Solar Wind Interaction with Venus Atmosphere

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Abstract:

In this study we have focused on the solar wind interaction with Venus' atmosphere. This is a captivating research area for knowing the Sun, solar wind, and the exciting atmospheric world of Venus. The solar wind, a constant stream of charged plasma particles emitted by the Sun outer region called corona, effect the dynamics and characteristics of Venus' (ionosphere, magnetosphere, and atmospheric properties). This interaction has shaped the planet's entire evolution and provides valuable insights into the long-term evolution of Earth-like planets. Through analyzing data from missions like (VEX, and the Wind spacecraft) we have deepened our understanding of the intricate relationship between the solar wind, and Venus. Through this study we can understand the plasma structures, magnetic field variations, and atmospheric changes. We have analyzed the data obtained from different missions and tried to explore Venusian atmospheric dynamics. This can help us knowing how the earth like planet changes over time and how greenhouse effect is generated? This study contributes to our understanding of planetary atmospheres and climate dynamics. We also discussed the chapman-ferraro equation that can help us in knowing the interplay between solar wind dynamics and its impact on the density of Venus' ionospheric plasma at the ionopause. Moreover, this work has broader implications for planetary science, astrophysics, and can help us to know how extraterrestrial life cannot exist, opening new avenues for future space exploration and expanding our knowledge of celestial phenomena outside our solar system.

Keywords:

Venus Atmosphere, Solar Wind Interaction, induced Magnetic Field, Plasma Structures

1. **Introduction**:

Sun being a closest star, is crucial to the existence of solar system and planets in it. The solar wind is a continuous flow of charged particles (ions) of different types, aroused from the sun, traveling at different velocities in our whole solar system. Solar wind was first predicted by Richard Carrington in 1859, and later on confirmed by various space missions. Especially by the work of Arthur Eddington and Kristian Birkeland [1]-[2]. Different Missions towards Sun like Stereo and the Parker Solar Probe has provided significant information about the solar wind's formation and properties. The Parker Model can help us in understanding the structure and behavior of solar wind, explaining how it originates from the Sun's outer region called corona and propagate charged particles into space. Understanding the Parker Model helps researchers knowing solar wind dynamics, which can includes variations in velocity, intensity, and behavior during different phases of the Sun's cycle[1].

Venus, which is sometimes called Earth's twin, has a dense toxic atmosphere mostly comprised of carbon dioxide and toxic sulfuric acid clouds. Why the Venus is too much toxic? And why there no chance of life existence which factor contributes here be discussed [3]. Venus experiences a unique interaction with the solar wind due to its slow rotational motion and lack of intrinsic magnetic field. This unique interaction result in different atmospheric characteristics of Venus. Different exploration missions of Venus has provided information and details about its interaction with the solar wind[2].The Solar wind interaction with the upper atmosphere of Venus produce a weak magnetic field but it not make it with other planets[4]. The resistances of ionosphere of Venus towards solar wind result in the phenomenon of bow shock. The study of solar wind interaction with Venusian atmosphere provides us significant information about the atmospheric evolution of Venus. The solar wind interaction with Venusian atmosphere is important for understanding its physical and chemical properties[5]. The data analyzation from various Venusian missions (VENERA, MARINER, and Pioneer Venus 1) enables us to explore the effects of the solar wind on Venusian atmosphere. VEX help us in explaining magnetic field of Venus when solar wind interact with the ionosphere of Venus [15]. So, the investigation of solar wind dynamics and its interaction with the Venusian atmosphere is a multi-dimension area that encompasses space physics, planetary science, and astrophysics[6] .

Another important thing is Atmospheric escape processes. Which contain the continuous loss of atmosphere from Venus when it interacts with the solar wind. This phenomenon has contributed to the relatively tenuous Venusian atmosphere compared to other planet like Earth's which is denser than Venus [11]. Understanding atmospheric escape provides insights into the long-term evolution of planetary atmospheres that can easily change due to external influences. We will also know here from (vex) mission regarding Venus atmosphere layers.

The purpose of our work is to analyze data from various Venusian missions .We will provide insights about the effect of sun and solar wind on Venusian chemistry[1] . The study of solar wind interaction with Venus enables us to examine various factors that have shaped the current environment on the planet. This interaction has made the characteristics of Venus different from other planets[7]. The Solar wind flow towards Venus played an important role in energy transfer from the Sun to Venus[1]. The continuous flow of energy from sun to Venus has the potential to change (and has potentially changed) the Venus physical and chemical properties. On the basis of these information, we get a valuable insights into the complex processes within Venusian atmosphere[8]. By exploring this interaction, we can broaden our knowledge of Venus and its overall composition and why life is impossible in it[9] .

Investigating the relation between the interplanetary magnetic field (IMF) and solar wind provides valuable information regarding the complex nature of Venus[12]. Understanding the IMF's properties and effects enhances our understanding of the Venusian magnetosphere and its response to solar wind variations.

The study of the solar wind and its interaction with Venus is an important research area dealing the Sun, solar wind, and atmosphere of Venus. Studying such interactions enable us to expand our knowledge about dynamics which shape planetary atmospheres (solar and other planets).

2. Methodology:

The solar wind originates inside the Sun and travel across the whole solar system. It travels different in different directions. The content of solar wind is formed during the fusion reaction in the sun[18] .This fusion reaction occurs in the Sun's core to generate the energy and light. The solar wind passes from multiple stages while traveling from core to the outer atmosphere of the Sun. During its journey, it interacts with the magnetospheres of celestial bodies (including Venus) due to which complex plasma structures (phenomenon) like the bow shock and magnetotail occurs[15]. Studying the interplay between the solar wind and plasma structures provides valuable insights into the dynamics and characteristics of these phenomena. The study sheds light on the various complex processes shaping the Venusian environment[2] .

2.1. Untangling the Intricacies of Plasma Structures:

As we know that the solar wind induces complex plasma phenomenon in Venusian atmosphere when interacted[1]. These phenomena affect the whole Venusian atmosphere and weather. To mathematically relate such phenomenon the "Chapman-Ferraro equation" is used. By applying the Chapman-Ferraro equation, for Venus' ionopause density, mathematically we relates ion density to solar wind ram pressure, magnetic field strength, and ionospheric plasma properties[7]. It shows the behavior of the solar wind and its influence on the density of ionospheric plasma at the ionopause region[4].This equation allows us to understand the complex relationship between plasma density, solar wind parameters, and magnetic field strength. The equation help in understanding the dynamics involved in space weather and space climate phenomena.

2.2. Venus ionopause:

Venus' ionosphere interacts directly with the surrounding solar wind plasma, and there is no well-defined boundary layer similar to other planet like Earth's magnetopause. Positioned at an altitude of 250-300 km above the planet's surface, the ionosphere is influenced by solar wind strength and the sun's activity cycle [6]. Without a significant intrinsic magnetic field, Venus lacks a complex ionopause like Earth's. The ionosphere extends outward and interacts directly with the solar wind, creating a dynamic region that showcases plasma waves, turbulence, and instability[16]. This region significantly impacts the behavior of the ionosphere and its interaction with the solar wind. The solar wind's ram pressure and the pressure of the ionospheric plasma also come in equilibrium stage at the ionopause[6].

At the ionopause, Solar wind ram pressure is:

$$P_{sw} = \frac{1}{2} p_{sw} v_{sw}^2 \quad (1)$$

And Dynamic pressure is:

$$p_{dy} = nkT + \frac{B^2}{2u_0} \quad (2)$$

Where n is the plasma density, k is the Boltzmann constant, T is the plasma temperature, B is the magnetic field strength, and u0 is the magnetic permeability of free space.

By comparing both equations (1) and (2)

$$P_{sw} = p_{dy}$$

$$P_{sw} = p_{d^y}$$

$$\frac{1}{2} p_{sw} v_{sw}^2 = nkT + \frac{B^2}{2u_0}$$

$$n_i p = \frac{1}{kT}\left(\frac{1}{2} p_{sw} w^2 - \frac{B^2}{2u_0}\right) \quad (3)$$

Some time we can also write the equation (3) in other form an alternative of them with some additional parameters in them the choice is of your and depend on the context use according to the requirement

$$n_i\rho = \frac{2k_BT}{B^2}\left(\frac{m_i}{m_p}\right)\left(\frac{p_{ip}}{p_{sw}}\right) \quad (4)$$

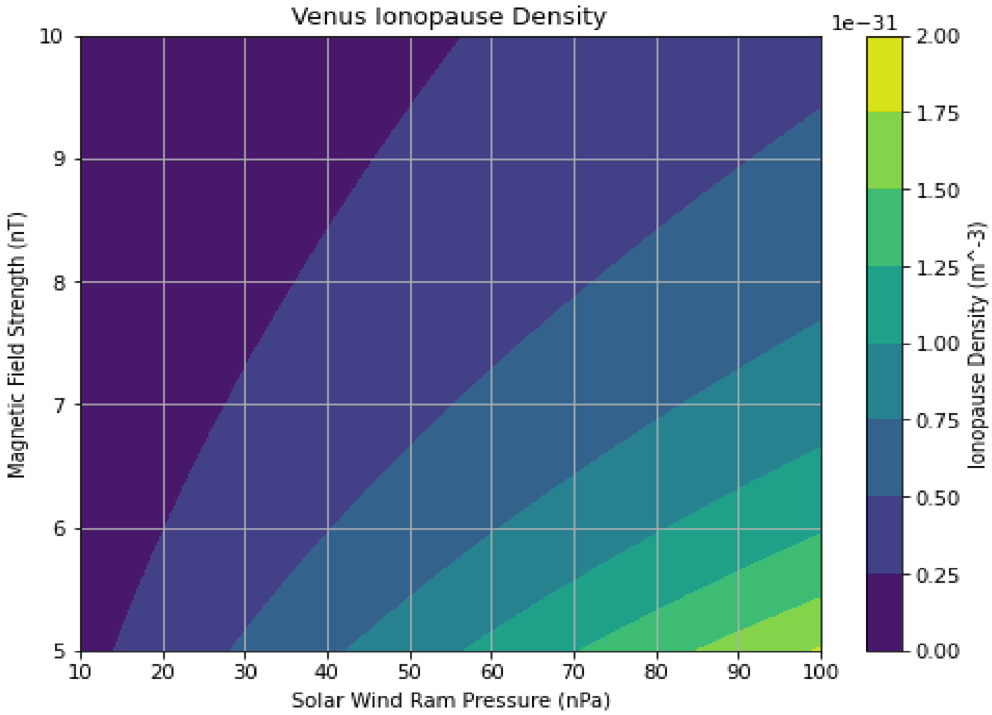
$(n_i\rho)$ Is the density of the ionospheric plasma at that location in both equations.

Where m_p the mass of a proton is, m_i is the mass of an ion in the ionosphere, and p_{ip} is the pressure exerted by ions.

Both are the Chapman-Ferraro equations (3) and (4) for Venus' ionopause density which shows the relationship between the plasma density at ionopause, the solar wind ram pressure, magnetic field strength, and properties physical parameters.

Figure 1:

Ionopause Density vs. Solar Wind Pressure & Magnetic Field:



The density of the Venus ionopause which is the boundary layer separating Venus' ionosphere from the surrounding solar wind plasma. In the plot map represent the level of color of ionopause density (taking specific parameter with specific time); with different colors indicating different density levels. By interacting with solar wind ionopause can be affected these plasma structures changes are important for knowing the dynamics of solar-wind Higher density Regions are representing by darker line and lower density regions is shown by lighter lines. Strong magnetic field can protect the ionosphere from solar wind by actually this is not interaction with Venus. Studying of the ionopause, can give us more information regarding the behavior of the solar wind and the planetary environment and we can know more about the processes that govern space weather and climate [8]. By examining the figure (1) in our data file lines, we can know how the ionopause density changes across different combinations of solar wind ram pressure and magnetic field strength.

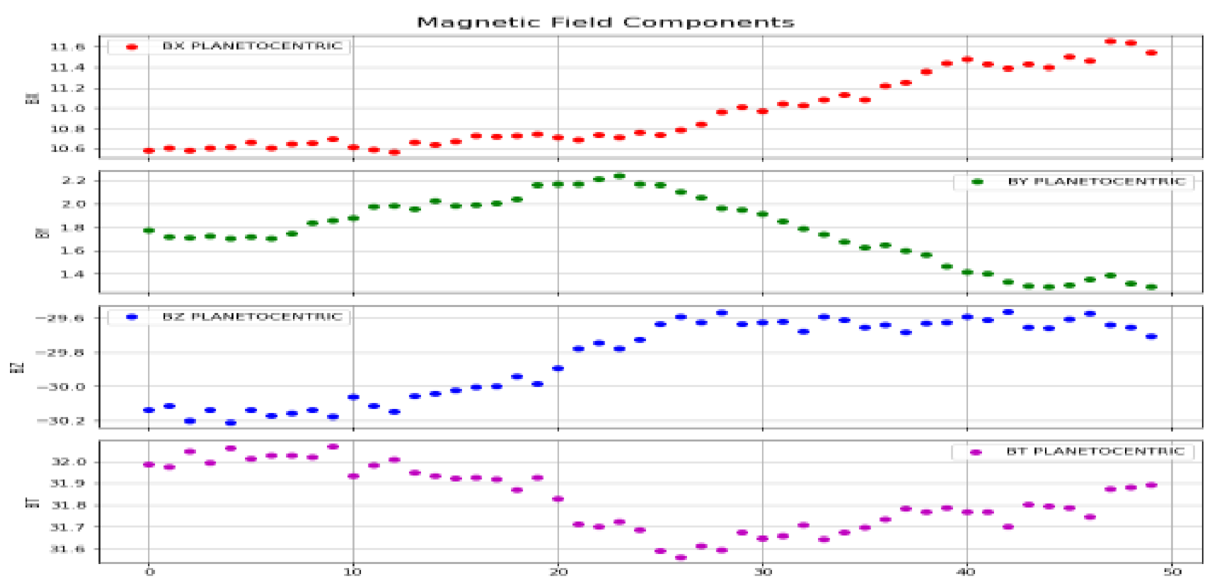
too much strong magnetic field like other planet (earth). And strong solar wind ram pressure can exert a strong dynamics pressure on the ionosphere [1]. This plot provides important sights in the behavior of the Venus ionopause and how it varies in response to different solar wind conditions and magnetic field strengths. But the plot does not necessary represents direct relation in which one factor is increased or decreased by the presence of other. There is need of some other multiple factor.so the aim of this investigation is to improve our understanding of space weather and the planetary environment [14]. So, these factors (solar wind ram pressure and magnetic field strength) can help us in explaining behavior of Venus ionopause which is important for knowing the planet space environment.

2.3. Exploring the Magnetic Field Variations around Venus:

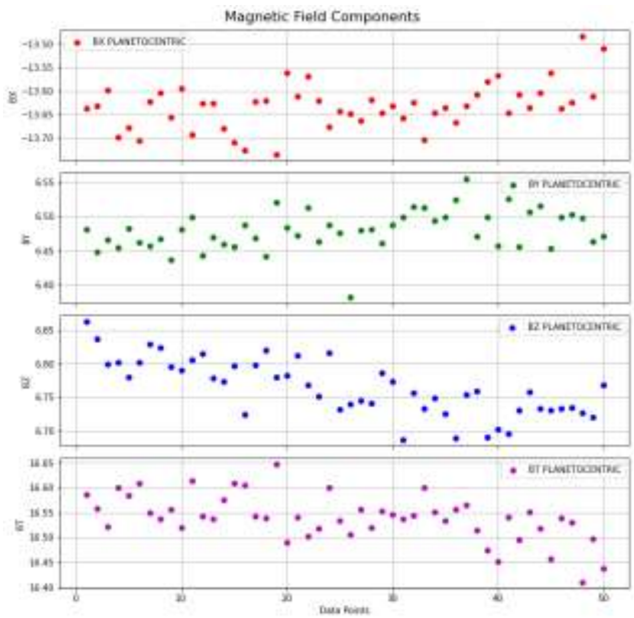
The data from magnetometer instrument of "VENUS-EXPRESS" shows magnetic field measurements of Venusian atmosphere. This mission was launched by the European Space Agency (ESA) in order to understand Venusian atmosphere, ionosphere, and magnetosphere dynamics. The mission observes the solar wind interaction with Venus' ionosphere, which is an important phenomenon in shaping the planet's environment[4] . The dataset from the mission contains the measurement of strength of magnetic field during different time periods. These changes and measurements provide important understanding about the interaction between the solar wind and ionosphere. By measuring the magnetic field strength and direction they use fluxgate magnetometer gradiometer within a ship that can detect various variations. According to the coordinate relative to the sun by measuring these variation in these three component of magnetic field and magnitude gives information regarding the planet magnetosphere and there interaction with space environment. By measuring these quantity we can also know about the planet shape, surface and there evolution.

Figure 2.

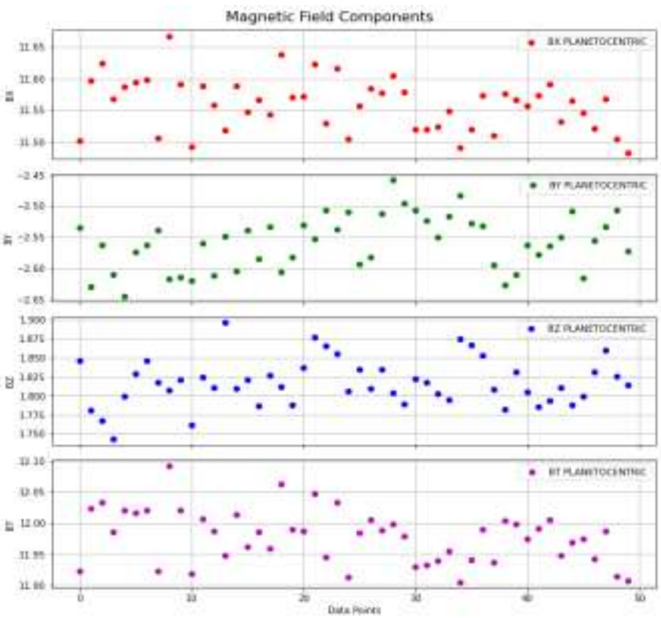
Temporal Variation of Magnetic Field Components (X, Y, Z) and Magnitude:



(a)



(b)



(c)

The figure (2) in our data other file shows the fluctuations and trends in Venusian magnetic field by representing the Venus magnetospheric dynamics. Analyzing the data may uncover patterns, periodicities, or anomalies. This will certainly help us to enhance our understanding of the complex processes near Venus.

The Venus Express spacecraft was equipped with a specialized magnetometer instrument (MAG) designed for measuring the magnetic field near Venus[7] .The MAG instrument gathered relevant data with the help of proper sensors capable of detecting and quantifying field strength and direction.

When the solar wind interacts with Venus ionosphere, it generates electrical currents by disturbing ions of ionosphere. This generated current then produces magnetic field variations around the planet. The MAG instrument aboard Venus Express observed and recorded these unique magnetic field variations around Venus[10]. But the variation is relatively small compared to other planets like Earth, where we would observe more significant variations in the line.

We can investigate the magnetic field characteristics by analyzing the gathered data, like fluctuations in field and response to incoming solar wind. These measurements helps us to understand Venusian magnetic field, atmospheric dynamics, internal processes in Venus, solar wind interaction and overall environment of Venus[4]. Measuring the magnetic field around Venus offers physicists numerous advantages, including a deeper understanding of planetary magnetospheres, insights into solar wind interactions, knowledge of planetary dynamics, improved space weather predictions, and contributions to fundamental physics research.

2.4. Unraveling the Venus atmosphere:

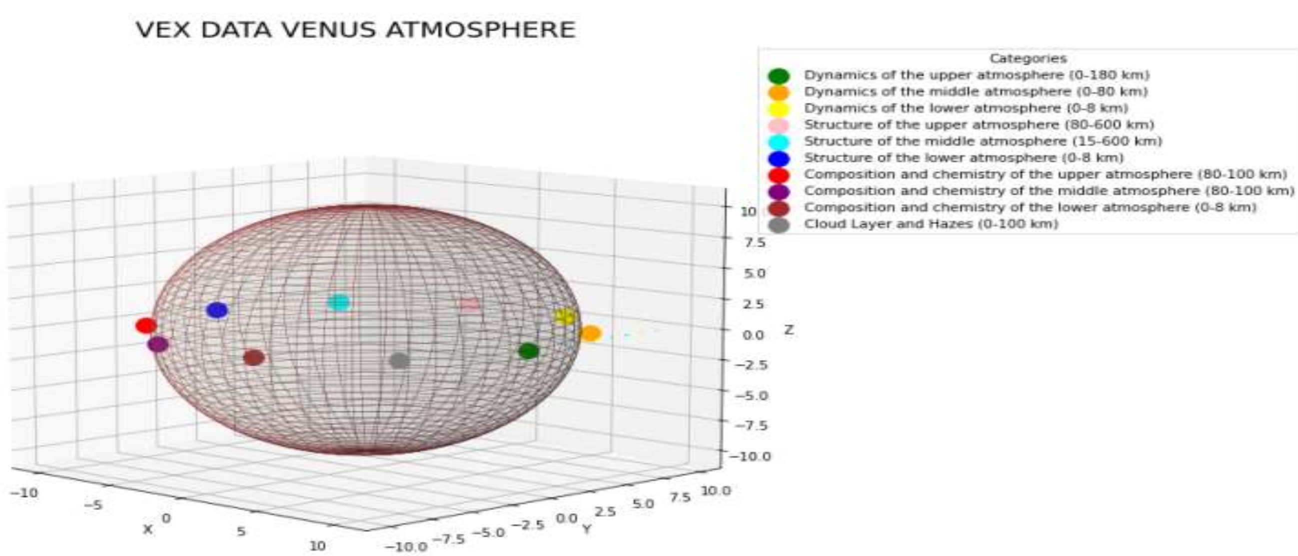
These researches and missions data enhance our understanding of the complex relationship between solar wind and atmospheric conditions on Venus. Variations in Venus atmospheric conditions were due to solar wind interaction which are understood through data analyzation and simulation[14]. The solar wind transfer heat energy to Venusian atmosphere leading to various changes like temperature increase, expansion of atmospheric gases and structure. This ionic nature of solar wind causes ionization of ionosphere, which then effect the incoming solar wind stream and Venus atmosphere.

Higher solar wind densities cause compression of the ionosphere which badly effect radio communications and plasma waves on Venus[4] .This study also show the effect of the solar wind on atmospheric escape, formation of clouds, optical properties, greenhouse effect, and energy balance. The study of Venus surface properties, geology, plasma environment, and magnetic fields contribute to our understanding of Venusian evolution and dynamics[5].

As we know that the solar wind exposure of venus have shaped the planets environment and properties. As Venus lacks an intrinsic (internal) magnetic field, therefore shows a uniques response towards solar wind [18].This uniques interaction affects the boundary between Venus atmosphere and space.This unique interaction highlty change atmospheric characteristics like the continuous loss of lighter gas.

Figure 3.

Venus Express Mission: Atmospheric Layers of Venus:



Different lander missions is sent to the Venus succesfully like (Soviet Union's Venera program) and they stay there but they are short lived unlike other planetary missions. And due to the planet hot, thick atmospheric condition a landar cannot survive for long time. The mission's vehicles can survive for just few minutes. Also the thick atmosphere(dense layer of cloud) make it difficult for lander to to see the venusian surface directly. They used various instrument for them[16].

Different techniques used there for knowing the ionosphere composition and chemistry, they can be investigated through solar and stellar occulation, in situ measurement of energetic neutral atoms and airglow mapping.

Similalrly the gas cloud interaction in the middle atmosphere and composition of the mesosphere can be done by the same method[3].

Additionally, observations of the lower atmosphere's composition and global circulation are made through spectroscopy, radio occultations, and imaging. Exploring the cloud layers, and hazes venus can be done in the same methods and there measurement includes some additional method like optical properties and occulation methods[2].

As in figure (3) in our data we have seen different layers of the atmosphere of venus which is according to(VEX) . Various Missions like VEX and the Wind spacecraft enhance our knowledge of solar wind's influence on Venus magnetic structure.but the venus express is an orbiter not lander. It cannot measure the planet internal structure and properties, but can measure the planet atmosphere and it interaction with solar wind and other things. For this purpose, it uses specific instrument like for magnetic field measurement (MAG).

This research has broader implications for planetary science and astrophysics, highlighting patternized properties and evolutionary environment of Venus. And expanding our understanding of celestial phenomena[18].

By examining plasma structures (bow shock and magnetotail) and the wide range consequences of solar wind, we broaden our knowledge of the universe and our survival in it[4]. Overall, this whole study and investigation show a complex relationship bewteen solar wind and Venus atmosphere.

3. Result and discussion:

The analysis of solar wind and their intricate interaction with the atmosphere of Venus has bring a significant responsibility to know the behavior and dynamics of both systems. Notably, higher solar wind velocities consistently result the raising atmospheric disturbances.

Meanwhile taking the data and then simulate it offer a valuable insight knowing the dynamics of Venus by due to inflow of solar plasma. This contributes to our understanding of the complex relationship between solar wind and the atmospheric conditions spreaded on Venus.

Furthermore, the study can highlights the energy losses of ion by the interaction of solar wind with upper atmospheric region of Venus that can cause expansion of upper atmosphere which result increasing temperature of Venus and greenhouse effects[2]. During periods of higher solar wind densities, the ionosphere experiences compression, with potential implications for radio communications and plasma wave behavior within the atmosphere.

Additionally, apart from the solar wind behavior on Venus' atmosphere, the study can also help us in explaining different layer of Venus by taking the data from different mission which includes composition, chemistry and different atmospheric layers. By measuring through various advanced techniques and instruments it provide valuable insights into the density, and behavior of the neutral atmosphere, ionosphere, cloud formation, and gas-cloud interactions. Understanding the cloud layer hazes further explain the planet climate geological activity, weather forecasting and potential habitability. Studying and analyzing the atmosphere can help us in knowing the history of planet

Similarly, the Venus induce magnetic field measurement can provide a valuable information regarding internal structure and space weather when it interact with the solar wind. The Venus express gives a complete data which has been instrumental in studying the planet's ionosphere, atmospheric escape, and magnetospheric dynamics. By comparing the magnetic field with other planets like earth further explain our broader knowledge of planetary magnetic environments and various space weather phenomena. This multidimensional approach can make our understanding of the workings surrounding the solar wind and its effects on Venus, thereby deepening our comprehension of celestial phenomena and planetary dynamic.

Here we have seen the three years variation of the magnetic field component and magnitude . we have observed that the plot(a) of figure 2 show less disturbance and variation as compared to plot (b) of figure 2 and plot (c) of figure 2.becasue it depend upon solar wind charcteristics some time the solar wind activity may be intense like in case of solar flare and coronal mass ejection. so in that case the venus induce magnetic fied will be effected in different way.

Table 1.

Magnetic field component and magnitude recorded at different time interval.

Time	BX	BY	BZ	BT
2012-01-26T07:17:03.595	10.5832	1.7790	-30.1350	31.9888
…	…	…	…	…
2013-12-08T08:53:29.966	-13.6374	6.4809	6.8627	16.5855
…	…	…	…	…
2014-01-01T06:26:50.555	11.5029	-2.5347	1.8461	11.9227
…	…	…	…	…

by measuring these magnetic field variation we know from them how the venus magnetosphere respond to the solar wind fluctuations, these variations are also link with volcanic activities. so with the help of them we can know the planet geology. and these variation in magnitude of magnetic field can show how the planet changed over a time.

But the variation observed here in magnetic field is very small as compared to other planet like earth and Mars.

4. Conclusion:

The whole study of interaction between the solar wind and Venusian atmosphere offer a valuable understanding of evolution and dynamics of the planetary atmosphere. Venus, unlike Earth, lacks an intrinsic magnetic field due to its slow rotational motion and solid iron composition of its core. The slow rotational motion and solid iron core doesn't fulfill dynamo mechanism to generate magnetic field [12] .However, Venus express (vex) magnetometer detected a weak induced magnetic field in the region surrounding Venus (the atmosphere and especially the ionosphere). This weak induced magnetic field is cause when solar wind and ionosphere of Venus interacts with each other. This interaction provides us important information about the physical and chemical changes occurred in planets due to external effects. Due to the absence of global magnetic field like in earth they cause greenhouse effect which makes the planet so much hot that does not support the existence of life.

The progress in studying solar wind interaction with Venus has more explored by missions such as Venus Express (VEX) spacecraft. Such missions are equipped with advanced instruments like VEX magnetometer which can help in measurement of magnetic field shown in Figure (2). This mission performs precise measurements and analysis of solar wind effect on Venus magnetic environment.

As a result, the missions and studies have made significant contribution to our understanding of the unique atmospheric dynamics and magnetic field interactions of Venus. This contributes a lot to a broader and more comprehensive knowledge of planetary systems and their evolutionary trajectories. In essence, this research not only deepens our understanding of Venus but also contributes to the broader scientific exploration of celestial phenomena, paving new paths of knowledge and expanding our understanding of the universe.

This research reveals behavioral patterns and evolutionary dynamics in planetary systems from a perspective unique to planetary science and astrophysics. Using these observations, we can gain understanding of planetary atmospheres, climate dynamics, and life on other planets. Through the meticulous examination of plasma structures and the far-reaching consequences of solar wind, our comprehension of the vast expanse of the universe and our place within it expands further.

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