitful partnership between the DOE and the National Science Foundation."

3. **Craig Kletzing, University of Iowa**:
   "The idea that these waves can energize the electrons that create the aurora goes back more than four decades, but this is the first time we've been able to confirm definitively that it works. These experiments let us make the key measurements that show that the space measurements and theory do, indeed, explain a major way in which the aurora are created."

4. **Michael Hahn, Columbia University, Executive Committee member of the Laboratory Astrophysics Division of the American Astronomical Society**:
   "These exciting results showing how Alfvén waves accelerate electrons to form the Aurora are a great example of how the interplay between observational and laboratory astrophysics can advance astronomy and space science. Making measurements directly in the magnetosphere is difficult, but by reproducing similar conditions in the laboratory we can put the physics under a microscope and understand in detail what is going on."

5. **Gregory Howes, University of Iowa, Principal Investigator of primary NSF/DOE project grant**:
   "This project required the development of specialized equipment and techniques over a number of years to show finally that Alfvén waves can accelerate electrons above the aurora. After reproducing the conditions in space above the aurora in the experiment, our collaboration launched a large Alfvén wave through the machine and, after a tense wait while processing our measurements, we were thrilled to see that we had finally succeeded in measuring the acceleration of the electrons as they surf on the Alfvén waves."

   "Showing how electrons surf on Alfvén waves above the aurora in the laboratory would not have been possible without bringing together the expertise of scientists that design and perform laboratory experiments, others that build instruments for spacecraft and measure the dynamics of the aurora in space, and still others that devise new theories on how to measure the acceleration of the electrons in space."

"In addition to resolving a long-standing scientific question about one of the causes of the aurora, the funding for this project has also supported the training of six young scientists who have all gone on to professional careers as faculty members and research scientists at universities and research institutes."

6. **Jim Schroeder, Wheaton College (IL), First Author of Nature Communications article**: "For a long time, the start of the auroral process with violent activity at the sun and the end, with electrons crashing into the upper atmosphere to give off light, have been known. What has remained unknown are the steps in between. This finding supplies an important piece of the puzzle. Alfvén waves are present above a large fraction of auroras, especially the bright and active auroras that occur during geomagnetic storms. Being able to say definitively that electrons are accelerated toward Earth in these conditions by surfing on Alfvén waves helps us understand these brilliant auroral displays. It's a result that appeals to our sense of awe and wonder; our eyes have been drawn upward by northern and southern lights for millennia. Understanding the physics of near-Earth space is practical too. Our society has become dependent on this region of space, heavily-populated with satellites, for communication and navigation, and the dynamics of geomagnetic storms and the aurora can adversely impact those satellites."

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11 Description of Graphics, Images, and Movies

We provide in this section a description of the relevant graphics, images, and movies relevant to our study of the phyics of the acceleration of auroral electrons by Alfvén waves in the laboratory.

Images/Graphics:

1. Magnetosphere Overview: Magnetotail Reconnection and Earthward Alfvén waves
   File: `MagnetosphereOverview.png`
2. Electron Surfing: Electron Acceleration by Landau Damping
   File: `ElectronSurfing.png`
3. The Glowing Aurora: Auroral Emission by collisional excitation
   File: `ElectronPrecipitation.png`
4. Depiction of accelerated electrons precipitating in the aurora
   File: `ISS_AcceleratedElectrons.png`
5. Panoramic View of the Large Plasma Device (LAPD)
   File: `LAPD_panorma.png`
6. End View of Large Plasma Device (LAPD)
   File: `LAPD_end.png`
7. Top View of Large Plasma Device (LAPD)
   File: `LAPD_top.png`
8. Aurora Australis
   File: `AuroraAustralis.jpg`
9. Alaskan Aurora
   File: `AlaskanAurora.jpg`
10. AuroraBorealis
    File: `AuroraBorealis.jpg`

Movies:

1. Movie of Aurora Caused by Space Weather
   File: `SpaceWeatherCauseAurora.mp4`

11.1 Magnetosphere Overview: Magnetotail Reconnection and Earthward Alfvén waves

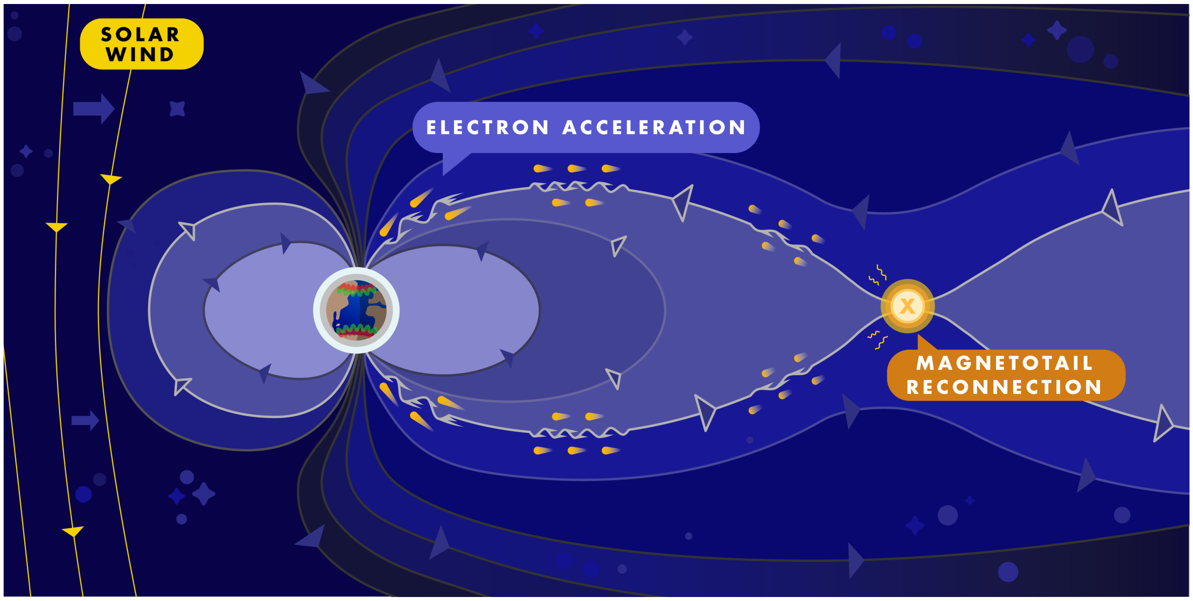

Figure 1: **Overview of the acceleration of auroral electrons by Alfvén waves**: During geomagnetic storms, oppositely directed magnetic field lines in the Earth's extended magnetotail are pushed together, undergoing a process called magnetic reconnection. As reconnected field lines (light gray field lines) snap back towards the Earth, they launch Alfvén waves. Those Alfvén waves gain speed as they travel along the magnetic field lines towards the Earth at high latitudes. Electrons (yellow dots) moving with speeds similar to the wave speed are picked up and "surf" on the wave, accelerating up to speeds of around 45 million mph. These electrons stream down towards the Earth and collide with the atoms and molecules in the thin upper atmosphere, causing them to emit the green or red light characteristic of the aurora.
Credit: Austin Montelius, College of Liberal Arts and Sciences, University of Iowa

File: `MagnetosphereOverview.png`

During geomagnetic storms, oppositely directed magnetic field lines emerging from the southern and northern hemispheres are pushed together in the distant magnetotail, breaking and reforming in a process called magnetic reconnection, as shown in Figure 1. The tension in the loops of reconnected magnetic field leads to those field lines snapping back towards the Earth, like a stretched rubber band that is suddenly released. This rebounding of the magnetic field launches Alfvén waves that travel along the Earth's magnetic field (the white field lines in the figure). As the Alfvén waves travel from the distant magnetotail toward the Earth, the increasing strength of the Earth's magnetic field causes those waves to accelerate from typical speeds of 5,000 km/s (or about 10 million mph) up to nearly 35,000 km/s (nearly 80 million mph). Electrons moving in the same direction as the Earthward traveling Alfvén waves can be efficiently accelerated by the wave to higher speeds. These electrons effectively "surf" on the electric field of the Alfvén wave, gaining speed through a mechanism known as Landau damping, a process first discovered theoretically by the brilliant Soviet physicist Lev Landau in 1946.

Ultimately, the electrons surfing on the Alfvén waves can be accelerated up to speeds up of 20,000 km/s (or 45 million mph). As these accelerated electrons stream down along the Earth's magnetic field, they eventually encounter the thin air of the upper atmosphere, where they collide primarily with oxygen and nitrogen molecules. The impact on those molecules kicks some of the electrons in those molecules into an excited state. Those excited molecules eventually relax by falling into their usual ground state and emitting a photon of light in the process, emitting mostly greenish-yellow light at 100 to 200 km in altitude (60 to 120 mi), and mostly red light at altitudes above 200 km (120 mi). This auroral light generates an oval of emission at high north and south latitudes (the green and red bands encircling the Earth's poles in the figure). Discrete auroral arcs, the undulating curtains of light that are the most awe-inspiring form of the aurora, are caused by the electrons that were accelerated by the Alfvén waves, waves driven initially by the magnetic reconnection occurring 120,000 km (or 80,000 mi) away in the distant magnetotail.

11.2 Electron Surfing: Electron Acceleration by Landau Damping

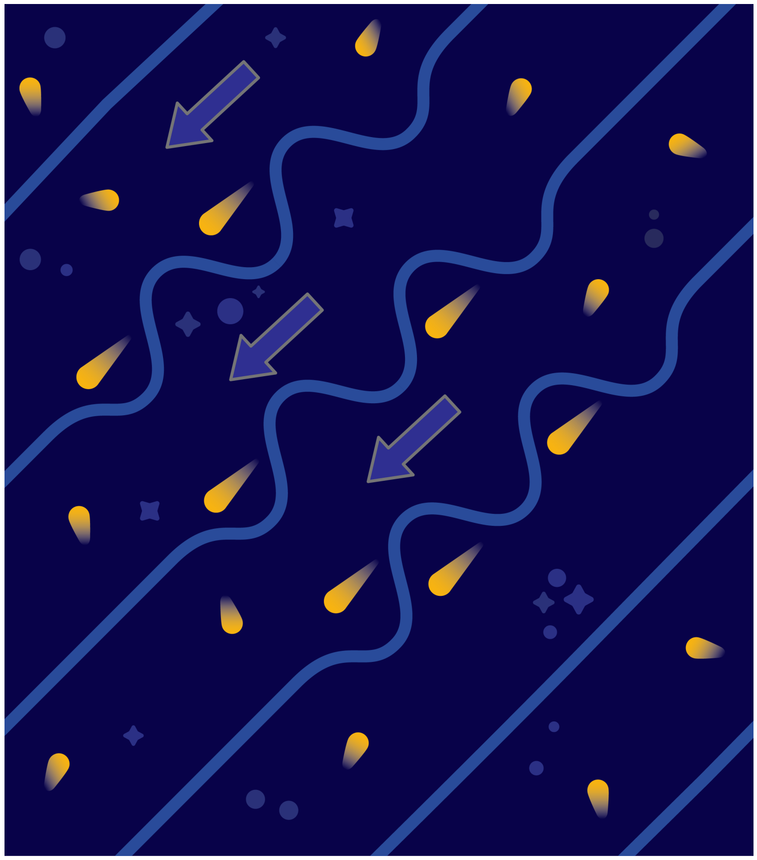

Figure 2: **Electron surfing**: Electrons surf on Alfvén waves that travel along the Earth's magnetic field (blue lines) to the high latitude regions of the Earth. Electrons in the very low density plasma that fills the Earth's magnetosphere have a variation of velocities in all possible directions (yellow dots with short tails). Electrons that happen to be moving along the magnetic field at nearly the speed of the Alfvén waves can "catch" the wave, a process called Landau damping, being continually accelerated as the wave moves ever faster towards the Earth (yellow dots with long tails). The electrons can be accelerated by the Alfvén waves up to speeds up of 20,000 km/s (or 45 million mph), eventually colliding with the molecules and atoms in Earth's thin upper atmosphere and leading to the glowing of the aurora.
Credit: Austin Montelius, College of Liberal Arts and Sciences, University of Iowa

File: `ElectronSurfing.png`

11.3 The Glowing Aurora: Auroral Emission by collisional excitation

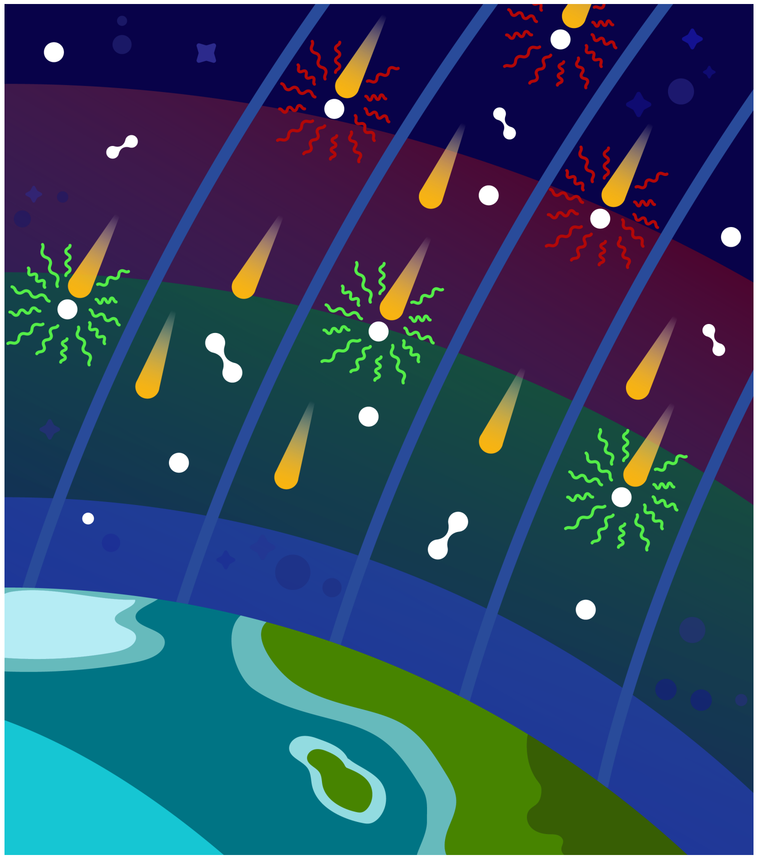

Figure 3: **The glowing aurora**: As the electrons that have been accelerated by Alfvén waves over a range of altitudes from 12,000–20,000 km (8,000–12,000 mi) stream along the Earth's magnetic field towards the Earth (yellow dots with long tails), they encounter the thin upper atmosphere at altitudes of a few hundred kilometers, in a region called the ionosphere. In this region, the electrons may collide not only with the oxygen O_2 and nitrogen N_2 molecules (white dumbbells), but also with single oxygen atoms O (white dots) freed from molecules by the Sun's ultraviolet light. Collisions with the precipitating electrons excite these atoms and molecules, causing them to emit light, leading to the discrete auroral arcs during geomagnetic storms. At altitudes above about 200 km (125 mi), electron collisions cause the oxygen atoms to emit red light, while at lower altitudes down to around 100 km (60 mi), the oxygen atoms emit the green light familiar in photos of the shimmering curtains of light in the aurora.
Credit: Austin Montelius, College of Liberal Arts and Sciences, University of Iowa

File: `ElectronPrecipitation.png`

11.4 Depiction of accelerated electrons precipitating in the aurora

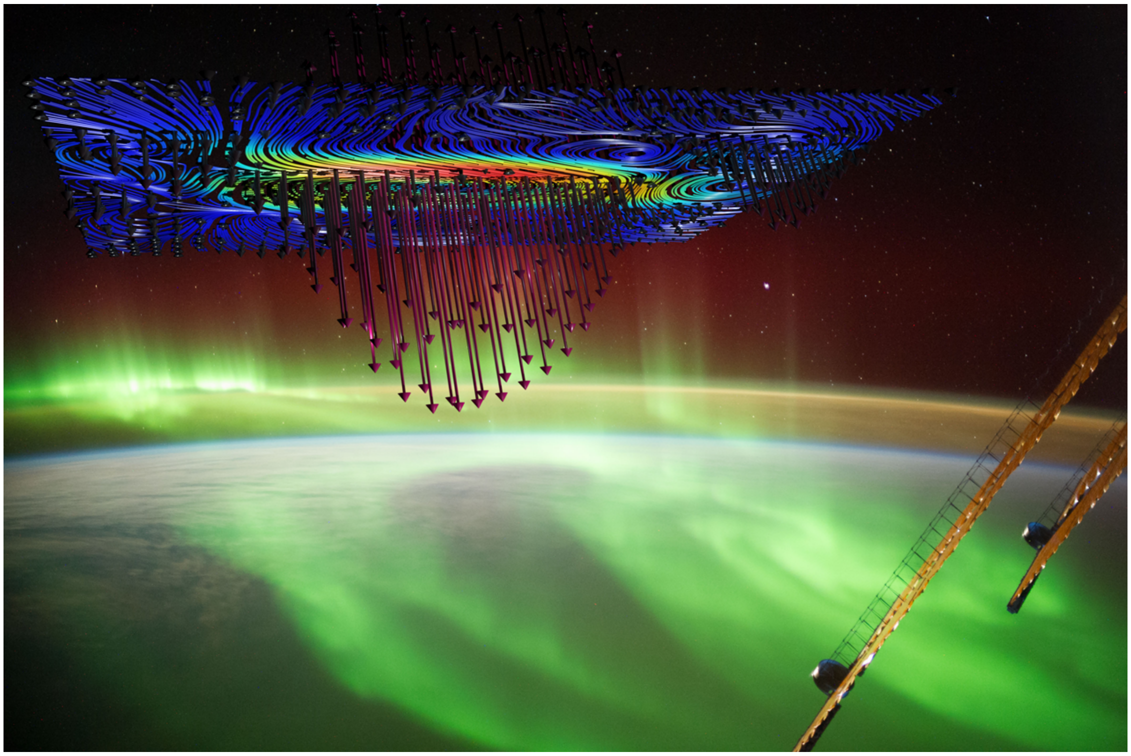

Figure 4: Artistic depiction of the Alfvén-wave-accelerated electrons precipitating into the aurora, causing a shimmering auroral display. Green contours are derived from the magnetic field measurements in the experiment, with the resulting electron acceleration as a function of position given by the colored arrows. A narrow beam of accelerated electrons (red arrows) leads to the curtain-like appearance of the resulting aurora. The auroral photograph was taken from the International Space Station (ISS) by Alex Gerst, a member of the Expedition 40 crew, on July 15, 2014.
Credit: Auroral photograph: Alex Gerst, NASA; Experimental Data Visualization: Steve Vincena, University of California, Los Angeles

File: `ISS_AcceleratedElectrons.png`

Source for Photograph: `https://images.nasa.gov/details-iss040e064788`

11.5 Panoramic View of the Large Plasma Device (LAPD)

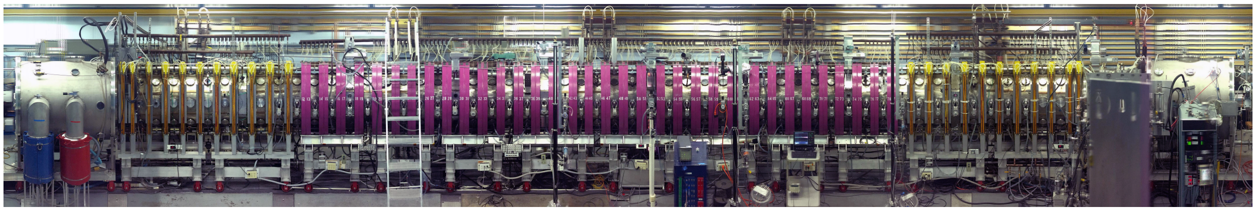

Figure 5: Panoramic view of the Large Plasma Device, a nearly 20 meter long, 1 meter diameter cylindrical vaccuum chamber wrapped powerful axial magnetic field coils (purple and yellow). This unique national collaborative research facility, supported by the US Department of Energy and National Science Foundation, makes possible detailed investigations of the physics of space plasmas, such as the Earth's auroral magnetosphere.
Credit: Basic Plasma Science Facility, University of California, Los Angeles

File: `LAPD_panorma.png`

11.6 End View of Large Plasma Device (LAPD)

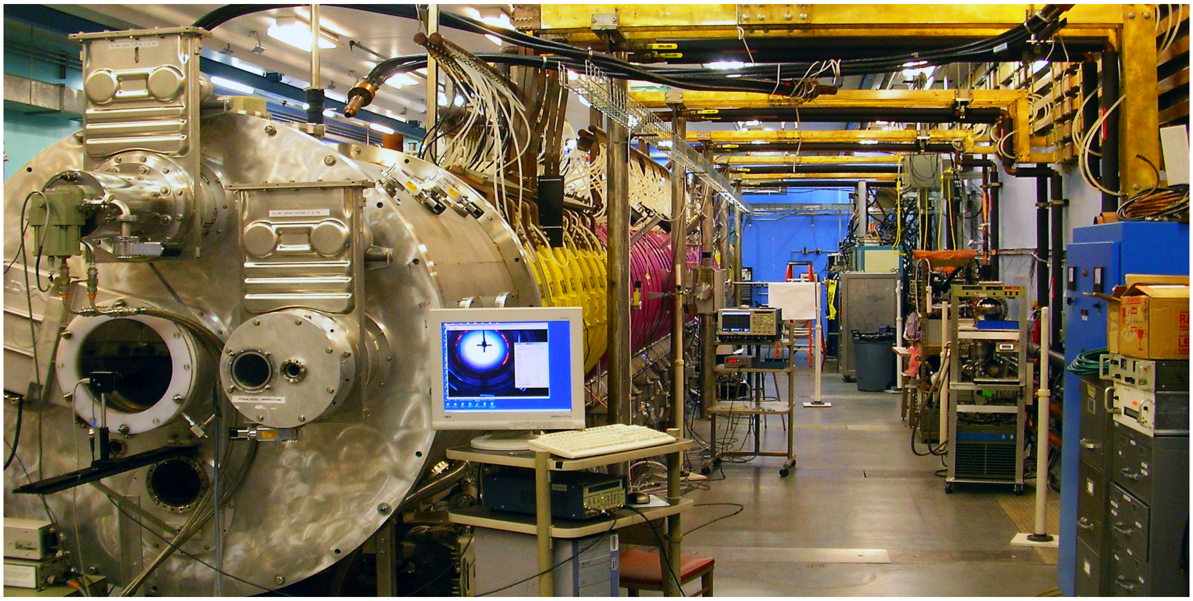

Figure 6: End view of the Large Plasma Device. On the computer screen is an image of the plasma discharge within the machine, taken by the camera viewing through the quartz window on the end cap of machine. Credit: Basic Plasma Science Facility, University of California, Los Angeles

File: `LAPD_end.png`

11.7 Top View of Large Plasma Device (LAPD)

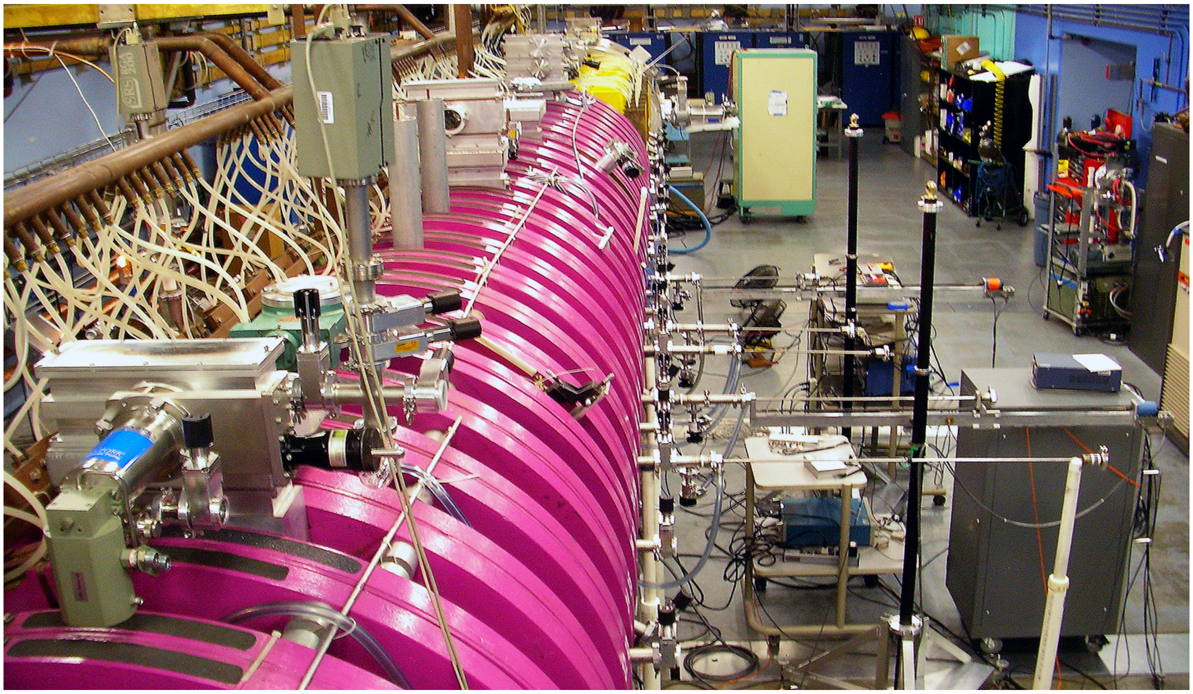

Figure 7: Top view of the Large Plasma Device, showing access ports to the plasma in between the purple magnetic field coils. The Sigma antenna was installed into the machine through one of these top access ports. On the side are diagnostic access ports with automatic probe drives enabling a full scan of the plasma across a perpendicular plane in the machine. The Whistler Wave Absorption Diagnostic gains access to the plasma through these side ports.
Credit: Basic Plasma Science Facility, University of California, Los Angeles

File: `LAPD_top.png`

11.8 Aurora Australis

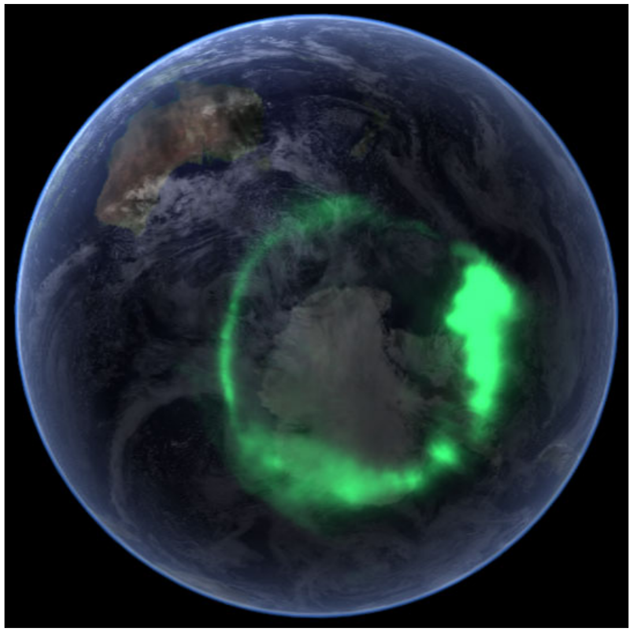

Figure 8: **Aurora Australis**: On September 7, 2005, a record-setting solar flare erupted in the Sun. Four days later, on September 11, 2005, the disturbed "space weather" caused by the flare triggered a geomagnetic storm at the Earth. NASA's IMAGE spacecraft captured this view of the aurora australis (southern lights), where a ring of auroral light encircles the Earth's south pole. The IMAGE observations of the aurora are overlaid onto NASA's satellite-based Blue Marble image. From the Earth's surface, the ring would appear as a curtain of light shimmering across the night sky.
Credit: NASA Goddard Space Flight Center

File: `AuroraAustralis.jpg`

Source: `https://images.nasa.gov/details-GSFC_20171208_Archive_e001871`

11.9 Alaskan Aurora

Figure 9: **Alaskan Aurora**: The aurora borealis captured in Alaska by photographer Jean Beaufort. The shimmering and swirling curtains of green light are typical of discrete auroral arcs occuring during geomagnetic storms. These green sheets of light dance in the night sky at an altitude of 100–200 km (60–120 mi). Credit: Jean Beaufort, CC0 Public Domain license.

File: `AlaskanAurora.jpg`

Source: `https://www.publicdomainpictures.net/en/view-image.php?image=298659&picture=northern-lights`

11.10 Aurora Borealis

Figure 10: **Aurora Borealis, Earth Magic**: The green glow of discrete auroral arcs reflecting off of the surface of a lake in the still of the night.
Credit: Axelle B, CC0 Public Domain license

License: CC0 Public Domain
Axelle B has released this "Aurora Borealis, Earth Magic" image under Public Domain license. It means that you can use and modify it for your personal and commercial projects.

File: `AuroraBorealis.jpg`

Source: `https://www.publicdomainpictures.net/en/view-image.php?image=151128&picture=aurora-borealis-earth-magic`

11.11 Movie of Aurora Caused by Space Weather

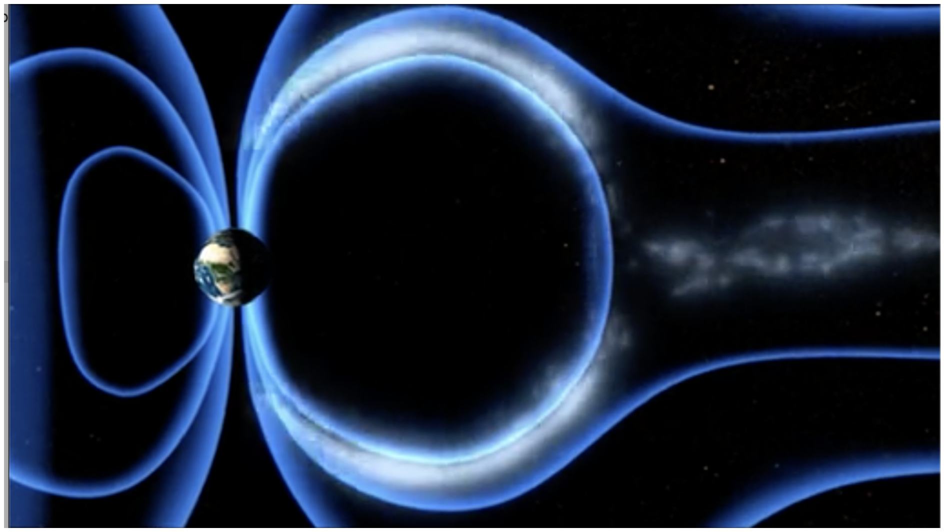

Figure 11: **Movie of Aurora Caused by Space Weather**: In this animation from NASA, violent events on the Sun, such as massive solar flares, launch disturbed space weather throughout the solar system. When the disturbed solar wind reaches the Earth, it can trigger a geomagnetic storm, where the Earth's magnetic field is swept around the Earth into the extended "magnetotail." There, the magnetic field lines emerging from the Earth's north and south poles are pushed together, undergoing a process called magnetic reconnection, where magnetic field lines break and reconnect. The reconnected field lines snap back towards the Earth, like a stretched rubber band that is suddenly released, launched Alfvén waves that travel along the magnetic field towards the high latitude regions of the Earth. At altitudes of 12,000–20,000 km (or 8,000–12,000 mi), electrons can by picked up by and surf on those Alfvén waves, accelerating to speeds of around 20,000 km/s (or 45 million mph). Those electrons stream down along the magnetic field lines and collide with the atoms and molecules in the Earth's thin upper atmosphere, causing them to emit light and thereby generating the fascinating glow of the aurora.
Credit: NASA

File: `SpaceWeatherCauseAurora.mp4`

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