Chapter 4:
Lightning Effects on Space Plasmas and Applications

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Running Title: Lightning Effects on Space Plasmas

ABSTRACT

At very low frequencies, the energy from a lightning strike can be trapped between the ground and the Earth's –ionosphere. Under certain circumstances this energy can couple through the ionosphere and enter into the magnetosphere where its propagation is determined by low-energy plasmas. It can also interact with high-energy plasmas at altitudes below about 20,000 km. This type of lightning –generated wave is called a whistler. Whistlers provided proof of the existence of the plasmasphere, a region of low-energy space plasma of ionospheric origin, and its typically sharp boundary called the plasmapause. Whistlers propagate in the plasmasphere along ducted and non-ducted paths. They can modify the distribution of high-energy electrons in the Van Allen radiation belts by pitch angle scattering into the loss cone causing these particles to precipitate into the atmosphere and be permanently lost out of the belts. Upcoming spacecraft missions will investigate whistler mode wave-particle interactions further in order to understand details of this space plasma process.

1. INTRODUCTION

Lightning is a high current discharge in air producing a column of hot plasma a few inches or less in diameter and a few km to over 80 km in length. A lightning bolt can carry a current of tens of thousands of amperes with a temperature of up to 50,000^{o} F. Lightning occurs where a large voltage buildup occurs such as cloud to ground, cloud to cloud and even cloud to the ionosphere. As an integral element of our climatology, lightning has been striking the Earth long before humans appeared. Today, it has been estimated that lightning strikes the Earth, on the average, about 45 times per second and is seen mostly over the continents [1] as shown in the annualized distribution of Figure 1. Updrafts in the atmosphere over land allow charge separation, a necessary process for lightning to occur. Over the ocean updrafts are significantly less frequent as is the occurrence of lightning. Nevertheless, at any one time there are over 2000 active storms with lightning on the Earth.

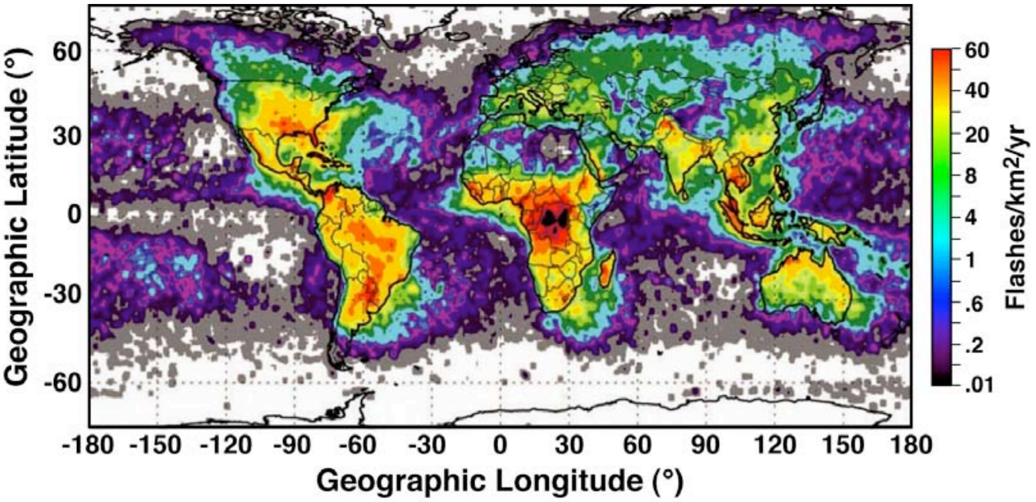

Figure 1. The yearly averaged worldwide distribution of lightning.

Lightning generates a broad spectrum of electromagnetic radiation. In addition to the emission of optical radiation, lightning emits at very low frequencies (VLF) below 10 kHz. This radiation is typically trapped in the wave-guide formed by the ground and the lower ionosphere. The frequency-time spectrum of lightning in the form of sferics and whistlers is shown in Figure 2. The intensity of the electric component of all electromagnetic waves received at the antenna in Figure 2 is color coded with red being the most intense and black the least intense. Like lightning at optical frequencies, sferics occur over a very brief interval of time. Sferics occur coincident with the optical lightning stroke and can be measured at distances of several thousand kilometers from the original lighting stroke since they are trapped in the ground-ionosphere wave-guide. The realization that whistlers were also signatures of lightning was not obvious and required considerable research.

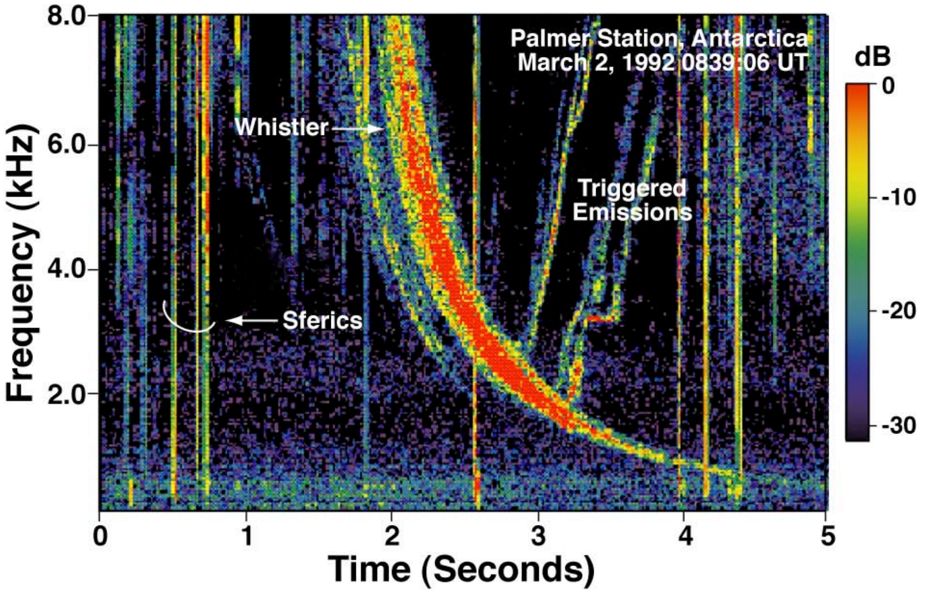

Figure 2. A frequency-time spectrogram of lightning sferics and the resulting whistler.

2. LIGHTNING WHISTLERS

In 1917, H. Barkhausen, an engineer in the German army during World War I, was assigned to eavesdrop on Allied communications. By using an Earth current detector connected to an audio amplifier and earphones, Barkhausen [2] later reported (from memory) hearing "a very remarkable whistling note" that he could not explain. Barkhausen recalled that the distinctive whistler tone sounded much like an incoming shell. The frequency range of a whistler is nearly the same as our audio frequencies allowing simple equipment to be used to convert these electromagnetic waves into sound waves. As shown in Figure 2, a whistler is an electromagnetic wave with a continuous tone that begins at a high frequency (~10 kHz) and rapidly decreases in frequency ending at a low frequency (several hundred Hz) within a few seconds.

After careful analysis, Barkhausen claimed that the whistlers were coming from the atmosphere. Years later, Eckersley [3] noted that whistlers were often observed about a second after a sferic, another broadband emission with very short duration. He speculated that the two were related with the whistler being the echo of the sferic. Eckersley speculated that whistlers were caused by lightning but failed to provide an explanation as to why the lower tones would arrive seconds later, which at light travel speeds, would have to have travel greater distances.

It was not until Storey [4] developed the initial theory of how whistlers are generated from sferics that the whistler phenomena changed from an unexplained natural oddity to an important research tool. Storey proposed that a lightning sferic propagated outside the Earth's atmosphere and that instead of encountering a vacuum encountered an expanded region of ionospheric material. The physics of how a sferic in the magnetosphere evolves into a whistler as it propagates is simply due to differences in the index of refraction of the plasma with frequency. The higher frequency waves travel faster than the lower frequency waves in a medium. Storey went on to state that there would have to be about 800 electrons/cm^3 near the equatorial plane at an altitude of about 12,000 km to produce the signature of a typical whistler.

In 1953 when he published his paper many of Storey's colleagues did not believe that such high densities could exist above the ionosphere. Storey would have to wait until the dawn of the space age for confirmation of the existence of the plasma region he invoked to explain the dispersion of sferics into whistlers

3. EARLY APPLICATIONS OF WHISTLERS

In 1959 the USSR launched two satellites toward the moon that carried scientific instruments designed to measure the density of ions along their trajectory. The principal investigator, K. Gringauz, immediately verified the higher density plasma found outside the ionosphere but he also found a strange and rapid fall off in the plasma density near 10,000 km altitude [5]. His results were not widely accepted in USSR science circles. What Gringauz had confirmed, discovered first by whistlers, was later called the plasmasphere, a region where low energy (a few eV) ionospheric material accumulates after diffusing into space along the Earth's dipole-like field-lines.

During the International Geophysical Year in 1957 a network of recording stations for whistlers were established on the west coast of the U.S. From whistlers that originated in lightning in the South Pacific and were recorded at Seattle and Alaska, Don Carpenter, a graduate student at Stanford, found clear evidence of what he called the plasmapause, the abrupt outer boundary of the region that Storey had discovered [6]. At the plasmapause boundary the plasma density drops by 1 to 2 orders of magnitude or more. This drop in density can easily be identified since it significantly alters the dispersion of whistler signatures in frequency-time spectrograms.

Recently, the Extreme Ultraviolet (EUV) imager instrument on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft has been used to study the plasmasphere. The IMAGE spacecraft was launched on March 25, 2000 into a highly elliptical polar orbit with initial geocentric apogee of 8.22 Earth radii (R_E) and perigee altitude of 1000 km. From this position above the northern hemisphere, EUV is able to observe the entire plasmasphere for many hours. The EUV instrument measures the singly charged helium ion (He^+) resonance scattering of sunlight at 30.4 nm with a time resolution of 10 minutes and a spatial resolution of 0.1 R_E [7]. A typical example of an EUV image of the plasmasphere, during quiet times, is shown in Figure 3. The sun is to the left in this image. Because the motion of plasma particles is along magnetic field-lines, the Earth's magnetic field is a convenient and descriptive coordinate system to use in near Earth space plasmas. The "L" parameter traces out a magnetic field-line and is frequently used in space physics. The value of L in units of Earth radii is denoted by the location where the field line it traces crosses the magnetic equator. As shown in Figure 3, the plasmapause at any location around the Earth, is typically located at approximately an L value of 4 during quiet times.

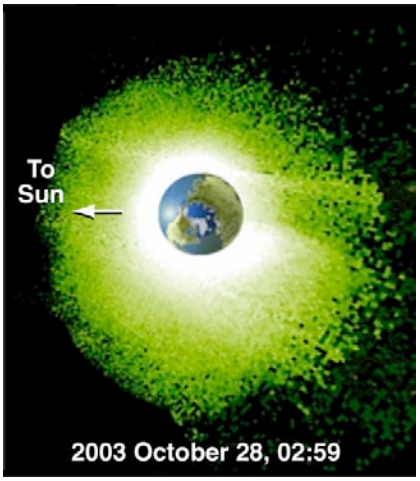

Figure 3: An image of the plasmasphere in He^+ scattered light.

The study of whistlers has been greatly enhanced by the availability of unique spacecraft data and sophisticated computer models capable of calculating whistler mode ray paths within a plasmasphere [8]. What have emerged, from this analysis, are two distinctly different propagation classes for lightning-generated whistler emissions that are referred to as ducted and non-ducted propagation.

In the plasmasphere the whistler mode radiation consists of electromagnetic waves whose upper frequency cutoff is either the local electron plasma frequency (f_p) or gyrofrequency (f_g), whichever is less [9]. The plasma frequency is proportional to the square root of the density and the gyrofrequency is proportional to the magnetic field intensity. Because of the large cold plasma density in the plasmasphere f_p is greater than f_g and supports whistler mode radiation in the VLF frequency range. Figure 4 schematically shows typical ray paths for both ducted whistlers and non-ducted whistlers (also referred to as magnetospherically reflected whistlers).

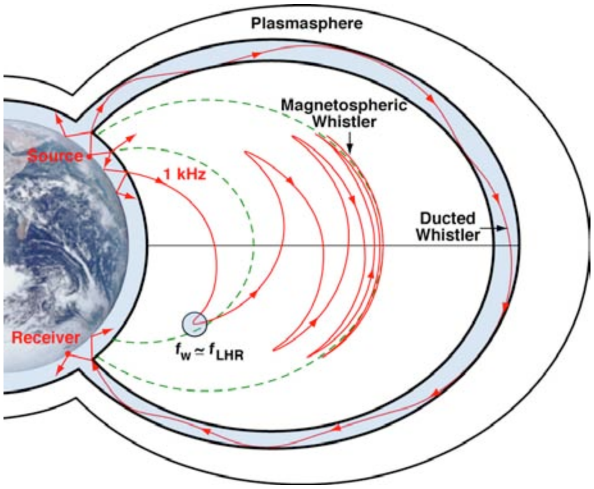

Figure 4: The propagation paths of ducted and non-ducted whistlers. Non-ducted whistler mode waves reflect when the wave frequency, f_W, is approximately equal to the local lower hybrid resonance frequency, f_{LHR}.

Ducted whistlers essentially follow the Earth's magnetic field lines since they are constantly refracted within a density enhancement of ionospheric plasma as it diffuses out into the plasmasphere along magnetic field-lines. The density enhanced duct facilities the propagation of VLF lightning energy up through the ionosphere and into the opposite hemisphere, allowing the ground reception of a whistler at the location of the receiver of Figure 4. One lightning flash can illuminate more than one duct in the plasmasphere causing multiple whistlers to be observed in the opposite hemisphere separated in time due to the different travel times in the different ducts. In other cases, some of a whistler's energy can be reflected in the opposite hemisphere causing some of the whistlers to return to near the original source region and be observed on the ground. Only a small fraction of lightning flashes produce whistlers observed on the ground since duct conditions are not always observed in the plasmasphere.

A larger number of lightning flashes produce non-ducted whistlers that propagate into the plasmasphere as shown in Figure 4. Non-ducted whistlers are not constrained to follow the Earth's magnetic field but follow a path that is determined by their frequency and the index of refraction of the plasmasphere, which is a function of the f_p and f_g at any location. For a more extensive discussion of whistlers the reader is referred to the classic book by Helliwell [10].

4. LIGHTNING WHISTLERS AND THE RADIATION BELTS

James Van Allen was the first to announce the discovery of an intense radiation belt around the Earth from analysis of data from his experiment on Explorer 1, launched on January 31, 1958. He also announced and discovered a second radiation belt at larger radial distances encircling the Earth from observations of his experiment on Explorer 4, launched July 26, 1958 [11]. Figure 5 is a schematic of the Van Allen electron radiation belts. The inner belt electron energies are between 0.04 and 4.5 MeV while the outer electron belt has energies up to 7 MeV under normal conditions. These belts are separated by a “slot region” that has electron fluxes several orders of magnitude less than the adjacent belts of the same energy. The location of the slot region is typically between an L shell (a surface of L around the Earth) of 2 and 3. Although not shown there is only one energetic proton radiation belt in the energy range from 1 to about 400 MeV. In comparison with Figure 3 the plasmasphere co-exists with the inner and most of the outer radiation belts. There are several sources for the radiation belts. Among the sources are particles originating from cosmic ray interactions with neutral atoms in the upper atmosphere. These interactions create fast neutrons (neutral particles) that decay within minutes, as they move freely outward into space, into protons and electrons, which due to their new charge state, become trapped by the Earth’s magnetic field. Another source is from geomagnetic storms.

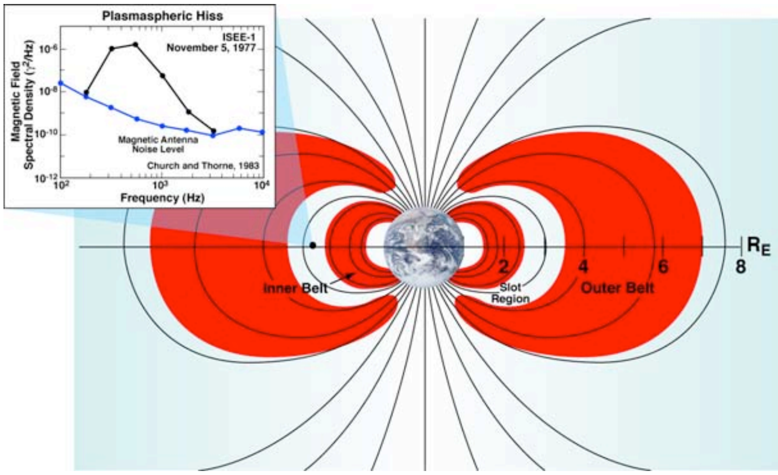

Figure 5: A schematic of the inner and outer electron radiation belts.

The classic theoretical work by Kennel and Petschek [12] held that, under certain circumstances, whistler mode waves increase in energy from a gyroresonance interaction with radiation belt electrons causing the electrons to change their direction of motion with respect to the Earth’s magnetic field. This type of interaction is illustrated in Figure 6. The gyrating electrons are affected by the whistler wave’s electric field changing their pitch angle from θ_1 to θ_2, where $\theta_1 > \theta_2$. This angle is called the particle’s pitch angle with smaller angles allowing the particle to penetrate closer to the Earth. From multiple interactions with whistler mode waves an electron’s pitch angle will approach 0° resulting in the electron being lost from the radiation belts as it collides with particles in the lower ionosphere or upper atmosphere and fails to return into the belts. This wave-particle interaction, therefore, produces what is called pitch angle scattering.

A number of researchers [13, 14,15] have shown that a well known emission in the plasmasphere called plasmaspheric hiss is likely the dominant whistler mode wave responsible for pitch angle scattering and maintaining the electron slot region between the inner and outer electron belts. An average spectrum of plasmaspheric hiss is shown in the inset of Figure 5. Plasmaspheric hiss is a broad diffuse band of electromagnetic radiation in the 100s of Hz to 4 kHz frequency range that is confined to the plasmasphere.

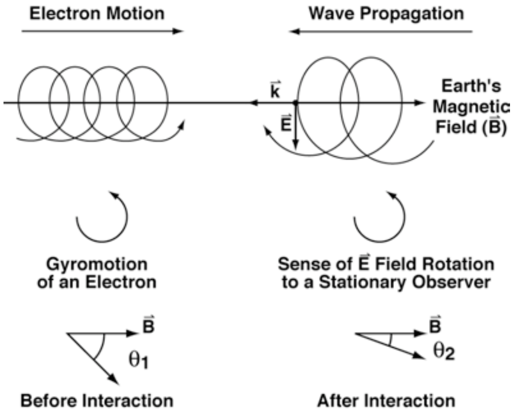

Figure 6: Gyroresonance interaction between an electron and a whistler wave.

The spectral structure of a discrete lightning whistler (as shown in Figure 2) and plasmaspheric hiss (broad-band, diffuse) are very different. However, there is now a growing body of evidence that indicates a lightning origin for plasmaspheric hiss, at least over part of its spectrum. Sonwalkar and Inan [16] were the first to observe that lightning-generated whistlers often trigger hiss emissions. These observations led the authors to the conclusion that lightning served, to an unknown extent at that time, as an embryonic source of plasmaspheric hiss. Motivated by this study, Draganov et al. [17] used ray-tracing calculations to demonstrate the evolution of magnetospherically reflected whistler wave energy into hiss-like spectra, via the settling of wave energy on specific L-shells. Magnetospherically reflecting whistlers do not bounce off the plasmapause but are internally reflected within the plasmasphere. Draganov et al. also found that lightning-generated whistlers tend to settle on preferred L-shells in the plasmasphere with the lower frequency components settling at higher L-shells and higher frequency components on lower L-shells. These waves lead to the formation of a hiss-like spectrum with durations of up to ~10^2 seconds at low frequencies (~1 kHz).

Most recently Green et al. [18] took the average electric wave spectral density of plasmaspheric hiss measured by the plasma wave instrument on the Dynamics Explorer I spacecraft and mapped this data to geographic coordinates. Figure 7 is a summary of these results at 3 kHz. Similar to the world distribution of lightning in Figure 1, the world distribution of plasmaspheric hiss (at frequencies above 500 Hz) follows the continents as shown in Figure 7. In addition, it was found that plasmaspheric hiss is stronger on the dayside than the nightside and stronger in summer than in winter, qualitatively matching the diurnal and seasonal variations of lightning. It is important to point out that the relationship of plasmaspheric hiss with the continents holds for only a portion of the emission spectrum (from below 1 to 4 kHz) and that another generation mechanism of plasmaspheric hiss must also be occurring at the very lowest portion of the spectrum. These observations strongly support lightning as an important source for plasmaspheric hiss that, through particle-wave interactions, maintains the slot region in the radiation belts.

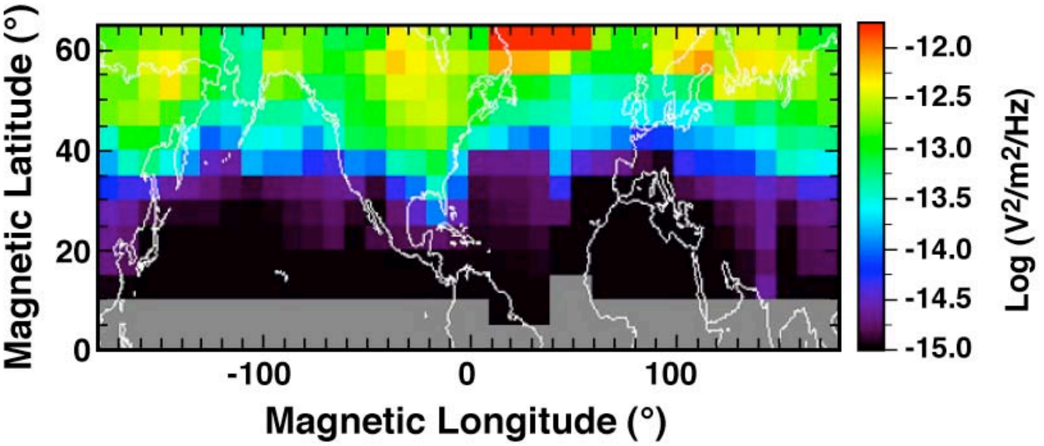

Figure 7: The geographic distribution of plasmaspheric hiss at 3 kHz.

There is a significant amount of direct evidence that individual lightning flashes are producing the precipitation of energetic electrons from the Van Allen radiation belts. Lightning-induced electron precipitation (LEP) events are produced by non-ducted lightning whistlers. Most recently, ground VLF receivers have been set up at a number of locations to form the Holographic Array for Ionospheric-Lightning (HAIL) system [19]. This array provides high-resolution measurements of ionospheric disturbances caused by various phenomena, including the precipitation of radiation belt electrons [20]. The HAIL system of receivers measures the amplitude of well-established VLF transmitters. The transmitter waves travel in the Earth-ionosphere wave-guide and are refracted back toward the Earth from the D-region of the ionosphere (40-100 km altitude). The D-region is most extensive on the dayside since its dominant source is photo-ionization. On the nightside, the source of nearly all D-region plasma is from collisions with precipitating radiation belt particles with energies > 50 keV. By correlating the measured amplitude variations from the HAIL array at night with lightning data from the National Lightning Detection Network (NLDN) the extent of LEPs can be observed.

Panel B of Figure 8 is the high-time resolution measurements from Parker, Colorado (PK) of the NAU transmitter in Puerto Rico. The first amplitude spike is from lightning in Texas and the rapid decrease in amplitude over time t_d is due to D-region effects (electron precipitation) on the received signal. Panel A of Figure 8 shows the line of sight from PK toward the NAU transmitters for the corresponding data in panel B. When all other data is combined in the HAIL network (receiving stations shown as open circles) then the contours of the extent of the precipitation can be drawn as shown in panel A. The dashed line in panel A of Figure 8 shows the ground mapping of the L shells of the slot region of 2 and 3. Figure 8 clearly shows the extent of the precipitation of the radiation belt electrons out of the slot region after the lightning whistler waves have been introduced into the plasmasphere.

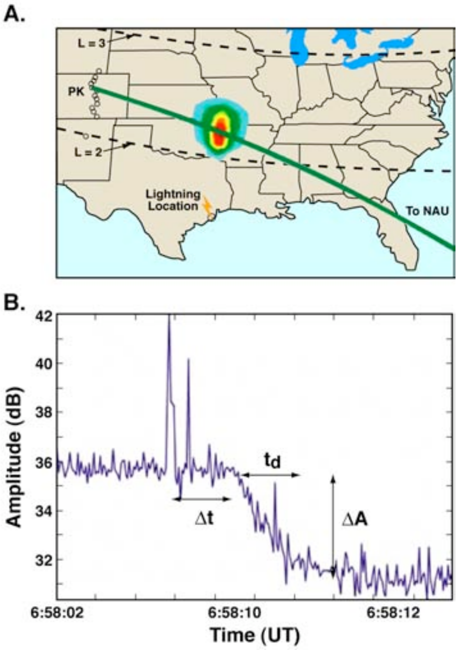

Figure 8: Lightning-induced electron precipitation event.

5. NEW MISSIONS AND NEW UNDERSTANDING OF SPACE PLASMAS

NASA has recognized the importance of studying whistler wave-particle interactions and is planning to launch the Radiation Belt Storm Probes (RBSP) in 2011. Other science objectives for RBSP include characterizing and understanding the acceleration, global distribution and variability of radiation belt electrons and ions that produce the harsh environment for spacecraft and humans. In addition, the Air Force Research Laboratory is developing the Demonstrations and Science Experiment (DSX) satellite for flight in 2009 in order to better characterize and understand the dynamics of the radiation belt slot region. The DSX will carry several science payloads designed to measure the distribution of energetic particles, plasmas and electromagnetic fields, and to investigate the wave-particle interactions that led to the formation and maintenance of the slot region.

It has also recently been realized that an in-depth understanding of the wave and particle environment in the radiation belts may be important for our national security because of the threat of a high altitude nuclear explosion or HANE event [21]. A HANE event is believed to be able to produce three or four orders of magnitude more radiation in the belts, easily destroying existing satellites over a period of weeks to months in medium and low Earth orbit. In addition to communication spacecraft, our Global Positioning System spacecraft, orbiting the Earth at the outer edge of the slot region, would all be vulnerable from a HANE event. From greater understanding of how the whistler mode wave-particle interaction occurs it may be possible to exploit our knowledge of this natural loss process to artificially accelerate the loss of energetic particles from the radiation belts, thus mitigating effects of a HANE event.

This summary of lighting effects provides one limited example of the space plasma research that contribute to important applications and our understanding of the cosmos (see Chapter 2). The Sun and our space plasma environment near Earth are important as well for its impacts on technology systems, the focus of enhanced space weather research [22].

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