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Structure of Earth's Magnetic Field and Solar Wind Interaction

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Abstract:

This paper gives a brief understanding about the structure of Earth's magnetic field and the occurrence of various phenomena in the different layers of the interaction between plasma particles present in the solar wind and Earth's magnetic system. Auroras, space weather, and geomagnetic storms are just a few of the phenomena that are influenced by the dynamic interplay between plasma particles present in the solar wind and Earth's magnetic system. The goal of this paper is to observe and gain a better understanding of the dynamics of the Sun's corona and chromosphere. to investigate flare exchanges, the physics of partly ionized plasma, the coronal magnetic field and heat transmission mechanisms, coronal mass ejections (CMEs) and their origins, and chromosphere and coronal heating. Research on this topic involves studying the effect of plasma particles in the solar wind as they travel towards Earth.

Keywords: Plasma, Solar Wind, Magnetic Interaction, Space Weather.

1. Introduction

In the year 1957- Eugene Parker started investigating an unanswered subject in astrophysics" particle emission from the sun?" He was an assistant professor at the University of Chicago. Since Earth's atmosphere doesn't escape into space, many researchers assumed that the sun would also not experience such a phenomenon. However, astronomers had discovered a peculiar phenomenon that comet tails always point away from the sun, regardless of the direction they were traveling in, almost as if something were blowing them away. Parker started to calculate and based on his calculations, he concluded that if the sun's corona had a million-degree temperature, then particles would be expanding away from their surface and eventually becoming faster than light. Later, this phenomenon was coined as" SOLAR WIND". The Sun expels charged particles, primarily protons, electrons, and particles, but also heavy ions, continuously in the form of the solar wind, with an average mass loss rate of 2x10-14 $M_\odot$ per year. The solar wind, a massive bubble of supersonic plasma that engulfs Earth and other planets and shapes their surroundings, is created as the Sun continuously expels materials into space. Consisting of a constant flow of plasma particles, solar wind plays a vital role in space weather and has a great impact on Earth's magnetosphere. It is crucial to comprehend the mechanics of the solar wind and how it interacts with Earth's magnetic field, forecast space weather events and protect technological infrastructure. For many years, it has been acknowledged that there are two forms of solar wind at solar minimum: slow wind derived from the streamer belt regions and fast wind coming from coronal holes. Although the material in the solar wind is in a unique condition or state called plasma, it is still composed of regular matter, the behavior of which is understood to some extent. Numerous factors distinguish the slow solar wind (SSW) from the fast solar wind (FFW), such as higher proton density, lower proton temperature, higher electron temperature, higher heavy ion ionization states, and higher first ionization potential (FIP) bias. Through ensemble studies that

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combine the solar wind from several solar wind streams over a variety of time periods, such broad features of the SSW can be determined. [1].

2. Fast and Slow Solar Wind

The solar wind is created by the outward expansion of accumulated charged particles, i.e. plasma, from the Sun's outermost atmosphere (corona). This accumulated plasma is continuously heated to a point at which gravity is unable to encapsulate it. After then, it moves adhering to the magnetic field lines of the Sun that radiate outward. The magnetic field lines of the Sun coil up into a massive spinning spiral above its Polar Zones during its once-every-27-day rotation, producing a steady stream of wind. It was earlier thought that fast solar wind emerges from the open magnetic fields that are connected to large coronal holes but after further study its origin remains a mystery and hence it shows that we need to understand more about the Sun's heliosphere. Slow solar winds (SSW), on the other hand, arise from the density enhancements of the order of radial dimensions (Rs), called blobs, that is frequently released from coronal streamers and have a speed ranging from less than 100 km s-1 at 2Rs up to 300 km s-1 at 30Rs, which is the typical speed of SSW in hemisphere. These figures suggest that the release of SSW from blobs can be accounted for 15 percent during total solar maximum. [2].

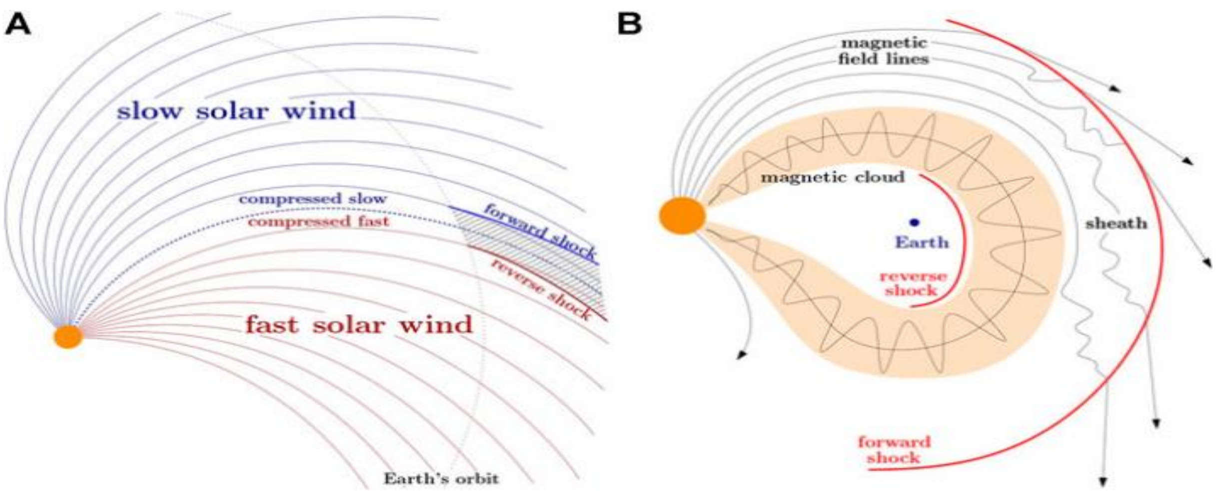

Figure-1 Fast and Slow Solar Wind [2]

Coronal streamers give rise to many small density structures at the rate of 60-100 minutes which have radial dimensions of 1Rs, also known as periodic density structures (PDSs) which were observed from coronagraph images. The measurements of in situ solar wind show that the slow speed wind carries some traces of fast speed winds. This shows that the speed of the wind cannot be considered as an indicator of the origin of solar wind. Inner corona (region that lies within 10R) serves as a storage for ionic charge states an elemental abundance. But the density and temperature keep changing dynamically during the transit of heliosphere and so the ionic charge states and elemental compositions can be associated with properties of solar wind sources. Information about formation of the solar wind and the SSW sources can be obtained from the measurements and remote sensing observations.

3. Heliospheric Current Sheet

Heliospheric Current Sheet, or HCS, is barrier around the Sun that divides opposing magnetic fields that originate on the Sun and are "open" (when only one end is attached to the Sun) These fields have opposing magnetic polarities, i.e., outward (positive) in the north and inward (negative) in the south, and they are closely connected to the Sun’s dipole magnetic field. The HCS reaches the most distant regions of the heliosphere which Pioneer and Voyager were capable of navigating. The solar wind’s features, such as speed, temperature, density, and composition, vary with distance from the HCS. It additionally functions as a magnetic equator. The HCS measures approximately 10,000 km wide at 1 AU, while the surrounding plasma sheet is 30 times thicker. The HCS field does not only vanish to a null and then resurface in the opposite meaning, in fact, the field rotates from one polarity to the other at a roughly constant amplitude. There is minimal evidence to support theoretical predictions that fields on opposing sides of the HCS will merge or rejoin. Coronal streamers, commonly referred to as helmet streamers, are long, cusp-like structures that are frequently observed during solar eclipses and white-light coronagraphs. These are closed magnetic loops which are located above the boundaries between the Sun’s surface regions with opposing magnetic polarities. These loops become longer and more pointed at the tips due to the solar wind, and they can reach up to a solar radius into the corona. [3].

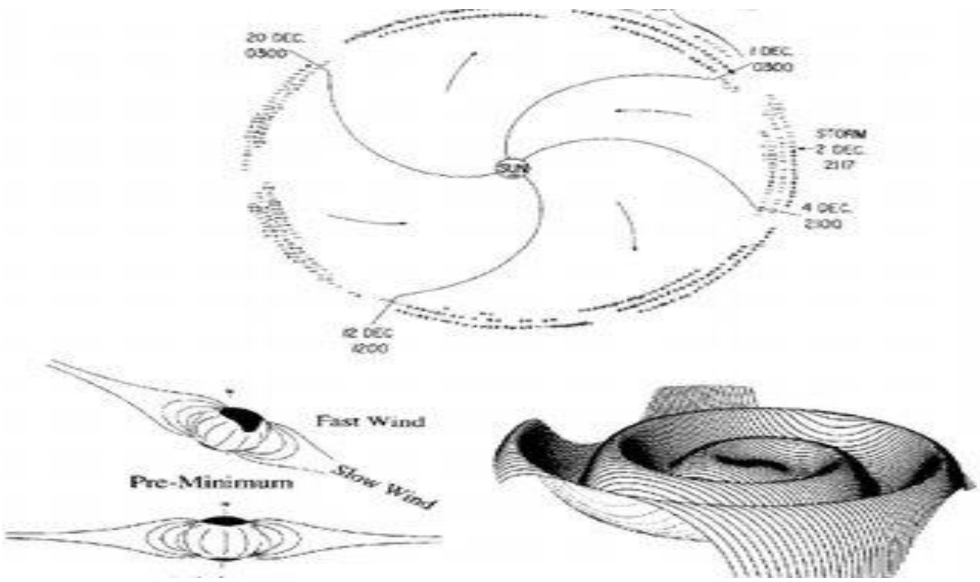

Figure-2 Heliospheric Current Sheet [3]

4. Interaction Between CMEs and HCS

Coronal mass ejections (CMEs), which originate in confined field zones, primarily occur in or close to the streamer belt at the lowest solar conditions [4]. There is a close relationship between CMEs and the HCS under certain circumstances. Streamers can be observed all around the Sun near solar maximum, and its unclear how CMEs and the HCS are related. Given that there are usually a lot of CMEs occurring during periods of high solar activity, one could speculate that the sector structure and current sheet would be disturbed. As Smith et al. (1986) point out, the sector structure is highly stable and only slightly alters when it gets close to sunspot maximum. To prove that there existed a global current sheet during solar maximum, more research was necessary. Parker spiral maintenance was seen at solar maximum, according to histograms of hourly averaged azimuth angles between 1978 and 1982 Additionally, a consistent correlation between the SSNL and the current sheet crossings detected by ISEE 3 was found by this investigation. Direct examination was also conducted into the impact of CMEs on the spiral structure and the HCS. The findings indicated that while a CME may have caused small disruptions to the coronal streamer belt, the belt quickly reassembled close to the helmet streamer’s original position during the HCS [5]. They are traces of sunspot magnetic fields that expanded and progressively drifted poleward at low latitudes. They are traces of sunspot magnetic fields that expanded and progressively drifted poleward at low latitudes. They exist for the duration of the solar cycle. UMRs are visible at the minimum and decreasing phase as the massive coronal holes in the polar cap. The polar cap fields, which have the opposite magnetic polarity, are believed to be eroded by UMRs from the trailing sunspots in each hemisphere as they approach higher latitudes, ultimately leading to their reversal. Throughout the solar maximum, an array of UMRs appear at the solar surface [6].

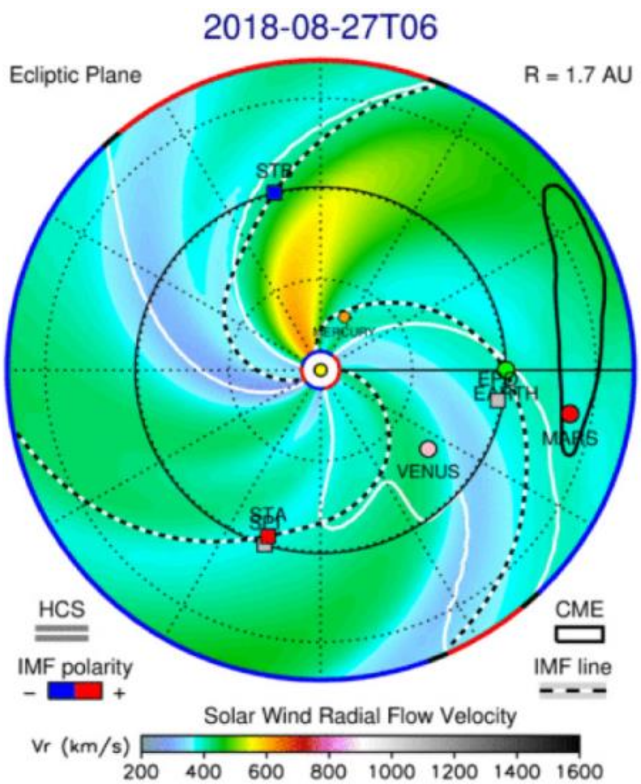

Figure-3 CME and HCS Interaction [5]

5. Earth's Magnetic Field System

The magnetic field that originates from the Earth's core interacts with the highly energized stream of particles coming from the Sun, called solar wind [7]. This field surrounding the Earth is called geomagnetic field or magnetic field. The Earth's magnetic field is believed to arise from the motion of convection currents which occurs due to interaction of molten iron and nickel, a process known as Geo-dynamo. Earth's magnetic field acts as a shield against the charged particles coming from the sun that possess the energy to destroy the ozone layer. One method of stripping involves gas being entangled in magnetic field bubbles, which are then torn off by solar winds. Estimates of the carbon dioxide that was lost from Mars's atmosphere due to the solar wind scavenging ions suggest that the planet's magnetic field dissipated, resulting in almost all its atmosphere being lost.

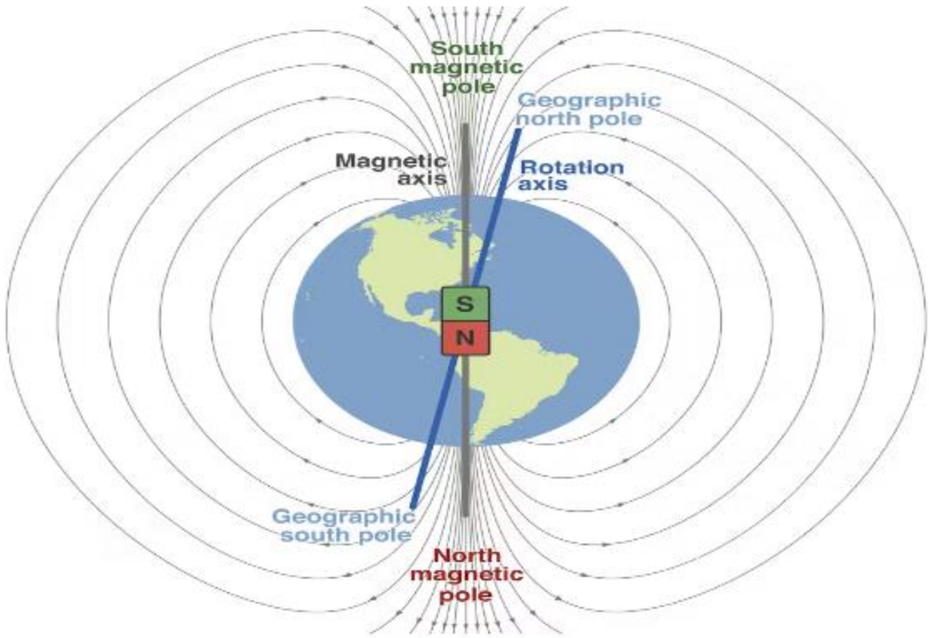

Figure-4 Magnetic Field [7]

6. Magnetosphere

Among other things, the Earth is an extremely strong magnet [8]. A plasma flow that is directed outward from the Sun and is known as the solar wind continuously impacts the Earth's magnetic field. The Earth's magnetic field is (in first approximation) completely enclosed behind the magnetopause, which is an electrical current layer formed by the interaction of the geomagnetic field and solar wind. The magnetosphere is the area that the magnetopause encloses. At the start of the satellite era, the Earth's radiation belts—which are made up of powerful charged particles confined by the geomagnetic field—were found deep within the magnetosphere. There are two fundamental components that make up the Earth's magnetosphere. The first is the magnetic field surrounding the Earth, which is produced by currents moving through the planet's core. When this field is outside of Earth, it resembles a bar magnet and is roughly aligned with the planet's spin axis. The solar wind, a completely ionized hydrogen/ helium plasma that constantly flows outward from the Sun into the solar system at velocities of around 300–800 km s-1 is the second component. A large-scale interplanetary magnetic field (IMF) permeates this plasma stream and is essential to Earth's interaction with the solar wind. The ionosphere of Earth is a third component that is also significant. Nevertheless, the magnetosphere is a dynamical system, much more than simply an enclosure for charged particles. One prominent example of magnetospheric dynamics that can be seen from both the Earth's surface and spacecraft in orbit is the visible aurora. Another is the magnetic fingerprints of electrical currents in the magnetosphere. The interhemispheric propagation of radio signals, irrespective of whether they originate from lightning strikes or are broadcast from ground stations, is significantly impacted by the magnetospheric plasma's spatial distribution. At rocket and satellite altitudes, many more examples of magnetospheric activity have come to light. For example, we find that the intensities of radiation-belt particles change with time in a way that implies impulsive amplification followed by exponential decay. The magnetospheric current exhibits a typical temporal fluctuation pattern.

Furthermore, the current-bearing plasma's ion composition appears to change over time in a way that clarifies the fundamentals of magnetospheric dynamics.

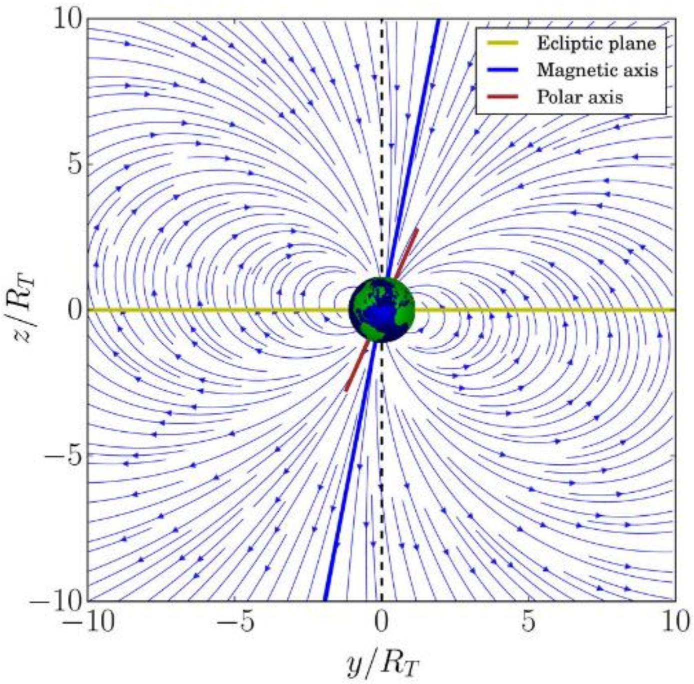

Figure-5 Geomagnetic Field Lines [8]

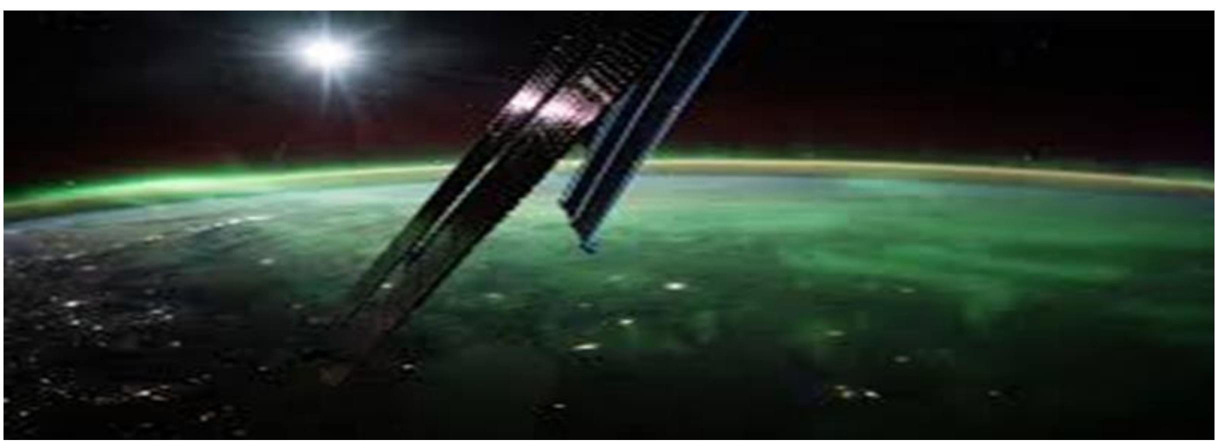

Figure-6 NASA EARTH OBSERVATORY: Aurora Borealis. [Source: NASA]

7. Magnetopause

The merging of the solar-wind and terrestrial magnetic fields of opposing sense, known as magnetic reconnection, is the primary mechanism that permits solar-wind plasma to pass through the magnetopause and enter Earth's magnetosphere. The present level of knowledge regarding reconnection is uncertain; it may occur periodically or continuously. Arguably, magnetopause is the magnetosphere's most important border. The solar wind and the magnetosphere itself first interact here. Mass, momentum, and energy exchange occurs here. Magnetopause and the magnetosphere operate paradoxically as an accelerator and as protective layer at the same time. It detects most of the solar wind surrounding the globe and shields us from its onslaught. It also speeds up solar wind plasma and energetic particles, which in turn powers the radiation belts and ring current. The nature of reconnection and its effects on the magnetosphere hold the key to solving this contradiction. The process by which individual field lines get linked to a new region and lose their identity is referred to as reconnection. Earth-based magnetic field lines typically stay in the magnetosphere and return to the planet in another location. In the solar wind, field lines often stay in the solar wind. However, some magnetic field lines lose their roots when they encounter the magnetosphere, making it possible to follow a magnetic field line that enters the solar wind and exits the magnetosphere and vice versa. Reconnection is the procedure that triggers this topological shift. The fundamental physics that allows for reconnection is highly debatable, even though its presence is undeniable. A component of the incoming solar wind flow magnetically with the magnetosphere during reconnection. It is unclear what factors influence the location and degree of reconnection, yet they are crucial to the magnetosphere's existence. The magnetic fields that link the magnetosphere and solar wind straighten, shorten, and accelerate the plasma on them once they are joined. These interconnected field lines are drawn tailward and re-extend when the solar wind passes through the magnetosphere. They pull on the solar wind, slowing it down and absorbing energy from it as they transition from the magnetotail into the flowing solar wind plasma. A Poynting flux of energy from the flow into the magnetotail may be conceptualized as this process. The energy flow is held in reserve in the tail lobes for potentially released during substorms or, in the event of a storm, more directly into the ring current. The solar wind flow would be far more effective in eliminating our neutral atmosphere even if the energy exchange is not a factor of the field if magnetopause had a different height. Moreover, during a solar proton event, energetic solar cosmic rays could ground all commercial aircraft, not just those that travel across the polar regions as they currently are. Nearly forty years ago, many of the ideas pertaining to magnetospheric physics and magnetopause were first put forth. The fact that these ideas are still up for dispute illustrates the complex way the Earth's highly three-dimensional dipole magnetic field interacts with the magnetized solar wind flow. To manage interaction, magnetic geometry is crucial. A significant bow shock modifies the solar wind, and as it moves into the magnetosphere, the shocked solar wind continues to evolve behind the bow shock, adding to its complexity [9].

8. Bow Shock

Consequently, a shock wave develops that causes the flow to slow down, heat up, and deflect. Subsequently, the magnetosheath plasma in the area behind the standing bow shock is under sufficient pressure to change the flow's direction and speed, causing it to veer around the obstruction. Here, it is important to note the location of the bow shock relative to the magnetospheric obstruction. The flow must be able to bypass the obstruction for it to pass through the shock. As a result, the shock will advance past the obstruction to the point when the magnetopause and the shock can both accommodate all the compressed solar wind. The compression ratio throughout the shock falls to unity (no compression) as the shock lessens, and the shock advances to infinity. The magnetic field and the plasma must both be transported around the obstruction as the solar wind is a magnetized fluid, yet these two amounts are quite distinct. A normal fluid gets deflected by a single compressional wave. But a magnetized fluid requires a combination of three waves to let any disturbance get transported through it. Magnetic flux tubes propagation is fixed only to perpendicular direction with respect to field direction unlike plasma which can travel in any arbitrary direction. The phase and group velocities of these waves—known as the fast, intermediate, and slow waves—are shown for two distinct plasma conditions. The group velocity charts on the far right demonstrate how the direction of the magnetic field substantially guides the intermediate and slow modes. It is possible for the fast mode to move both across and along the magnetic field. Rotating the direction of the field and flow is the responsibility of the intermediate mode. This may assist in bending the field to avoid obstruction. The ratio between the intensity of the magnetic field and the density of plasma is altered by the slow mode. This may be compared to expanding the flux tube, which alters the density but not the field strength. As a result, on a field line" hung up" on the dayside magnetopause, the density may fall. We refer to this type of development as a slow mode expansion fan. The plasma depletion layer is an observable phenomenon that occurs close to magnetopause. The layer in question is made up of an area where the magnetic field intensity is growing and the density is decreasing, close to the subsolar magnetopause. A standing density increase in front of the plasma depletion layer is another, more contentious, discovery. The slow mode compression that is in front of the slow mode expansion has been the interpretation given to this. It is evident from these alterations in the plasma that, whatever the reason behind them, the plasma's characteristics are changing as it diminishes from the shock. Reconnection is a process where magnetic forces play a significant role, therefore factors that increase the magnetic field's intensity or lower the plasma density should speed up the process. Reconnection should occur at a slower rate when there are effects that decrease the magnetic field and/or increase density. Geomagnetic activity data have evidence of this impact. Due to its high dynamic nature, magnetopause presents another challenge for researchers. First, there is a lack of stability in the bow shock and foreshock area. Second, even in the absence of external perturbations, the reconnection process itself is not particularly stable. Third, when plasma's characteristics develop along streamlines, free energy is created that may influence the creation of waves. The mirror generated instability is one of these instabilities, which transforms structure in configuration space into structure in velocity space.

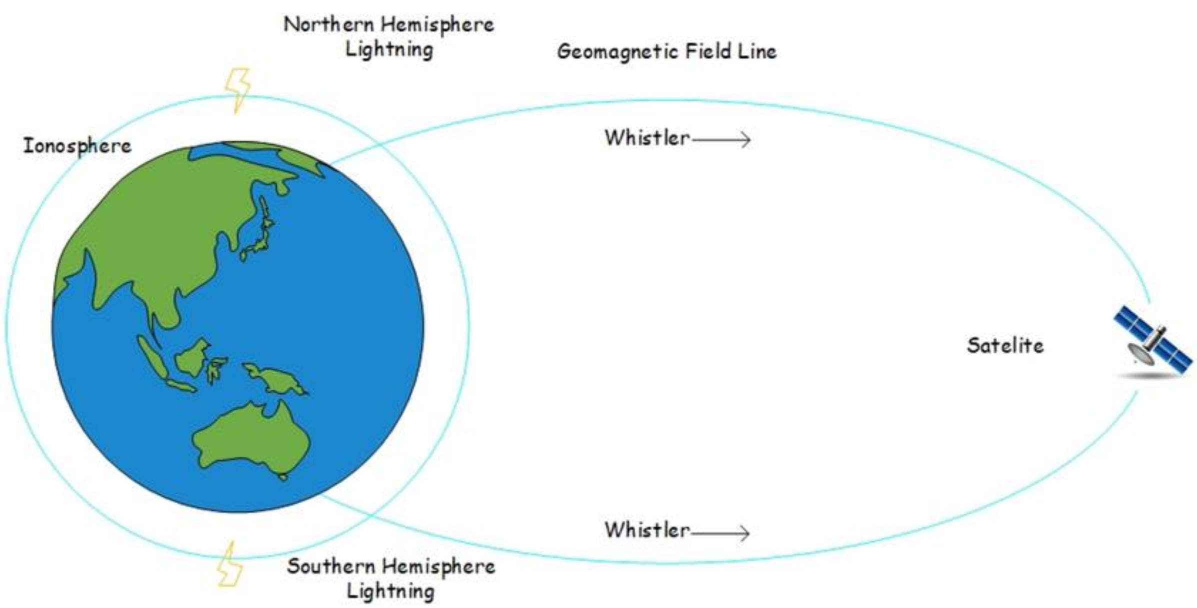

Figure-7 Propagation of lightning whistlers along the magnetic field line. [Source: NASA]

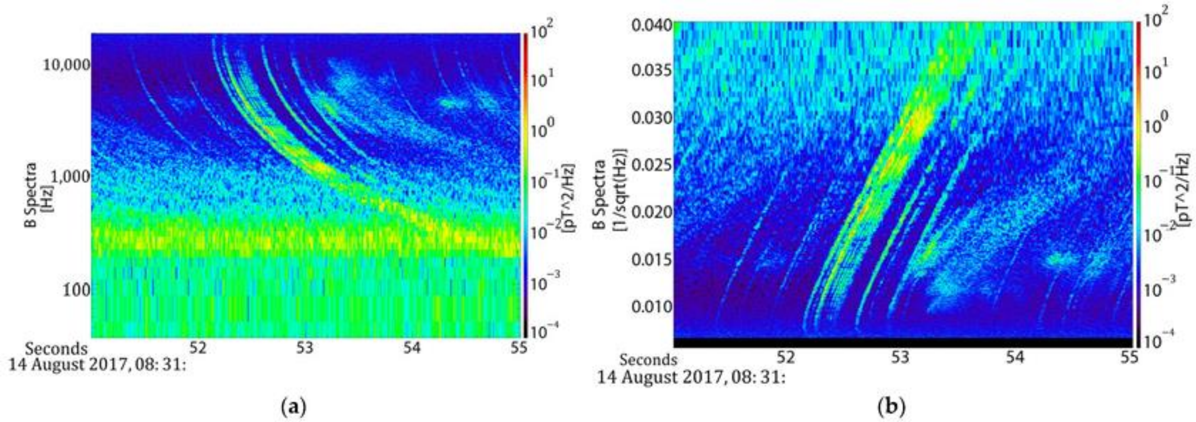

Figure-8 Lightning whistler observed by the Arase satellite on 14 August 2017 at 08:31:51–08:31:55 UT: (a) Dynamic power spectra of lightning whistler waves. (b) Converted dynamic power spectra of lightning whistler waves. [9]

9. Magnetotail

In the present study, we characterize the primary types of plasma waves that arise in the far magnetotail and investigate how these waves relate to measurements of the magnetic field and plasma taken simultaneously on the same spacecraft. The Imp 8 spacecraft, which travels through the magnetotail at radial distances of around 23.1 to 46.3 RE, provided the observations utilized in this study. Imp 8 detects three main forms of plasma waves in the far magnetotail: electrostatic electron cyclotron waves, whistler mode magnetic noise bursts, and wide band electrostatic noise. The strongest and common kind of plasma wave seen in the far-off magnetotail is called electrostatic noise, and it is a broad band emission that happens in the frequency range of around 10 Hz to a few kilohertz. Large magnetic field gradients close to the plasma sheet's outer edges and areas with high plasma flow rates that are either pointed toward or away from the earth are host to this noise. The virtually monochromatic tones that make up the whistler mode magnetic bursts seen by Imp 8 span a few seconds to a few tens of seconds. These noise bursts are associated with areas carrying considerable field-aligned currents, and they occur in the same region as the broadband electrostatic noise, although more rarely. Imp 8 seldom detects electrostatic electron cyclotron waves in the far-off magnetotail. These waves are exceedingly rare, but since they have been seen in areas close to the neutral sheet when the plasma is very hot, they could be quite significant. In 1983, ISEE 3 was within 12 RE of the nominal tail axis and was approximately 225 RE behind the Earth for 40 days. The spacecraft ventured into the magnetosheath during this period, spending at least 70 percent of its time in the magnetotail. Nonetheless, even when it was quite close to the center of an average tail, ISEE 3 stayed inside the magnetosheath for prolonged periods of time throughout five geomagnetically disturbed phases that spanned one to three days during this time. Most of these findings may be explained by the non-radial solar wind flow linked to interacting solar wind streams, which pulls a compressed tail away from the nominal posit ion during these periods, according to simultaneous observations of the solar wind direction and thermal pressure. The solar wind is more radial during the multiple few-hour intervals of substantially northward interplanetary magnetic field (IMF) during these periods, which is why the spacecraft can remain inside the magnetosheath. Currently, ISEE 3 appears to be oscillating between two regions: one is a lower-temperature, lower-density, magnetosheath-like region with a density slightly below the normal magnetosheath, and the other is a higher-temperature, lower-density, tail-like region with a density above the normal tail. Large Bz and Bx components are present in both areas, and they tend to change as though the spacecraft were shifting from one side of the tail to the other. According to the theory, the magnetotail during these periods of northward IMF (Interplanetary Magnetic Field) is mostly made up of field lines that close in on the spacecraft Earthward, with a thin tail that still exists at 225 RE and waves back and forth across the spacecraft. Recent MHD (Magnetohydrodynamics) simulations by J. A. Fedder and J. G. Lyon (submitted article) with northward IMF circumstances providing evidence in favor of this theory, displaying a fully closed tail that only reaches 155 RE. If the extended tail can be eliminated by relatively uncommon long-duration, extremely northward IMF intervals, then it is plausible that more frequent, less northward IMF intervals might have significant, if less dramatic, effects on the tail shape. [10]

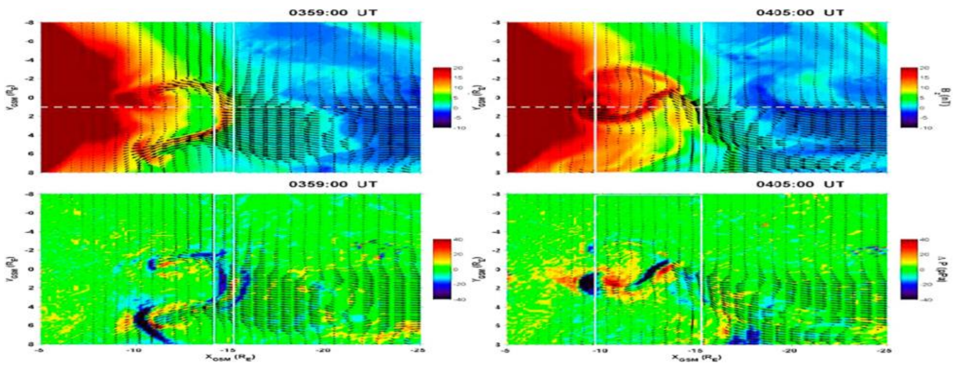

Figure-9 Simulation result by J. A. Fedder and J. G. Lyon [10]

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8.Conflict of Interest

The authors declare that there are no conflicts of interest to report in this article.

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