



Sudan University of Science and Technology
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A Study of Field Line Resonance (FLR) Phenomenon Via in Situ Observations

دراسة ظاهرة تردد خط المجال بواسطة الرصد في موقع
الفضاء

A dissertation submitted in partial fulfillment for the requirements of a master
degree (M.Sc.) in Physics Science

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إستهلال

" إِنَّ فِي خَلْقِ السَّمَاوَاتِ وَالْأَرْضِ وَاخْتِلَافِ اللَّيْلِ وَالنَّهَارِ وَالْفُلْكِ الَّتِي تَجْرِي فِي الْبَحْرِ بِمَا يَنْفَعُ النَّاسَ وَمَا أَنْزَلَ اللَّهُ مِنَ السَّمَاءِ مِنْ مَاءٍ فَأَحْيَا بِهِ الْأَرْضَ بَعْدَ مَوْتِهَا وَبَثَّ فِيهَا مِنْ كُلِّ دَابَّةٍ وَتَصْرِيفِ الرِّيَّاحِ وَالسَّحَابِ الْمُسَخَّرِ بَيْنَ السَّمَاءِ وَالْأَرْضِ لآيَاتٍ لِقَوْمٍ يَعْقِلُونَ (164) "

سورة البقره (164)

DEDICATION

I would like to dedicate this work to my parents, brothers, sisters, friends (especially to Ekram Hashim) and my aunt Fatima Mohammed Yousif. And I also dedicate this work to the soul of the deceased my uncle Salah Abdalla and my colleague Moawia Alrahama.

ACKNOWLEDGEMENTS

The acme of this work is for the sake of ALLAH. And I would like to acknowledge my supervise Magdi Elfadil Yousif, my teachers and tutors in the simulation laboratory in Sudan University of Science and Technology.

ABSTRACT

In this research field line resonance (FLR) phenomenon have been investigated to occur in earth's magnetosphere, and that is for a further verification of this phenomenon via data analysis. FLR could be generated in a specific plasma medium, e.g. generated via a fast mode wave within the coupling system of solar wind- earth's magnetosphere (SW-M). Hence, many previous studies have focused on studying the FLR in earth's magnetosphere because of the importance of this phenomenon in mechanisms of energy and momentum transfer from solar wind into earth's magnetosphere.

Here, in situ magnetic data were collected form the Geostationary Operational Environmental Satellites (GOES). And then from these time series data the power spectrum density in the Pc3-4 frequencies range ($7-100^{mH_z}$) were obtained, and dynamic magnetograms (DM) were plotted. That is, in order to check FLR features in the enhanced amplitudes of waves obtained from the DM. Two types of pulsations was obtained, i.e. toroidal and poloidal modes waves, and the FLR features were observed in both these waves.

It was concluded that FLR phenomenon take place, to some extent, frequently in the plasma environment of the SW- M coupling system.

مستخلص

في هذا البحث تم التحقق من وجود ظاهرة رنين خط المجال في الغلاف المغناطيسي الأرضي و أكد وجودها بطريقة تحليل بيانات لموقع فضاء. فظاهرة رنين خط المجال تتولد في وسط محدد من البلازما، كمثال لها موجه النمط السريع التي تنشأ عندما تتفاعل الرياح الشمسيه مع الغلاف المغناطيسي الارضي. وهناك عدة دراسات ركزت علي دراسة ظاهره رنين خط المجال في الغلاف المغناطيسي للارض و ذلك لاهميتها في نقل الطاقة والزخم من الرياح الشمسيه الي داخل المجال المغناطيسي الارضي.

جُمعت بيانات مغنطيسييه من القمر الصناعي (GOES)، و من ثم تم تحليل هذه البيانات وفقاً لمتسلسلاتها الزمنية و الحصول علي طيف القدره عند مدي الترددات المستمره ((Pc3-4) (7-10 mH_z)) بواسطه رسومات ديناميكيه (magnetograms) من اجل تحسين سعه موجه رنين خط المجال المتحصل عليها. و وجد ان هناك نوعان من النبضات المغنطيسييه (انماط موجات طوليه و عرضيه) تم رصدها.

خلُصت الدراسة الي ان موجه رنين خط المجال هي موجات موضعيه، وتحدث باستمرار في محيط البلازما عند منطقه التصادم (التفاعل) بين الرياح الشمسيه والغلاف المغناطيسي الارضي.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
FFT	Fast Fourier Transforms
FLR	Field Line Resonance
GOES	Geostationary Operational Environmental Satellite
GSE	Geocentric Solar Earth
IAGA	International Association of Geomagnetism and Aeronomy
MHD	Magnetohydrodynamic
ST-FT	Short Time- Fourier Transforms
SW-M	Solar wind-Magnetosphere
ULF	Ultra Low Frequency
UVI	Ultraviolet Imager

CHAPTER ONE

1. INTRODUCTION

1.1. Preface

It is well known that the earth has a magnetic field surrounding it. This field is due to the flow of minerals fluids in the nucleus of the Earth, and according to the laws of electrodynamics, this magnetic field is mainly created around any moving electric charge. Earth's magnetic field is produced by currents in a liquid conducting core and continuously regenerated by a dynamo mechanism. The surface field is very complex and therefore it must be also regenerated by a dynamo of solar wind.

The role of the magnetic field around the Earth is to protect the Earth surface from the cosmic rays of the universe, and harmful sunlight, however, it does not affect the rotation of the Earth, the sun sends high energy charged particles towards Earth's surface, the magnetic field moves them towards the poles, which throw them away and keep the surface of the planet saved. This process occurs because of very complex interactions between solar wind and earth's magnetic field which mediated by what is called MHD waves. (Merrill, our magnetic earth, 2010)

One of the motivation of studying types of high energy particles coming from the solar wind is to find another sources of clean energy, such study led to a field known as Plasma Physics. And the development of this scientific field allowed scientists to use Plasma in many fields. There are several factors that affect magnetic field lines causing resonances of this field lines. For example, a field line resonance (FLR) occurs when a fast mode magnetohydrodynamic (MHD) wave resonance stimulate resonance with the natural field line frequency of a nearby closed magnetic field line

in the earth's geospace environment. Studying of the FLR phenomenon plays a great role in space weather.

1.2. Statement of the research problem

Recently, space weather has become a vital major, because it address many earth's space phenomena in a way as to understand coupling parameters in order to forecast dangerous events (like enhancements in energetic killer electron fluxes) in the space environment that may encounter space flights and human being exploring the space. FLR phenomenon is one of space weather important phenomena, because it gives us a view on how changes took place in the space environment. The FLR phenomenon shows how energy pass from solar wind into the earth's magnetosphere. Hence, understanding and evidencing of FLR therefore is so important in particular from point of view of how to get proof of FLR from suitable data.

1.3. Objectives of the research

This study is focus on understanding FLR phenomenon, and aim to Study field line resonance (FLR) Phenomenon via in situ observations, consequently the flowing objectives are state

- To select suitable satellite data from a provider.
- To calculate Short Time Fourier Transforms (ST-FT) or Fast Fourier Transforms (FFT) of the satellite magnetic data and get power spectrum density of waves in the Pc3-4 frequency range: $7-100\text{ mHz}$.
- To specify FLR feature from the dynamic magnetograms obtained from magnetic data.

1.4. Methodology of the research

In this dissertation, satellite magnetic data is obtained (Papitashvili, 2019), and that is to study FLR phenomenon. Then data were analyzed using a matlab code dedicated for calculating the Fast Fourier Transformation and for plotting the dynamic spectrum magnetograms. The power density of spectrum of the filtered data in a period ranged to 24 hr with 1 min resolution for Pc3-4 pulsations frequencies ($7-100\text{mH}_z$) is obtained from the GOES satellite data. These power density spectrum is used to check features of the FLR, e.g. poloidal and toroidal features.

1.5. Outline of the research

In chapter one introduced a general introduction of research, including, statement of research, objective and methodology, in chapter two gave an overview about Plasma and Earth's space environment and the mechanism of ULF and previous studies, chapter three presented Field Line Resonance (FLR) phenomenon, and in chapter four presented Data, methodology, results and conclusion.

CHAPTER TWO

2. PLASMA AND EARTH'S SPACE ENVIRONMENT

2.1. Introduction

In the previous years the global has highly developed in all aspects especially the scientific research, but still reach for power resources to be pure, safe, and clean on the earth. Among such research, scientists have come up with a science called plasma physics, which is the key of modern technology.

Plasma physics also has incalculable and innumerable USES in space technology, so it must be studied with the space plasma and its impact on spacecraft and others. There is no doubt when this science gets enough attention, it's industrial and economic payoff will be enormous.

Plasma is present in the earth in its aurora borealis and the ionosphere is also plasma, as it reflects radio communication.

Plasma physics is a multidisciplinary science which its applications extends from fundamental research to understanding the universe and space physics. Understanding the Sun's mechanism to produce fusion energy, the transmission of radio waves and television by means of its reflection in the ionosphere and semiconductor applications are located in the field of plasma physics. This reflects the overlap between plasma physics and other sciences because of their importance in industry and academic point of view.

2.2. Plasma definition

Plasma is a Greek word (πλάσμα), which means mold-able. First used with blood plasma. There is a container carrying a set of charged particles (electrons, ions, neutral atoms and dust) called plasma state.

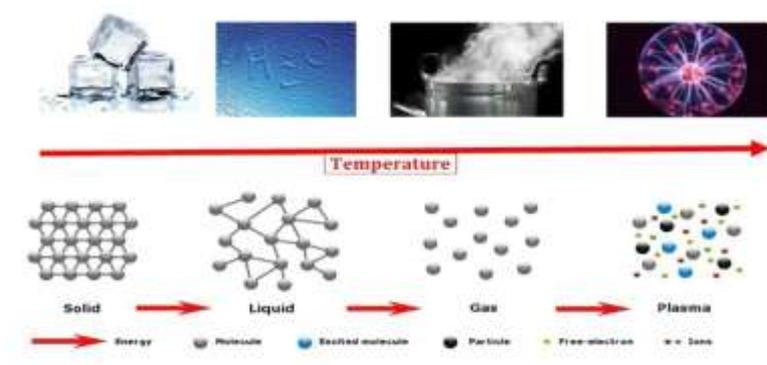


Figure (2.1) illustrates the transition from state to state that occurs at certain temperatures. But this is not the case for plasma state, where the transition from gas to plasma occurs as a result of continuous ionization of the gas. (Ezzat, PlasmaSpringSchool@Port-Said, 2018)

2.2.1 Plasma history

In 1879 Crook observed ionization of gas in radiation matter process, afterwards Thomson studied the ionization properties of the gas.

Meghnad Saha introduced saha's equation in 1920 that relates the ionization state with the pressure and the temperature at the equilibrium state. It based on quantum and statistical mechanics it study the rates of ionization and recombination.

Saha's equation

$$\frac{n_i}{n_n} = 3 \times 10^{27} \frac{T_e^{\frac{3}{2}}}{n_i} e^{-\frac{E_{ion}}{T_e}} \dots\dots\dots (1.1).$$

$$\chi_i = \frac{n_i}{n_i + n_n} \Rightarrow n_i = n_n \Rightarrow \chi_i = 50\% \dots\dots\dots (1.2).$$

χ_i :Degree of ionization

Here n_i and n_n are, respectively, the density (number per m³) of ionized atoms and of neutral atoms, T is the gas temperature in Kelvin, and E_{ion} is the ionization energy of the gas.

The use of the term “Plasma” for an ionized gas first was used in 1927 by the American scientist, Irving Langmuir. The theory of plasma formed under practical studies after periods of observation. Hannes Alfvén (around 1940) is the pioneer in this field, who developed the theory of magnetohydrodynamics (MHD), in which plasma is treated essentially as a conducting fluid.

The development of research led to the discovery of the Earth’s ionosphere, a layer with partially ionized gas in the upper atmosphere, which reflects radio waves, and is responsible from the fact that radio signals can be received when the transmitter is over the horizon. (Moselm, 2017)

Plasma exists in the sun, galaxies and the space. The universe composed of 96% dark energy and dark matter, 4% normal matter; 99% of the visible matter is in the plasma state. (Moselm, 2017), but there was no mathematical model to describe it until Alfvén constructed it, in 1970. A plasma is a quasi-neutral gas, consists of charged and neutral particles, which exhibits collective behavior. Plasma is seen as a neutral matter in large macroscopic scale, however that is not the case when the scale reduces, and it becomes clearly charge matter in a microscopic scale.

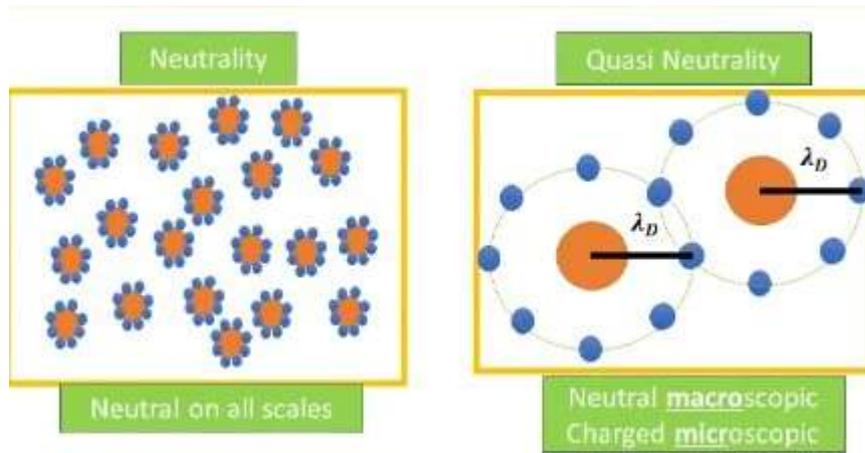


Figure (2.2) explain that two cases of plasma system. (Ezzat, PlasmaSpringSchool@gmail.com, 2018)

We know that, any charged particle has an electric potential according to coulomb law, the potential affect any other charged particle if is placed around, even in a long distance. If the two charged are opposite, then the plasma neutrality property, in some large scale, But if we put some electrons around a positively charged particle, the other electrons will not be affected by the electric potential, and thus we deal with a Quasi-neutral property, which we refer to it as Debye shielding.

2.2.2 Debye shielding

$$\lambda_D = \left(\frac{\epsilon_0 \kappa_B T_e}{n_e e^2} \right)^{1/2} \dots \dots \dots (1.3).$$

λ_D : Debye length

T_e : Electron temperature in Kelvin

κ_B : Boltzmann constant

n_e : Electron density

ϵ_0 : Electric permittivity

e : Electron charge

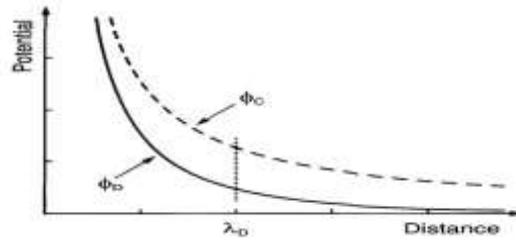


Figure (2.3): distribution of potential for charge particle in space and plasma. (Ezzat, PlasmaSpringSchool@Port-Said, 2018)

2.2.3 Properties of plasma

Debye shielding $\lambda_D \ll L$ where L : Length of plasma system.

Collective behavior occurs when $N_D \gg 1$ Plasma frequency $\omega_p > 1$.

Plasma exists anywhere including that the space as (solar wind, ionosphere and magnetosphere, etc.) under same conditions above, we can see that in chapter two below.

2.3. Solar wind

The sun always emits a continuous highly conducting fluid of plasma (particles charge, as electrons, neutral particles, protons, a little of Helium ions) into the interplanetary space and in all directions. This plasma is known the solar wind. (Baumjohann & A.Treumann, 1997)

The main cause for space weather effects is our sun. Solar wind or the stream of charged particles travel faster at supersonic speeds (which depends on density) about 500km (Baumjohann & A.Treumann, 1997), (which caused magnetic storms when they reach the neighborhood of the Earth). It is variable with time. (Hanslmeier, 2007) Solar wind flows flux of charged particles about 450km/s at all time and in all directions from the sun, and estimated electron density was about 600cm^{-3} . (Kivelson, et al., 1995).

The existence of the solar wind was first suggested to understand magnetic storms on the Earth. Such a perturbation cannot be caused by electromagnetic radiation from the sun because it takes 8 minutes to reach the Earth. (Hanslmeier, 2007)

The solar activity are important effects on spacecraft such as spacecraft charging (surface charging and deep discharges) and single event effects. The effects on humans in space are also to be considered (radiation, particles). (Hanslmeier, 2007)

The typical solar wind parameters are $n = 320\text{cm}^3$, $\kappa_B T_i < 50\text{eV}$ and $\kappa_B T_e 100\text{eV}$. The drift velocities of these charged particles close to the Earth are about 300-800 km/s. This flow of charged particles reaches the Earth orbit and interacts with the geomagnetic field forming a complex structure denominated magnetosphere that protects the Earth surface from these high energy particle. (Conde, 2014) The external sources of magnetic field of Earth.

2.4. Magnetosphere

When the solar wind (full of fluctuations) hits on the Earth's dipolar magnetic field (Earth magnetic field is connected with the Sun magnetic field lines (Merrill, McElhinny, & McFadden, 1996/1983), it can't simply penetrate it but rather is slowed down and to a large extent, deflected around it and in this region a bow shock is generated, the region of thermalized plasma behind the bow shock is called magnetosheath. The region separating the bow shock and magnetosheath is called magnetopause, and the cavity generated by the terrestrial field has been named magnetosphere. (Baumjohann & A.Treumann, 1997). The plasma in the magnetosphere consists mainly of electrons and protons, and small

fractions of H^+ , O^+ ions. The plasma inside the magnetosphere is grouped into different regions with quite different densities and temperatures (Baumjohann & A.Treumann, 1997). Space weather events occur over a wide range of time scales: the Earth's magnetosphere responds to solar-originated disturbances within only a few minutes, global reconfiguration occurs within 10 minutes. (Hanslmeier, 2007)

The solar wind effectively drags the geomagnetic field along with it and an elongated comet-like tail is formed on the dark side, first discovered by Ness (1965) and known as the geomagnetic tail, or magnetotail. Its position is along the sun-Earth line on the sun side, may be estimated by balancing the dynamic pressure of the solar wind ($2\rho V^2$, where ρ is mass density of the solar wind and V its speed) against the magnetic pressure ($B^2/2\mu_0$), where B is magnetic field and μ_0 is permeability (Merrill, McElhinny, & McFadden, 1996/1983). At low latitudes the largest electron densities are found in peaks on either side of the magnetic equator, which is called the equatorial anomaly (Hanslmeier, 2007). The first US spacecraft, in 1958 detected intense charged particles radiation trapped by the geomagnetic field in what are now known as the VAN ALLEN radiation belts (Inside the Earth's magnetosphere) (Menk & Waters, 2013).

On the sunward side of the Earth, the geomagnetic field is compressed by the solar wind, on the opposite side of the Earth, the geomagnetic field extends. Thus the field forms an elongated cavity which is also known as the Chapman-Ferraro Cavity around the Earth. Within this cavity are the Van Allen Radiation Belts (which composed of electrons and protons). (Baumjohann & A.Treumann, 1997). The radiation belt lies on dipolar field lines between about 2 and 6 R_s , it contains energetic electrons and ions which move along the field lines and oscillate back and forth between the two hemispheres. There are two belts of particle concentration: a) small

inner belt between 1 and $2R_E$ (it is relatively stable), where protons of energy $50MeV$ and electrons with energies $>30MeV$ reside and b) outer larger belt from 3 to $4R_E$ (it varies in its number of particles), where less energetic protons and electrons are concentrated. (Baumjohann & A.Treumann, 1997) Charged particles trapped in the belts spiral along the field lines while bouncing between the northern and southern mirror points. (Hanslmeier, 2007)

Inside the radiation belt, the ions drift westward while the electrons move eastward around the earth. The outer part of the magnetotail is called magnetotail lobe. (Baumjohann & A.Treumann, 1997)

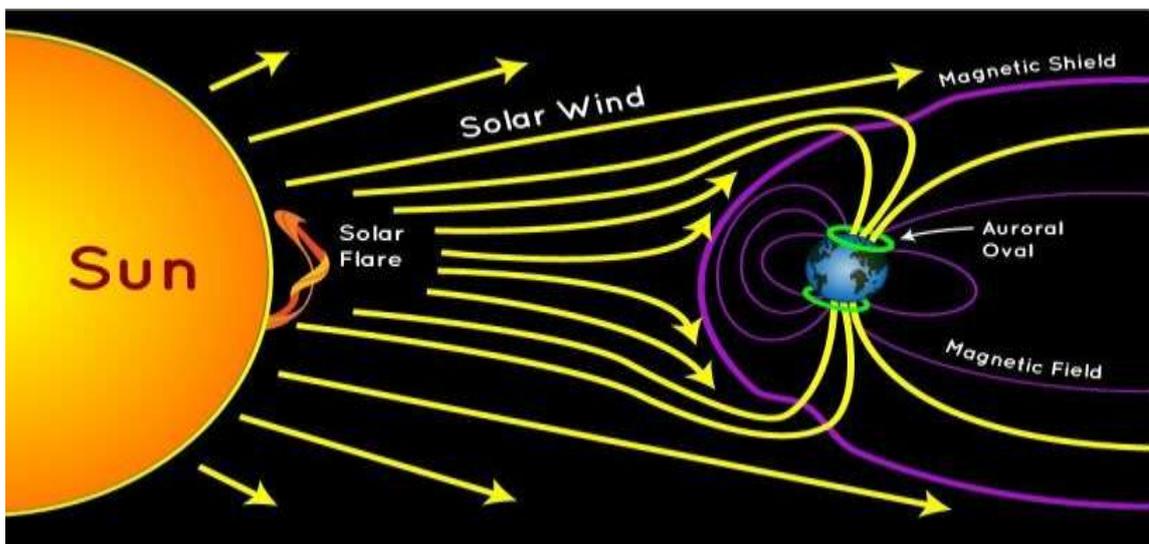


Figure (2.4) illustrate the solar wind magnetic field interacts the Earth's magnetic field (Credit NASA). (Wang, 2018)

2.5. Ionosphere

Plasmas in the ionosphere about $100Km$ above the Earth's surface. Further out are the Van Allen radiation belts. (Menk & Waters, 2013)

Thermosphere (also called ionosphere): the temperature rises up to $1000K$ at a height of $250km$. in this region, thermal conduction is very important.

The extension is up to 600km. the structure of the ionosphere is strongly influenced by the solar wind. One measure of the structure of the ionosphere is the free electron density, which is an indicator of the degree of ionization. Incoming solar radiation with wavelength larger than 300nm (in the visible part of the spectrum) penetrates down to the bottom. Radiation with 200nm <<300nm is absorbed in the stratosphere (ozone layer) and solar radiation below 100nm at higher layers. However, this layer (the ionosphere has a variety of effects on the waves seen at the ground [Hughes, 1974]) is extremely important for modern telecommunication systems since it influences the passage of radio waves. The ionosphere, roughly between 50 and 1500 km above the Earth's surface, is subdivided into the D region (50-90km), the E region (90-120km), and the F region (120-1500km). The ionization originates from the interaction of solar ultraviolet radiation with various atmospheric constituents. The electron density increases from the D region to F region. (Merrill, McElhinny, & McFadden, 1996/1983)

2.6. Geomagnetic field

The intensity of Earth's magnetic field is a function of time and position (in 3d space). The SI unit "Tesla" (symbol T) is used to measure the density of magnetic flux, also called the magnetic field when it is multiplied by the area of the magnetic field lines. The unit used to describe the geomagnetic field is nanotesla (nT), $1nT = 10^{-9}T$.

The first clear description of magnetic field was by William Gilbert in 1600, through a series of experiments which showed that the Earth is magnetized and possesses magnetic poles. The total strength of magnetic field is around $0.066nT$ near the poles and $0.024nT$ near the equator.

The geomagnetic field is a centered magnetic dipole $1=r^3$ up to distances about double inclined 11° with respect to the planet axis. The angles of declination (the deviation of the local geomagnetic field lines from geographic north) and inclination (the angle of intersection with the Earth's surface).

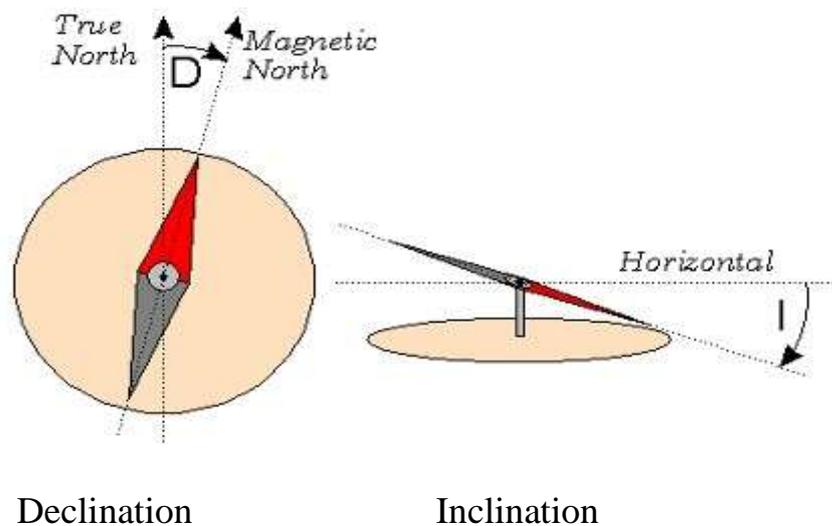


Figure (2.5) explain that Declination and Inclination angles of local geomagnetic field. (Berger, 2017)

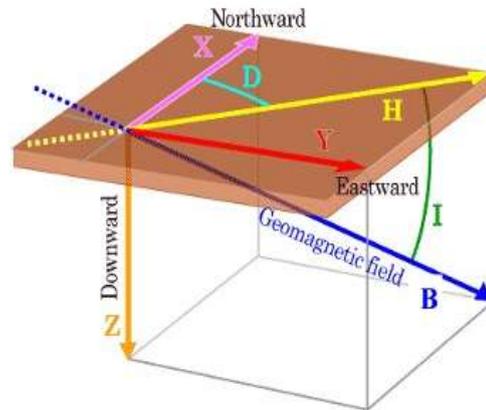
Orthogonal components are commonly chosen to be X, Y and Z for the directions towards geographic north, east and vertically down, respectively. The strength of the field at the Earth's surface ranges approximately from $30\mu T$ at the equator to $60\mu T$ at the poles.

Magnetic field vectors in geographic coordinates

B [nT]: magnetic field vector
 H [nT]: horizontal component of B
 Z [nT]: vertical component of B
 X [nT]: geographic north component of H
 Y [nT]: geographic east component of H
 D [$-180^\circ \dots 180^\circ$]: declination
 I [$-90^\circ \dots 90^\circ$]: inclination

For the vectors apply:
 $B = H + Z = X + Y + Z$
 $H = X + Y$

For the lengths of vectors apply:
 $B = \sqrt{H^2 + Z^2} = \sqrt{X^2 + Y^2 + Z^2}$
 $H = \sqrt{X^2 + Y^2}$



Other notations often used:
 $X = B \cos I \cos D$

Figure (2.6) introduces the fundamental magnetic field vectors in geographic coordinates by determining the locations of these poles, it is very important aims for early explorers. (For more detail of this can see book of magnetoseismology by Frederick W. Menk and Colin L. Waters). (Menk, et al., 2013)

2.7. ULF and magnetohydrodynamics (MHD) waves

Ultralow frequency (ULF) waves incident on the earth are produced by processes in the magnetosphere and solar wind. These processes produce a wide variety of ULF hydromagnetic wave types that are classified on the ground as pi irregular and pc continuous pulsations dependent on waveform and wave period by IAGA committee in 1963, each type is subdivided into frequency and according to special phenomena (Jacobs et al., 1964). Hanns Alfvén to describe a simple process that creates a low frequency wave that propagates along a magnetic field line and the wave he described is now called the Alfvén wave (MCPHERRON, 2005). Waves of

different frequencies and polarizations originate in different regions (depends on conditions of solar wind dynamic pressure and magnetic field) of the magnetosphere. The occurrence of various waves also depends on conditions in the solar wind and in the magnetosphere. Changing in the IMP or increase in solar wind velocity can have dramatic effects on the type of waves seen at a particular on the Earth. (MCPHERRON, 2005)

The geomagnetic pulsations are the signature of ULF (in the range 1MHz to 10MHz) waves that propagate through Earth's magnetosphere and carry energy throughout the magnetosphere (Menk & Waters, 2013), which called (MHD) waves. They were discovered more than 140 years ago by Stewart (1861).

There are many sources of ULF waves, this waves pass through the magnetopause (magnetopause is one of these sources) and propagate through the magnetosphere and carry energy throughout the magnetosphere. Internally they interact with waveguides, cavities, and field lines creating the pulsations actually seen at the surface. There are three types of ULF waves, which are described MHD waves: These names (fast, Alfvén and low) are based on the speed of the wave along the magnetic field. The interplanetary plasma and the solar wind interact with the geomagnetic field to form a complex structure (Hanslmeier, 2007)

The properties (i.e., quantities like density, temperature and pressure) of a collection particles had described, which governed by the basic conservations in fluid, over small spatial volumes. (Kivelson & Russel, 1995)

The low frequency oscillations in the magnetic field have been recorded in the equatorial plane with a magnetometer. An MHD analysis is given for an idealized model in which the earth is considered a perfect conductor, the

background magnetic field is that of a dipole, and the plasma density varies as a power law. For the case of a standing Alfvén wave the poloidal and toroidal (see later) wave equations uncouple and solved numerical. (Cummings, O'Sullivan, & P. J. Coleman, 1969)

If we have to include some effects like electric and magnetic fields and currents in plasma fluid, it call in this case magnetohydrodynamics (MHD) equations. Moreover this waves arise from perturbations of a system (pressure change, sound waves carry pressure perturbations). In a magnetized plasma, dynamics are controlled not only by particle pressure but also by the electromagnetic field. It is easily understood that waves related to perturbations of the both particle pressure and fields are important. There are three types of compressional waves which are an intrinsic signature of different processes taking place in the magnetosphere. (MCPHERRON, 2005).

First wave is called the fast-mode wave, can both propagate and transport energy in any direction and generate compression and rarefaction both of the magnetic field plasma. Second wave called Alfvén waves which propagate along the direction of the ambient magnetic field and produce magnetic perturbation transversal to the field lines. Compressive MHD waves, which propagate in the magnetosphere, can drive, through a resonance mechanism, standing oscillations of the geomagnetic field lines which behave as strings with the ends fixed in the ionosphere (MCPHERRON, 2005)

The magnetic pressure and particle pressure increase and decrease at the sometime. It is propagation perpendicular to magnetic field and seen as alternating compressions and rarefactions of both the field and density. (MCPHERRON, 2005)

The third wave is called slow wave. It carries perturbations in which the particles pressure and density vary out of phase with perturbation and of the magnetic pressure (Kivelson & Russel, 1995). Its phase velocity, v_s , is less than or equal to V_A . Largest of the direction field line. And it does not propagate perpendicular to magnetic field. (Menk & Waters, 2013). Last wave known is medium wave is called Alfvén wave (transverse waves existing only in magnetized plasmas (D Gary Swanson 2003) does not change the plasma density, plasma pressure, or field magnitude, it is characterized by oscillating perturbations of the transverse magnetic field, the electric field, the plasma velocity, and current density and it is considered a fundamental parameter of MHD plasma (Kivelson & Russel, 1995). The fast mode and Alfvén mode propagate with the Alfvén velocity along the field. This velocity is given by $V_A^2 = \frac{B^2}{\mu_0 \rho_0}$, where B is the field strength and ρ the plasma density. Perpendicular to the field the fast mode speed is a combination of the Alfvén and sound speeds, $Cm^2 = Cs^2 + Cv^2$, The Alfvén mode speed is zero, i.e. does not propagate in this direction. Parallel to the field the slow mode moves at the sound speed $Cs^2 = \gamma \frac{K_B T}{m_i}$ and like the Alfvén wave, does not propagate perpendicular to the field (Menk & Waters, 2013).

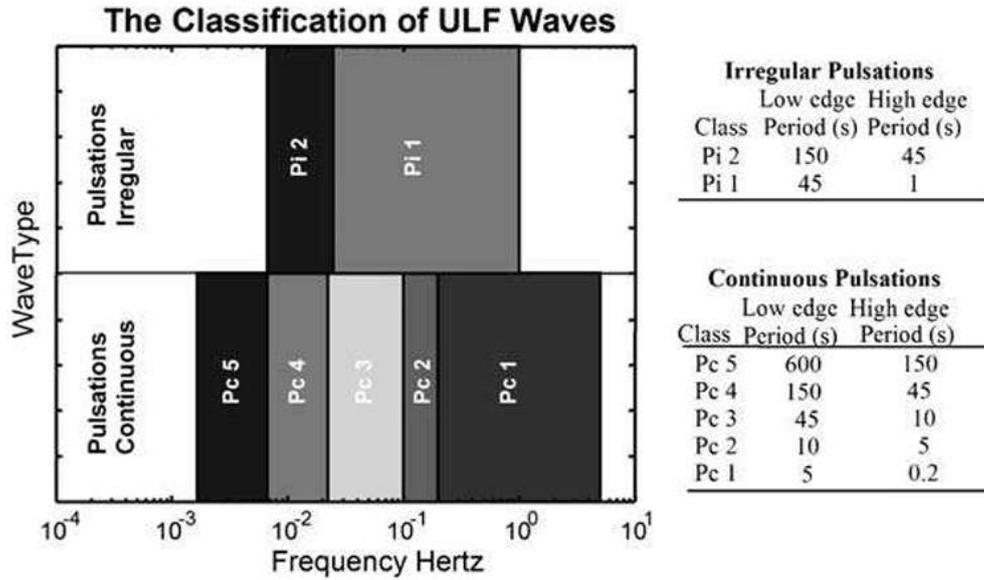


Figure (2.7) showing that the classification of ULF waves, which is division for two types continues and irregular that difference according to range of frequencies. (MCPHERRON, 2005)

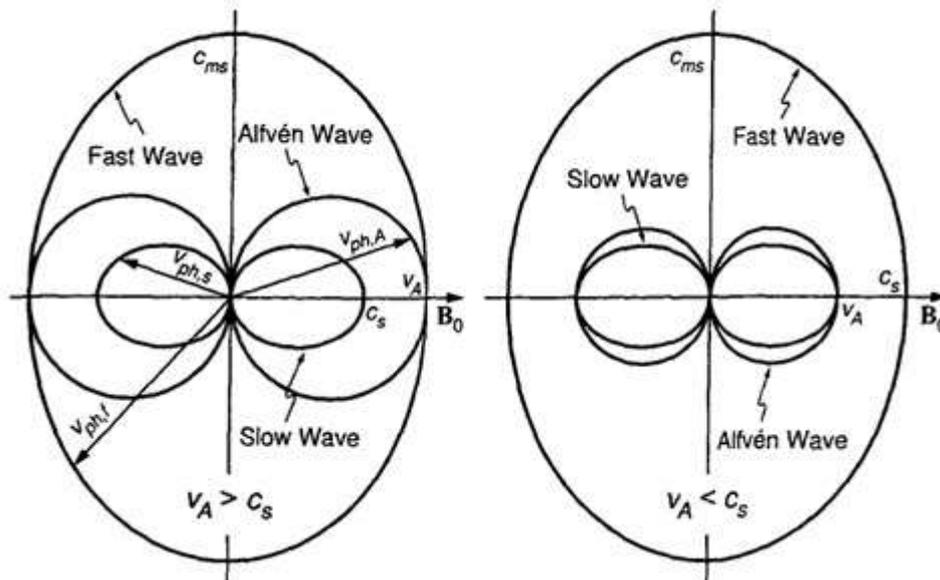


Figure (2.8) explain that the three types of compressional waves, which known as MHD waves. (MCPHERRON, 2005)

2.8. Previous studies

Polar Ultraviolet Imager observations of solar wind-driven ULF auroral pulsations (K. Liou, 2008)

In their paper (K. Liou, 2008) used analysis of a sequence of auroral images acquired by the Polar Ultraviolet Imager (UVI) during a long-duration (1.5 hr. on 26 Sept. 1999) solar wind dynamic pressure enhancement reveals auroral intensity variations in the Pc5 band. Power spectral analysis indicates that the “auroral pulsations” appeared in multiple frequency bands predominantly in the day sector and the dawn-dusk flank of the oval, with the maximum wave power skewing toward the dawn sector.

(UVI) observed the field line resonance phenomena in aurora at event, which obtained discrete frequencies of four values 1.3, 1.9, 2.6, and 3.4. This frequencies used the relation between UT (hour) and aurora intensity. This research used, the relation between UT (hour) and magnetic field. And explain that three types of pulsations which can be expected Global mode.

Field line resonances and waveguide modes at low latitude

(Menk, waters, & Fraser, Newcastle 2000)

In his paper (Menk, et al., Newcastle 2000) studied and investigated experimentally of the properties of low-latitude Pc3-4 ($7-100 mH_z$) geomagnetic pulsations, which included some specific topics and presented mathematical modeling of waveguide mode waves in the magnetosphere which explained features of these observations.

CHAPTER THREE

3. FIELD LINE RESONANCE (FLR)

PHENOMENON

3.1 Preface

As we know late the compressive MHD waves, which propagate in the magnetosphere, can drive, through a resonance mechanism, standing oscillations of the geomagnetic field lines which behave as strings with the ends fixed in the ionosphere (MCPHERRON, 2005)

3.2. Field line resonance

The field line resonance (FLR) is created when the frequency of hydromagnetic waves in Earth's magnetosphere matches the eigenfrequency of the field line. (Southwood, 1974; Chen and Hasegawa, 1974).

Field lines of the Earth's dipole behave like vibrating strings. The ends of the field lines are frozen in the conducting ionosphere and can't move but they can bend. In their equilibrium positions there is no force orthogonal to the lines. However, if some process displaces a field line, a tension force develops that tries to restore it to its equilibrium shape. However, because the field line is loaded with gyrating particles it picks up momentum that causes it to overshoot the equilibrium. The field line oscillates until other processes damp it. (MCPHERRON, 2005)

Field line resonance is very important mechanism for the generation of pc3-4 (7-100 mH_z) geomagnetic pulsations. We find the resonant frequency increases with decreasing latitude. it is generally believed that

ULF waves propagate through the magnetosphere and couple to and drive standing oscillations of field lines (orr, 1984, Allan and poulter, 1992) (Menk, waters, & Fraser, Field Line Resonances and Waveguide Modes at Low Latitude, Newcastle 2000)

There are two primary modes of oscillation of a dipole field line [Southwood and Hughes, 1983].

The toroidal mode is a displacement in the azimuthal direction creating an azimuthal magnetic perturbation, the poloidal mode is a radial displacement with radial magnetic perturbations. Either mode may oscillate with different harmonics. The fundamental harmonic depicted in the left side (a) contains an odd number (one) of half wavelengths between the ends of a field line. The second harmonic in the right side (b) contains an even number (2) of half wavelengths. Many different harmonics may be simultaneously excited when the field line is excited by a broadband source (Sciffer & Waters, 2008).

The toroidal mode of field line resonances is most commonly observed in space. The reason is that azimuthal perturbations do not change the field magnitude or cause plasma density changes.

In addition, field lines azimuthally adjacent to the vibrating line have nearly the same resonant frequency and so can vibrate in phase with the initially disturbed line. In fact, these properties identify this mode as the Alfvén wave.

The poloidal mode is harder to excite because field lines are oscillating in a radial direction and radially adjacent field lines have different frequencies. Inevitably, adjacent field lines will oscillate out of phase and there will be compressions and rarefactions of the field. This mode of field line resonance corresponds to the fast mode.

The simplest approximation to the fundamental frequency of a field line is obtained by integrating the Alfvén travel delay $dt = \frac{ds}{V_A}$ along a field line.

The local delay depends on both the field strength and the plasma density through V_A (Alfvén velocity). Longer field lines have longer resonant periods (lower frequencies). Field lines with more, or heavier particles will also have longer periods. This behavior of Alfvén velocity and resonant period (Waters et al., 2000). In the simple model used to obtain these curves, the magnetopause is located at $10 R_e$, the plasmapause at $5 R_e$, and the ionosphere at $1.1 R_e$. The sudden decrease in velocity and frequency at about five R_e is caused by the increase in plasma density across the plasmapause. The decrease close to the ionosphere is caused by the presence of oxygen ions in the upper ionosphere. The slow increase in resonant frequency from $3 mH_z$ at the magnetopause to $20 mH_z$ at the plasmapause, and a much larger increase inside the plasmapause, are caused mainly by a rapid increase in field strength and a decrease in field line length. Although the plasma density increases inward, this change is too slow to overcome the effects of the magnetic field. (MCPHERRON, 2005)

A study of the magnetic pulsations using data from the GOES Satellite. Three component dynamic magnetic field spectrograms have been used to survey ULF pulsation activity. The dynamic spectra were examined (for 24hr) to find events which fall into two basic categories: first: toroidal modes (fundamental and harmonic resonances) and second: poloidal modes, which include compressional oscillations. The occurrence rates were determined as a function of L value and local time. The main result is a comparable probability of occurrence of toroidal mode oscillations on the dawn and dusk sides of the magnetosphere inside geosynchronous orbit, while poloidal mode oscillations occur predominantly along the dusk side, consistent with high azimuthal mode number excitation by ring current ions.

The toroidal fundamental and harmonic resonances are the dominant mode seen on the dawn-side of the magnetosphere. The narrow band signal of it, with $\Delta f < 2mH_z$ seen in the toroidal component and frequency decreasing as L-shell increases (Samson and Rostoker, 1972), is considered to be the resonance. If the frequency is less than $10mH_z$, the event is identified as a fundamental resonance, otherwise as a harmonic. (Hudson, Denton, Lessard, Miftakhova, & Anderson, 2004)

Poloidal mode (Pulsations) are characterized by a narrow band signal in the radial and compressional components with frequencies less than $10mH_z$. Poloidal pulsations are expected to have slightly lower FLR frequencies than the toroidal mode, as discussed in Cummings et al. (1969) the occurrence rates of poloidal pulsations. The oscillations occur predominantly on the dusk side of the magnetosphere. None are seen at noon. (Hudson, Denton, Lessard, Miftakhova, & Anderson, 2004)

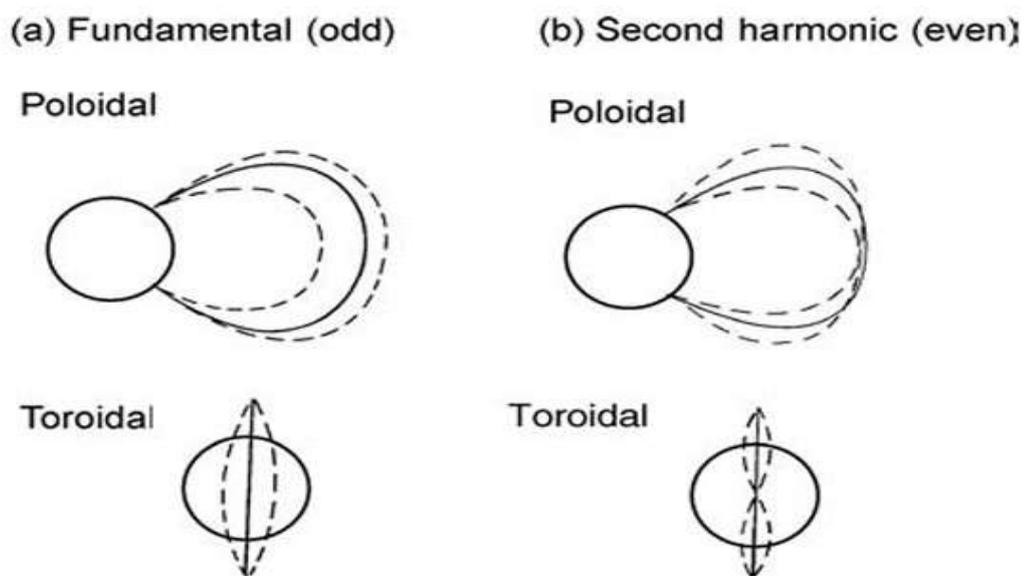


Figure (3.1) illustrate representation of (a) fundamental (odd mode) and (b) second harmonic (even mode) standing oscillations of geomagnetic field lines. Decoupled toroidal and poloidal modes are shown, with dashed lines depicting the displaced field lines. (Hudson, Denton, Lessard, Miftakhova, & Anderson, 2004)

CHAPTER FOUR

4. DATA AND METHODOLOGY, RESULTS, DISCUSSION AND CONCLUSION

4.1. Data and methodology

Data of geospace magnetic field (B_x , B_y , B_z) in Geocentric Solar Earth (GSE) coordinate system were collected from (Papitashvli, 2019). We selected some days to check FLR, since these day were previously confirmed to have FLR features in the ground (Suliman, et al., 2013) and they are: 26 Sept. 1999, 31 Dec. 2008, 5 May 2008, 23 May 2008, 26 Nov. 2008, 11 Oct. 2009, 19 Jan. 2009, 25 Jan. 2009, 26 Jan. 2009, 13 Jan. 2009, 4 Sept. 2009, 20 Sept. 2009. We obtained satellite magnetic data from (Papitashvli, 2019). Then we analyzed the data using a matlab code dedicated for calculating the Fast Fourier Transformation of the data and to plot the dynamic spectrum magnetograms. The power density of spectrum of the filtered data in the period range (24hr with 1 min resolution) and in the Pc3-4 pulsations frequencies ($7-100\text{mHz}$). We tested days above using data from some satellites i.e. Polar, Cluster, Themis and GOES, which most of them do not have enough data, so we selected GOES data and got the following results.

4.2 RESULTS

The following figures show resulted dynamic magnetograms of different types of pulsations obtained from in situ satellite data, for three days in a full 24 hr time span a day.

In event 19 Junoury 2009

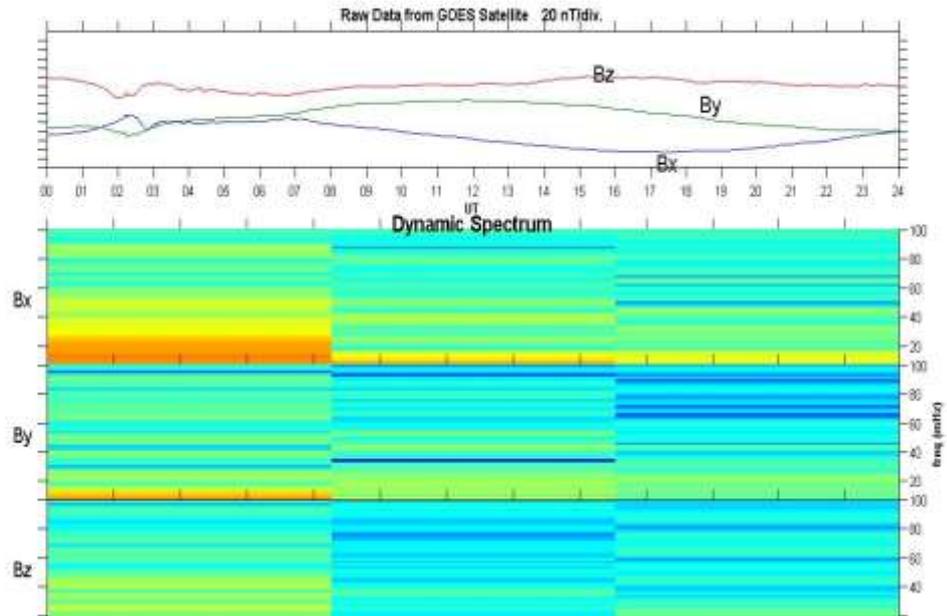


Figure (4.1) shows event **19 January 2009** for 24 hr. it is explain that FLR Poloidal pulsations which is discret frequency.

In event 23 May 2008

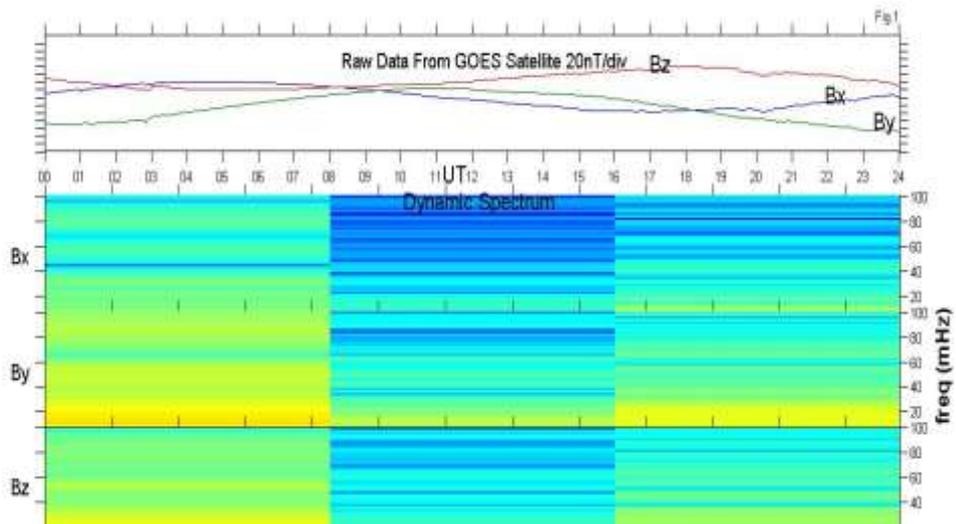


Figure (4.2) explain that the observed of toroidal pulsation measured by the GOES Satellite on 23-05-2008.

In event 31 Dec 2008

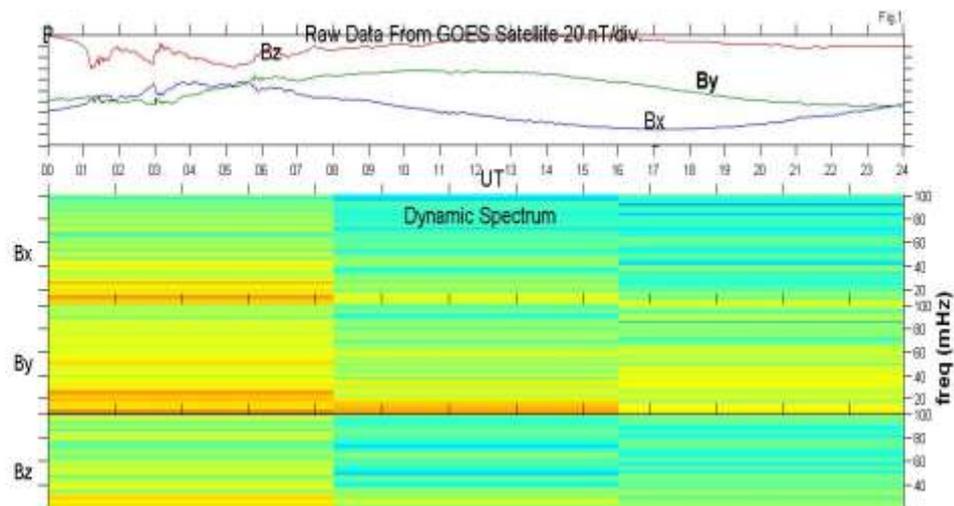


Figure (4.3) explain that the observed of mixed pulsations (toroidal and poloidal) which measured by the GOES Satellite on 31-12-2008.

4.3 Discussion

The lower frequency pulsations were driven directly by the solar wind, whereas the higher frequency ones were associated with global compressional cavity mode (K. Liou, 2008)

Analysis of a sequence of pulsations images acquired by the Geostationary Operational Environmental Satellite (GOES) during a long-duration (24 hr.) in different days, the power spectral analysis by using Matlab code for Pc3-4 for range of frequencies between 7-100 mH_z , indicates that for each day there are one of the two types of pulsations, poloidal, toroidal and third type is mixed of them.

4.4 Conclusion

Pc3-4 pulsations was observed to occur in two types toroidal, poloidal mode or mixed of them. The matching between the Earth magnetic field and solar wind magneic field indicates that there is resonance, which is known as field line resonance (FLR).

4.5 Recommendation

It is necessary to have integrated in situ and ground geospace data, and it is also so essential that researchers work in groups so as to achieve this integrability of space science data. In shedding light to all of the

aforementioned importance of coming together we recommend that installation of ground devices as well as launching satellite missions should be seriously considered by all scientists working in space science research.

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