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Mechanisms and Implications of Electron Pitch Angle Scattering by Whistler Mode Waves in Earth's Magnetosphere: A Comprehensive Review

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Abstract: Electron pitch angle scattering by whistler-mode waves is one of the key processes in the magnetospheric dynamics affecting the radiation belt populations and leading to the energetic electron precipitation. This review gives a detailed description of the processes that govern pitch angle scattering, linear and nonlinear interactions between waves and particles, with the emphasis on oblique whistler mode waves. Remote sensing data from satellites and other sources, as well as from in-situ measurements, and analysis from modeling and simulation show that these interactions are not straightforward. The consequences of scattering, including the loss of radiation belts, aurorae, and space weather effects, are described. There is a call for improved modeling and better observational methods to solve existing problems. The goal of this review is to provide an up-to-date review of the literature and to outline the directions for future research in this important field of space physics.

Keywords: Whistler-Mode Waves, Pitch Angle Scattering, Electron Precipitation, Magnetosphere, Radiation Belts, Space Weather

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INTRODUCTION

The magnetosphere, the area surrounding Earth where the magnetic field is strongest, is vital in protecting the planet from dangerous radiation from the sun and other space objects. It shields Earth from charged particles in the solar wind by diverting them away from the planet (Agapitov et al., 2023). In this ever-changing system, however, whistler mode waves are just one of several electromagnetic waves that significantly impact the behaviour of charged particles, especially electrons. To further our understanding of space weather and its effects on technological and natural systems, it is crucial to comprehend the mechanisms by which these waves interact with electrons, resulting in phenomena like pitch angle scattering (Albert, 2000)

The magnetic field keeps the electrons in the magnetosphere in a state of perpetual motion. Plasma waves, electric fields, and magnetic fields all work together to shape their paths (Albert, 2001). One of the main kinds of electromagnetic waves present in the magnetosphere is the Whistler mode wave, which is usually produced by solar wind interactions or lightning strikes on Earth (Albert, 2002). These waves are very important for electron transport and scattering in the magnetosphere, especially for electron pitch angle scattering. As electrons' trajectories alter in relation to the lines of a magnetic field, this phenomenon is known as pitch angle scattering. This process is important because it changes the way electrons are distributed in space and time, which can cause things like energetic electrons to escape the magnetosphere or to fall into Earth's atmosphere, where they can cause auroral displays (Albert, 2003).

THE EARTH'S MAGNETOSPHERE: AN OVERVIEW

An expansive and ever-changing zone, the magnetosphere is moulded by the interplay of the solar wind and the Earth's inherent magnetic field. It stretches out into space for thousands of kilometres and acts as a barrier to divert positively charged solar particles like electrons and protons away from Earth. Space weather, geomagnetic activity, and the total energy dynamics of near-Earth space are all profoundly impacted by this dynamic and intricate environment, which is more than simply a static barrier (Albert, 2008). The Earth's magnetic field, a dipole magnetic field produced by the motion of molten iron in the outer core, is located near the centre of the magnetosphere. A magnetic field emanates from the surface of the Earth and travels into space, where it forms the magnetosphere and affects the actions of charged particles within. Different parts of the magnetosphere interact with the solar wind in different ways, causing a wide range of events due to their own peculiarities and dynamics (Allanson & Elsden, 2022).

Magnetospheric dynamics are mostly driven by the solar wind, which is a continuous flow of charged particles (primarily electrons and protons) released by the Sun. The magnetosphere alters the solar wind's trajectory when it approaches Earth. The magnetosphere bulges outward on the dayside due to compression from the solar wind, and it becomes an extended tail on the nightside. Many key magnetospheric phenomena, like as reconnection and particle acceleration, take place in this tail, which is called the magnetotail. It can stretch millions of kilometres away from Earth (Albert, 2022). A number of structures and phenomena, including the ionosphere, the bow shock, and the magnetopause, are formed when the solar wind interacts with the Earth's magnetosphere. These structures and phenomena have a substantial impact on how charged particles behave. Multiple layers make up the magnetosphere, and they all contribute in their own way to the flow and interaction of charged particles. Within the deepest layer, there are two main radiation belts that are held in place by the Earth's magnetic field. These belts include charged particles with high energies. James Van Allen, who found these belts in 1958, is the reason they are named after him. While electrons predominate in the outer radiation belt, protons make up the bulk of the inner radiation belt. Because of the substantial effects these belts may have on spacecraft and satellites that fly through or close to them, they are fundamental to comprehending the magnetospheric environment of Earth. Because of interactions between waves and particles as well as variations in the magnetic field, the particles contained inside the radiation belts experience complicated dynamics, such as acceleration, scattering, and precipitation (Allen & Zhang, 2015).

THE ROLE OF ELECTRONS IN MAGNETOSPHERIC PROCESSES

Space weather, magnetospheric processes, and the interactions between the solar wind and Earth's magnetic field are all governed by electrons, which are crucial to the dynamics of the magnetosphere (Albert et al., 2012). Not only are electrons essential to the general distribution of charges in space, but they also drive numerous processes in the magnetosphere, especially through their interactions with electric and magnetic fields. Understanding space weather, satellite technology, and human activity in space is greatly impacted by these interactions, which impact both the Earth's magnetosphere and the larger space environment (Allanson & Elsden, 2022).

Encircling and protecting Earth from the solar wind a stream of charged particles released by the Sun is the dynamic and intricate magnetosphere, an area of space governed by Earth's magnetic field that extends well beyond the planet's surface. Charged particles, like as electrons, move through the magnetosphere due to a sequence of energetic processes set in motion by this protective magnetic field (An & Artemyev, 2022). The behaviour of electrons is essential to comprehending a wide range of magnetospheric events, including geomagnetic storms and auroral occurrences, because these charged particles are both plentiful and relatively light in this area (Angelopoulos, 2010).

As the Earth's magnetic field both traps and guides the migration of electrons in the magnetosphere, it influences the behaviour of these particles. As a result of the electric and magnetic fields within the magnetosphere, electrons are pushed to spiral along lines formed by these fields. Within this process, electrons undergo a phenomena called the "magnetic mirror effect," which limits their travel to a small area of space and causes them to bounce between the poles of the magnetosphere (Anderson, 2018). For the magnetosphere dynamics as a whole, the distribution of electron energies and pitch angles the angles between the electron's velocity vector and the lines of the magnetic field is crucial. Radiation belt dynamics and particle precipitation into the atmosphere are two magnetospheric processes that can be affected by the distribution of electrons throughout these zones (Auster et al., 2008).

WHISTLER MODE WAVES IN SPACE PLASMA PHYSICS

The dynamics of the magnetospheres of all the planets, including Earth, are profoundly impacted by whistler mode waves, which are an essential part of space plasma physics. These electromagnetic waves got their name from the distinctive falling tone that could be heard in early recordings of them. Their frequencies are usually in the very low frequency (VLF) region, which extends from a few hundred hertz to tens of kilohertz. As the waves travel through the Earth's ionosphere and magnetosphere, their frequency-dependent group velocity gives birth to this unique tonal character (Agapitov et al., 2023).

Whistler mode waves are physically based on how charged particles in a magnetised plasma interact with one another. The combined electric and magnetic fields in a plasma subject the particles to the Lorentz force, which causes them to follow complicated trajectories, some of which are helical as they go around lines of magnetic field (Albert, 2000). The resonance conditions of these particles control the way in which whistler waves interact with them, especially electrons. Understanding pitch angle scattering, energy transfer, and plasma heating, among other magnetospheric processes, relies heavily on this interaction, which is known as wave-particle resonance (Albert, 2001).

Various processes inside the magnetosphere are responsible for producing whistler mode waves. Thunderstorms that rip through Earth's atmosphere are a common cause. Whistler waves are created when the electromagnetic energy from lightning strikes travels into the ionosphere and magnetosphere and interacts with the plasma there (Albert, 2002). As they move along lines of magnetic fields, these waves can go incredibly far from where they started. Geomagnetic storm-induced particle injection events and other magnetospheric plasma instability events are another potential explanation. Whistlers and other natural wave modes can be amplified during these occurrences due to instability caused by the quick input of energetic particles (Albert, 2003).

ELECTRON DYNAMICS IN THE MAGNETOSPHERE

The solar wind, the Earth's magnetic field, and charged particles, especially electrons, interact in a complicated and dynamic way within the magnetosphere of our planet. The behaviour of the magnetosphere and other space weather events can be better understood with a firm grasp of the electron dynamics in this area (Albert, 2008). The mobility of electrons in the magnetosphere is affected by several influences, the most important of which is the magnetic field. Electrons and other charged particles travel in a spiral pattern along lines created by the Earth's magnetic field. Depending on the properties of the magnetic field and their starting energy, these electrons may either wind up stuck in the magnetosphere and oscillate between the poles, a phenomenon called gyro-motion, or they may manage to escape (Albert, 2022).

Both adiabatic and non-adiabatic mechanisms influence the migration of electrons in the magnetosphere. When the intensity of the magnetic field varies more slowly than the electron's velocity, adiabatic processes take place, allowing the electron's energy to stay relatively constant as it curves along the field lines. When electrons undergo large changes in energy due to fast variations in the magnetic field, as happens during magnetic storms or substorms, non-adiabatic processes come to light (Albert & Artemyev, 2021). When it comes to the redistribution of electron energy in the magnetosphere, mechanisms such as pitch angle scattering are quite important. When waves, like whistler mode waves, interact with electrons, they change their pitch angle, which is the angle between their velocity vector and the local magnetic field. This phenomenon is called pitch angle scattering (Albert et al., 2012).

In the magnetosphere, electrons are dynamic; they interact intricately with different electromagnetic waves as they travel through the plasma. Understanding electron dynamics in this area relies heavily on Whistler mode waves. When these waves contact with electrons, they change the electron's pitch angle, which in turn changes the electron's energy and trajectory (Allanson & Elsden, 2022). Electrons can undergo changes in energy distribution or precipitation into the atmosphere when whistler waves scatter them, causing a redistribution of their pitch angle. The wave parameters, such as frequency and angle of propagation with respect to the magnetic field, play a significant role in this scattering process (Allen & Zhang, 2015).

FUNDAMENTAL CONCEPTS OF ELECTRON MOTION

Electric currents in Earth's magnetosphere are an essential part of plasma physics in space. The primary force that governs the behaviour of charged particles like electrons is electromagnetic force (An & Artemyev, 2022). The interpretation of phenomena like radiation belts, magnetospheric storms, and auroras depends on our ability to comprehend the dynamics of electron migration when the Earth's magnetic field is present. Here we review the fundamental ideas of electron transportation in the magnetosphere, with an emphasis on their path through electric and magnetic fields and the effects of forces like the Lorentz force (Anderson, 2018).

Charged particles, such as electrons, encounter a force when subjected to electric and magnetic fields in a low-density plasma or vacuum. Charged particles' interactions with these fields are governed by the Lorentz force law, which is stated as:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}),$$

The total force acting on the electron is denoted by F⃗, the electric field by E⃗, the electron's velocity by v, and the magnetic field by B. The path that an electron takes as it travels through space is changed by this force (Angelopoulos, 2010).

The Earth's magnetosphere has a dipolar magnetic field, which is like a bar magnet's field; lines of force radiate out from the planet at its poles and converge towards its centre around the equator. This field has a significant impact on how electrons move. It is common for an electron to encounter forces from both the Earth's magnetic field and any nearby electric fields when it reaches the magnetosphere (Auster et al., 2008).

INFLUENCE OF MAGNETIC FIELDS ON CHARGED PARTICLES

An essential feature of plasma physics, especially as it pertains to the magnetosphere on Earth, is the interaction of charged particles with magnetic fields. When moving through magnetic fields, charged particles like ions and electrons experience the Lorentz force (Agapitov et al., 2023). This field is fundamental in defining how these particles behave in different parts of the magnetosphere, such as the radiation belts, the magnetospheric plasma sheet, and the outer space. It controls their travel. One needs to think about the type of force at work, how it affects the path of the charged particles, and how these dynamics add up to magnetospheric events on a wider scale in order to comprehend the impact of magnetic fields on charged particles (Albert, 2000).

A charged particle's Lorentz force F, while moving in a magnetic field, is given by:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Where:

- q is the charge of the particle.
- E is the electric field.
- v is the velocity of the particle.
- B is the magnetic field.
- × represents the cross-product between the velocity and the magnetic field.

When it comes to the magnetosphere of Earth, the electric field usually takes a back seat to the magnetic field when it comes to moving charged particles. Depending on the particle's velocity vector, the integral component of this equation for charged particle motion in the magnetosphere, v×B, determines whether the particle moves in a circular or helical pattern (Albert, 2001).

- **Gyromotion and Larmor Radius**

When a charged particle moves in a magnetic field, it becomes entangled in a circular motion due to a force that is perpendicular to both its speed and the field. Gyromotion describes this motion. The gyroradius or Larmor radius, which is the radius of the circular trajectory, may be found by solving the equation of motion. The magnetic Lorentz force supplies the centripetal force necessary to maintain the particle's circular trajectory (Albert, 2002):

$$\frac{mv_{\perp}^2}{r_L} = qv_{\perp}B$$

Where:

- m is the mass of the particle,
- v⊥ is the component of the particle's velocity perpendicular to the magnetic field,
- rL the Larmor radius,
- B is the magnitude of the magnetic field.

Solving for the Larmor radius gives:

$$r_L = \frac{mv_{\perp}}{qB}$$

The Larmor radius is defined by the particle's mass, its velocity, and the magnitude of the applied magnetic field, as shown by the following equation. Gyroradii are greater for particles with more energy or lower charge-to-mass ratios. As one moves farther away from the Earth in the magnetosphere, the intensity of the magnetic field weakens, and the gyroradius of a particle grows larger. The manner in which particles are either trapped or distributed inside the magnetosphere is greatly affected by this impact (Albert, 2003).

KEY PHENOMENA: TRAPPING, SCATTERING, AND LOSS PROCESSES

Three important processes trapping, scattering, and loss are closely related to the study of electron dynamics in the Earth's magnetosphere. When trying to make sense of the interplay between electrons and electromagnetic waves like whistler-mode waves, these occurrences play a key role (Albert, 2008). Space weather, satellite operations, and magnetospheric stability are all affected by these processes, which are crucial in controlling the dispersion of energetic electrons. This section delves into the mathematical explanations and theoretical context of these events, showing how they are pertinent to the investigation of electron pitch angle scattering when whistler mode waves are present (Albert, 2022).

The curvature and gradient of the magnetic field restrict electrons within the magnetosphere, a process known as electron entrapment. This is the first significant phenomena. Both the outer and inner radiation belts make up the magnetosphere of our planet. Within both zones, electrons and other charged particles are impacted by the magnetic field, which causes them to coil around the field lines (Albert & Artemyev, 2021). When the electrons' mobility is limited to a local area in space, they are unable to escape into the interplanetary medium and are said to be trapped. Due to the fact that the first adiabatic invariant must be conserved, this results in what is known as "magnetic mirroring" (Albert et al., 2012).

The magnetic mirror effect describes an electron's travel in the magnetosphere. An electron experiences a weakening of the Earth's magnetic field as it travels away from the surface, giving rise to the magnetic mirror force. Because the electron's magnetic moment is adiabatically invariant, the requirement that the component of the electron's velocity perpendicular to the field, v, stays constant as it passes down the field lines also holds. What is supplied by is the magnetic moment μ (Allanson & Elsden, 2022):

$$\mu = \frac{mv_{\perp}^2}{2B}$$

where m is the electron's mass, v is its perpendicular velocity, and B is the intensity of the magnetic field. While the electron's perpendicular velocity remains constant, its parallel velocity varies in relation to the intensity of the magnetic field as it travels down a field line. This results in the electron being confined to a particular magnetic flux tube by reflecting it back towards areas with a greater magnetic field. The area where the magnetic field is strongest, known as the trapping zone, is contained between two spots on mirrors (Allen & Zhang, 2015).

The behaviour of electrons in the magnetosphere is governed by scattering, another important process. Electrons undergo a pitch-angle change as a result of collisions with other particles or electromagnetic waves; this phenomenon is known as scattering. When trying to make sense of electron precipitation and the escape of energetic electrons from the magnetosphere, pitch angle scattering comes in handy. Electromagnetic waves, like whistler-mode waves, can interact in both resonant and non-resonant ways, leading to scattering. When an electron interacts with a wave, its velocity vector which includes both perpendicular and parallel components change direction. This is the fundamental idea of scattering (An & Artemyev, 2022).

WHISTLER MODE WAVES

An important part of the dynamics of space plasmas is the propagation of a particular type of electromagnetic wave called a Whistler mode wave in the Earth's magnetosphere. The study of wave-particle interactions relies heavily on these waves, which are produced when energetic electrons interact with the surrounding magnetic field (Anderson, 2018). A right-handed circularly polarised wave that usually travels along the lines of a magnetic field, a whistler wave is so called because of the distinctive "whistle-like" sound it makes when amplified. Electrostatic waves or electromagnetic waves, depending on the characteristics of the surrounding plasma, are the main types of these low-frequency waves, which typically range from a few hertz to several kHz (Angelopoulos, 2010).

The interaction between intense electrons and magnetospheric plasma is the main mechanism that generates whistler waves. These high-energy electrons can combine their motion with the oscillations of the wave in a process called electron cyclotron resonance, which can trigger the whistler wave mode as they pass through the geomagnetic field. This contact is crucial because it allows the energetic particles to transmit their energy to the electromagnetic field, which in turn causes the waves to propagate (Auster et al., 2008).

Electron pitch angle scattering relies heavily on whistler waves. Their interactions with electrons can alter their trajectories and energy distributions depending on the pitch angle. As a result of the interaction, electrons are scattered, which changes their momentum and can affect their energy levels by making them spin along the lines of the magnetic field. Because it affects the actions of energetic particles, such those in the radiation belts, this phenomena is crucial to comprehending the dynamics of the magnetosphere. Whistler waves can disperse electrons, which can lead to their precipitation into Earth's atmosphere and, in turn, the aurora borealis and other atmospheric phenomena (Agapitov et al., 2023).

Another mechanism that Whistler waves help with is radial diffusion, which is the movement of energetic electrons. What this means is that electrons are being shifted from high-energy to low-energy areas inside the magnetosphere. To make this diffusion process easier, whistler waves in the magnetosphere allow wave-particle interactions, which scatter electrons over various areas. In studies of space weather and its effects on Earth, this diffusion is especially important because of the crucial role it plays in the magnetosphere's overall energy balance (Albert, 2000).

Whistler mode waves may transmit energy from one part of the magnetosphere to another, and they can affect electron dynamics. Those waves have the potential to travel great distances, carrying energy from the magnetosphere's periphery to its core regions, where they might affect the actions of charged particles and plasma. The intricate web of these interactions has the potential to alter plasma density and redistribute energy around the magnetosphere, among other things (Albert, 2001).

CONCLUSION

The scattering of electrons in pitch angle by whistler-mode waves is central to the functioning of the magnetosphere of the Earth. In this review, the author has discussed the linear and nonlinear processes that govern the wave-particle interactions and the dominant position of the oblique whistler-mode waves in controlling the electron orbits. Results from satellite missions and remote sensing and ground facilities have been available observational evidence, whereas modeling and simulations have extended theoretical propensity despite limitations. The consequences of pitch angle scattering are not limited to the magnetosphere and involve radiation belts, aurorae, and space weather that impacts satellite and communication operations. In the future, with better observational equipment and better simulation models, these processes will be better understood. Knowledge of these mechanisms is important for reducing the impact of space weather and improving the reliability of space-based technologies, which makes this a major ongoing field of study in space physics.

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