VARIATION OF SOLAR WIND PARAMETERS OBSERVED DURING SOLAR CYCLE 24

Abisha S Santham [1]*, Mariya Shaniya [2] and A. Iren Sobia [3]

[1*]Research scholar Reg.No: 21113092132005, Department of Physics and Research Centre, Muslim Arts College, Thiruvithancode,Tamilnadu, India.

[2]Research scholar Reg.No: 21213092132006, Department of Physics and Research Centre, Muslim Arts College, Thiruvithancode,Tamilnadu, India.

[3]Assistant Professor, Department of Physics and Research Centre, Muslim Arts College, Thiruvithancode, Tamilnadu, India.

Affiliated to Manonmaniam Sundaranar University, Abishekapatti-627012,Tirunelveli,Tamilnadu,India.

*Corresponding Author : abishassantham01@gmail.com, irensobia@gmail.com

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Abstract

The present paper was focused on the variation of Solar wind dynamic pressure, magnetic pressure and thermal pressure during the year 2009-2019 of the solar cycle 24. The daily averaged data taken from STEREO A spacecraft are used to determine the phases of solar wind plasma parameters. This paper analyzes the parameters of solar wind compared ascending, maximum and declining phases of the solar cycle 24. The solar wind data compared ascending and declining phases decreases in the solar wind dynamic and thermal pressure, observed for the ascending phase relative to that for the declining phase. The coronal holes increase an ascending phase of the solar cycle. The magnetic pressure depends on the number of sunspots *i.e.* maximum for the maximum phase. Thermal, magnetic and dynamic pressure variations are larger in solar maximum than in solar minimum, as expected because the majority of parameters have a stronger variation in solar maximum.

Key words: coronal hole, solar wind, dynamic pressure, magnetic pressure, thermal pressure.

1.INTRODUCTION

The Sun continually emits a supersonic stream of cool (3×10^{4} K), low density (5 cm^{-3}) plasma known as the solar wind. The solar wind is a continuous plasma flow originating from the Sun and expanding to the whole heliosphere (Bruno and Carbone 2013). The solar wind separates into fast and slow wind streams whose large-scale distribution evolves markedly during the solar activity cycle. Slow solar wind flows are usually found in the vicinity of streamer/coronal hole boundaries (S/CH), while the fastest wind flows stream out of coronal holes. Hence, the distribution of fast and slow wind streams follows the cyclic variations of the magnetic field structure of the solar corona (McComas *et al.,* 2008; Smith 2011). Coronal holes are the lowest density structures in the Sun's corona at comparably low coronal temperatures of about 1 MK. Therefore, they appear as dark structures in EUV images (Hofmeister 2017). The 11 yr solar cycle (SC) is characterized by periodic changes in solar activity indicators such as the number of sunspots, coronal holes, and active regions (ARs), as well as the occurrence rate of solar energetic events such as filament eruptions, flares, and coronal mass ejections. Co rotating interaction regions (CIR) is a region formed in interplanetary space by the interaction of fast and slow streams in the solar wind. The fast solar wind in the coronal hole collides with the slow solar wind. The interaction produces a shock wave and accelerates particles Park *et al.,* (2017). The high speed streams interact with the heliospheric current sheet, which is characterized by slow speed and high density streams, and their interaction creates the so called co rotating interaction regions, which compress the interplanetary magnetic field, intensify it. Variations in the ratios of thermal and magnetic pressures between the fast and slow streams associated with interaction region. Solar wind dynamic pressure is the most important external condition, which determines the shape and size of a magnetosphere, and also influences several other magnetosphere boundaries and currents. The shape of the magnetosphere is determined by the balance between the pressure within it and the dynamic pressure of the solar wind.

Sources of solar wind dynamic pressure changes include interplanetary shock fronts preceding coronal mass ejections (CMEs) with fast bulk speeds (Marcia and Raymond 1997) the leading edge of the co-rotating interaction regions (CIRs) Gibson *et al.,* (2009), the front edge of the heliosphere plasma sheet (HPS) Winterhalter *et al.*,(1994) and also small scale dynamic pressure changes associated with plasma bubbles, hot flow anomalies (HFAs) etc. The magnetic pressure is simply proportional to the density square therefore the increase of the magnetic pressure can compensate for the decrease of the thermal pressure Hennebelle (2019). The solar wind flows outward from the Sun, forming the heliosphere, a bubble in interstellar space. The heliosphere's size is determined by the dynamic and thermal pressures of the solar wind, as well as the external pressures of the interstellar medium and magnetic field (Richardson and Wang 1999). The highest magnetic pressure is found at the leading edge of high speed streams. Since several observers have reported high densities, temperatures and magnetic field intensities ahead of fast streams. The plasma's magnetic pressure ($B^2/8\pi$) dominated the thermal pressure (nkT) due to its higher than average solar wind magnetic Field strength (B) and its unusually low plasma temperature (T) and density (N) Bothmer (1998). During the plasma transport of solar wind into the magnetosphere, the dynamic pressure of the solar wind becomes more important. In fact, the dynamic pressure in the solar wind is much greater than the thermal pressure. The leading edge of high-speed streams has the highest thermal and magnetic pressures. This is not surprising given that several observers have reported unusually high densities, temperatures, and magnetic field intensities ahead of fast flowing streams (Burlaga and Ogilvie 1970). The most likely state is one in which total plasma thermal pressure equals magnetic field pressure. The solar wind dynamic and thermal pressures and the interplanetary magnetic field (IMF) control the shape and location of the earth’s magnetopause. The solar wind dynamic pressure is the single most important factor determining the position of the solar point Martyn (1951) and the shape of the magnetosphere (Ferraro, 1960). In contrast, the strength and orientation of the IMF exert and important influence on the shape of the magnetosphere. This study analyzes the variations in solar wind plasma parameters dynamic pressure, magnetic pressure and thermal pressure observed by the STEREO spacecraft during its orbits around the Sun.

2. MATERIALS AND METHODS

Data Observation

The data used in this study are from the plasma and supra-thermal ion composition (plastic) investigation aboard stereo. STEREO-A contains the Sun Earth Connections Coronal and Heliospheric Investigation Howard *et al.*,(2008), a series of instruments that present continuous spatial coverage of heliospheric observations from the low corona to 1AU. For this study the data were daily averaged over one-hour intervals. To conduct the SIR survey for the STEREO mission, the daily averaged magnetic-field and solar-wind-proton data from the In situ Measurements of Particles and CME Transients *(*IMPACT) Investigation (Luhmann *et al.*, 2008) and the Plasma and Supra-thermal Ion Composition (PLASTIC) Investigation (Galvin *et al., 2008*) respectively. The data available in 2009 – 2019 are proton density, proton temperature and proton velocity in the calculation of plasma thermal pressure, magnetic pressure and dynamic pressure. Data were obtained from the omniweb data explorer, *https://omniweb.gsfc.nasa.gov/coho/form /stereoa.html*.

Statistical Analysis

The dynamic pressure is calculated as

$$P_{dy} = \rho v_{sw}^2 \text{ (Pingbing Zuo 2015)}$$

where ρ is the mass density and v_{sw} is the speed of the solar wind.

The magnetic pressure is calculated as

$$P_m = B_m / 8\pi \text{ [dyn /cm}^2\text{]} \text{ (Jenny Marcela Rodriguez Gomez } et\ al.\text{,2019)}$$

where P_m is the magnetic pressure , *B* the magnetic intensity, π= 3.14.

The thermal pressure is calculated as

$$T_p = n\, k_B\, T$$

where n is the number density, T is the temperature, and k_B is Boltzmann's constant ($1.38064852 \times 10^{-23}$ $m^2\ kg\ s^{-2}\ K^{-1}$) (Daniel J. Gershman and Gina A. DiBraccio 2020).

All of the above assumptions were also used in the SIR survey of the Wind *and* Advanced Composition Explorer (ACE) data by (Jian *et al.*, 2011).

3. RESULTS AND DISCUSSION

The observed data depicts the changes in various solar parameters during the period from 2009 to 2019, which shows that in the starting of solar cycle 24, the Sun is quiet with low sunspot number and solar activity. The result shows 50 running averaged data from STEREO- A spacecraft.

Solar wind Dynamic pressure

Figure 1 presents the variation in year versus dynamic pressure of year from 2009 to 2019. The dynamic pressure rising phase fluctuated back and forth between increasing and decreasing, reaching its peak in October 2014. When the solar wind's dynamic pressure increases, stronger magnetic fields are produced. Next highest peak observed during the month of October 2017.

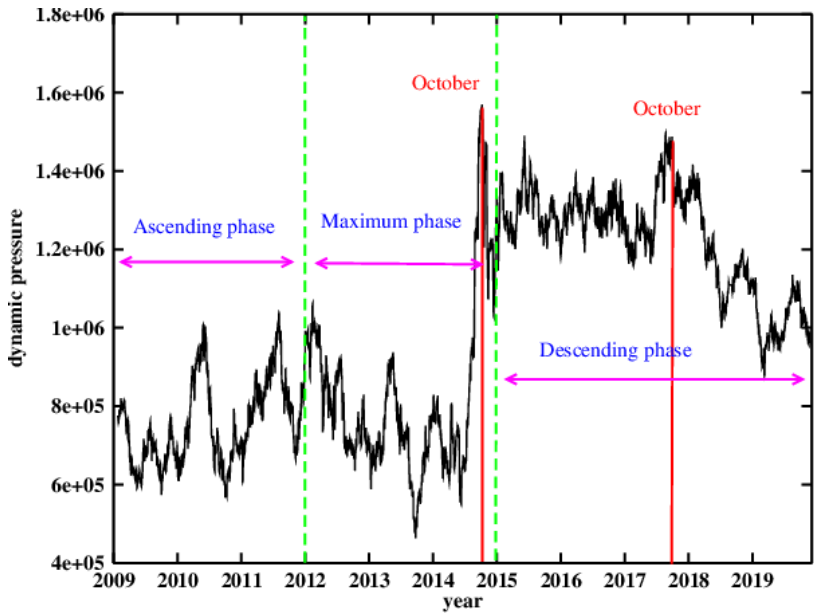

Figure3.1: Solar wind Dynamic Pressure of Solar cycle 24

Because the higher occurrence of co- rotating streams, during the solar cycle declining phase and solar minimum. After the highest peak the dynamic pressure, during the declining phase of the cycle the numbers of sunspots gradually decreased end of the solar cycle 24. It is clearly shown that the rising phase of the solar dynamic pressure minimum compared to the maximum and declining phase of the solar cycle 24**.**

The dynamic pressure of the solar wind is an important parameter for controlling the shape and size of the magnetosphere. A sudden increase in dynamic pressure can cause global disturbances in the magnetosphere, resulting in an increase in aurora intensity (Vorobyev 1974; (Zhou and Tsurutani, 1999); Zhou *et al.*, *(* 2003). The solar wind flows outward from the Sun, forming the heliosphere, a bubble in interstellar space. The size of the heliosphere is determined by the dynamic and thermal pressure of the solar wind, as well as the external pressure of the interstellar medium and magnetic field (Richardson and Wang 1999).

The proton dynamic pressure is calculated as $P_{dy} = \rho v_{sw}^2$ (Zuo, 2015; Aellig *et al.*, 2001). Where is the mass density and v_{sw} is the speed of the solar wind. In physical terms, P_{sw} represents the momentum flux of the solar wind and has a unit of nanopascals (nPa) Lu (2013). According to other studies (Dalin et al., 2002; Zuo et al., 2015), density variations account for the majority of rapid dynamic pressure changes while velocity variations only have a minimal impact. Dynamic pressure, according to Keunchan Park's 2017 research, is inversely correlated with density and square of speed. As a result of the balanced pressure seen in many small-scale solar wind formations, the overall pressure remains steady. Along with large scale dynamic pressure changes coming from the solar atmosphere, the magnetosphere can also be affected by smaller dynamic pressure changes that occur close to the foreshock zone, upstream of the bow shock (Shi et al., 2020).

Variations in the magnetic field and proton temperature cause changes in the dynamic pressure. Small-scale plasma structures with sharp and large variations in solar wind dynamic pressure are common in the solar wind, and are usually accompanied by a sharp change in ion flux and density (Khabarova and Zastenker, 2011). Both intrinsic and induced magnetospheres compress and expand outward depending on the strength of the upstream solar wind pressure (Sibeck *et al.*,1991). Several studies have examined the magnetosphere's response to changes in solar wind dynamic pressure in recent years (Boudouridis *et al.*,2003; Lee and Lyons 2004).

When the solar wind's dynamic pressure rises, the induced magnetosphere compresses until the compressed field's increasing magnetic pressure can again withstand the solar wind's dynamic pressure (Aniko Timar *et al.,* 2019). A high solar wind dynamic pressure, which is usually associated with a high solar wind speed, is the primary cause of strong magnetosphere compression. A CME usually causes a sudden increase in the solar wind's dynamic pressure. CMEs are formed as a result of regional connections in the solar corona (Lin and Forbes 2000). These reconnections are caused by magnetic-field-line merging (Fu *et al.,* 2015, 2017). In many interaction regions the higher proton density of the slow wind caused the dynamic pressure of the slow stream to be higher than the dynamic pressure of the fast stream when a large coronal hole extended to low latitudes, causing significantly higher speeds and temperatures, as well as lower average densities (Elliott et al., 2012). The solar wind dynamic pressure and the magnetic field magnitude are two parameters that change independently of heliolatitude. Shue *et al.,* (1997) found that a sudden increase in solar wind dynamic pressure compresses the magnetosphere on the dayside until the magnetic pressure in the magnetosphere matches the plasma pressure in the magneto sheath.

The maximum phase of solar cycle 24 is highest peak. Consequently, a rise in dynamic pressure can also be accompanied by a rise in geomagnetic activity. The dynamic pressure of the solar wind is particularly significant during the plasma transit of solar wind into the magnetosphere. Samsonov (2018) found that aside from the velocity of the solar wind, the dynamic pressure is also affected by the density of the solar wind, and both CMEs and CIRs are typically accompanied by an increase in density. The main cause of sudden dynamic pressure changes is an increase or decrease in density, with velocity changes playing a minor role (Dalin *et al.,* 2002; Zuo *et al.,* 2015). CME usually causes sudden increases in solar wind dynamic pressure. The reason for the formation of CMEs is the regional reconnections in the solar corona (Lin and Forbes 2000). These reconnections are the result of magnetic-field-line merging (Fu *et al.*,2015, 2017). The extended pressure to solar events, such as coronal mass ejections (CMEs) or the corotating interaction regions (CIRs), where fast and slow solar wind streams interact. Theoretically, a few of the pressure fronts might be connected to interplanetary shock waves with CME or CIR origins.

Solar wind Magnetic Pressure

Figure3.2 shows the magnetic pressures increases reached the maximum phase and then decreases. The magnetic fluctuations are balanced by both temperature and density variations. The first highest peak is observed maximum phase during the month of March 2015.

Next highest peak is observed ascending phase during the month April 2012. It is clearly shown that the maximum phase of the solar magnetic pressure maximum compared to the ascending and declining phase of the solar cycle 24. The magnetic pressure is very low in the declining phase compared to other active regions.

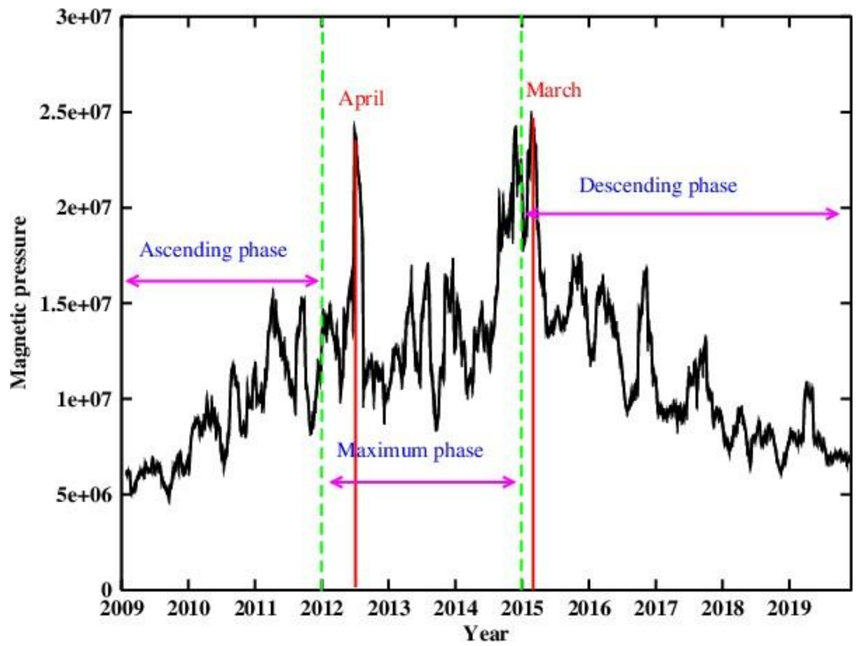

Figure3.2: Solar wind Magnetic Pressure of Solar cycle 24

It has been found these types low pressure regions form basic source of fast streams. Magnetic pressure variations are larger in solar maximum than in solar minimum, as expected because the majority of parameters have a stronger variation in solar maximum. The magnetic pressure defines $P_{m.}$

$$P_m = B_m / 8\pi [\text{ dyn /cm}^2]$$, Gomez *et al.*,(2019)

where P_m is the magnetic pressure , *B* the magnetic intensity, π= 3.14.

The term is commonly used in studies of the Sun and Earth's magnetic field, and in the field of fusion power designs. Also for the magnetic pressure that is proportional to the square of the magnetic field (Park et al.2017). Magnetic pressure is an energy density associated with a magnetic field. Any magnetic field has an associated magnetic pressure contained by the boundary conditions on the field. The magnetic pressure dominates the thermal pressure in the magnetosphere. The sudden changes in dynamic pressure, which are accompanied by changes in the magnetic field and proton temperature, are primarily caused by density changes rather than bulk speed changes (Dalin *et al.,* (2002); Zuo *et al.,* (2015).

According to (Barkhatov *et al.,* 2003) the evolution of small-scale solar wind structures could be influenced by the balance of total pressure across sharp pressure changes. The thermal and magnetic pressures are referred to as plasma static pressures Echer *et al.,* (2003). The plasma thermal pressure and magnetic field pressure changes have opposite signs; in almost every case, the plasma thermal pressure changes are significantly larger than the magnetic field pressure change Dalin *et al., (*2002). The solar wind, dynamic pressure, and magnetic pressure of Earth's dipole field are all represented as part of this pressure balance. When the solar wind pressure increases, the induced magnetosphere compresses until the growing magnetic pressure of the compressed field can no longer withstand the solar wind pressure (Nemeth *et al.*, 2017). The pressure of pickup ions is predicted to be substantially larger than the magnetic and thermal pressures of solar wind particles by a large body of theoretical research (Zank 2015). According to research (Richardson, 2008; Krimis et al., 2010), pickup ions greatly contribute to pressure in the far-off heliosphere and heliosheath. As a result of the strong magnetic field, the magnetic pressure rises while the air pressure outside falls. Park (2017) asserts that the relationship between magnetic pressure and the magnetic field's square is inverse. In an induced magnetosphere, the magnetic pressure of the compressed magnetic field balances the magnetic pressure of the approaching solar wind. As a result, the magnetic field strength in the pile-up zone is almost exactly reflected by the square root of the solar wind pressure. When the solar wind pressure increases, for instance, the induced magnetosphere is compressed until the rising magnetic pressure of the compressed field can once again resist the pressure of the solar wind. Nemeth (2017) .

The relationship between the magnetic intensity of solar cycle 24 and the magnetic pressure at higher altitudes is shown. The faculae and still sun areas are the main contributors during solar cycle 24. The calm sun's magnetic pressure, however, is quite strong through this cycle Rodriguez Gomez and Jenny Marcela et al., (2019). High-density events like to happen in co-rotating interaction regions (CIRs) and coronal mass ejections (CME) sheaths, regions squeezed by interplanetary dynamics, whereas slow-density events often occur in places of high magnetic pressure of solar origin. Therefore, an increase in dynamic pressure can also result in an increase in geomagnetic activity. The magnetic pressure is simply proportional to the density square, therefore the increase of the magnetic pressure can compensate for the decrease of the thermal pressure Hennebelle (2019). The plasma's magnetic pressure ($B^2/8\pi$) dominated the thermal pressure (nkT) due to its higher than average solar wind magnetic Field strength (B) and its unusually low plasma temperature (T) and density (N).

Solar Wind Thermal Pressure

Figure shows the solar wind Thermal Pressure variation of year from 2009 to 2019. From the figure3.3, the thermal pressure continuously fluctuates till 2014 and suddenly increases during 2015. The highest peak is observed during the month June 2015 at maximum phase. Next highest peak is observed during the month of October 2017 declining phase. It is clearly shows that the ascending phase of solar cycle 24 minimum compared to the maximum and declining phase. The thermal pressure of the solar wind, along with the external pressure of the interstellar medium and magnetic field, determine the size of the heliosphere. Richardson and Wang (1999).

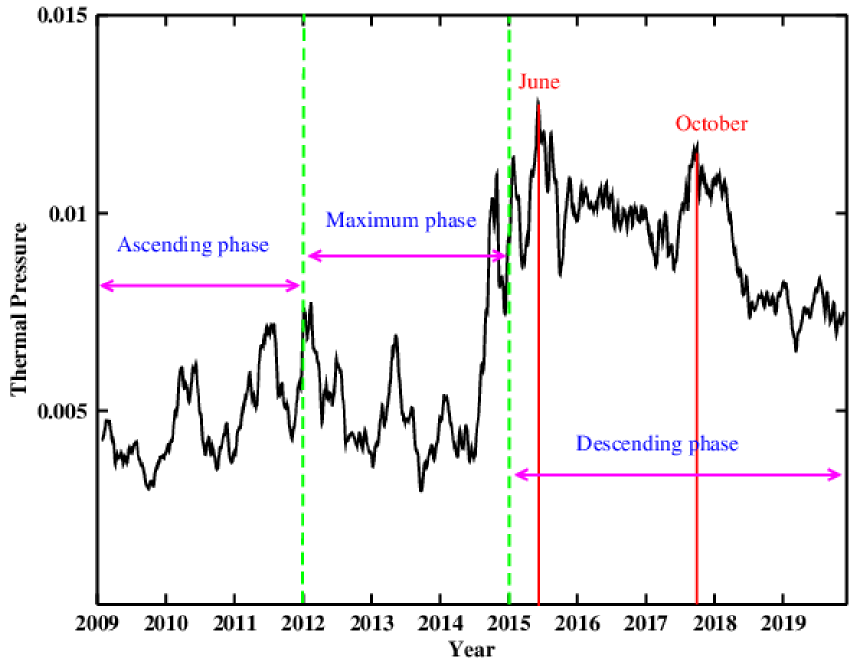

Figure 3.3: Solar wind Thermal Pressure of Solar cycle 24

The highest peak is observed during the month June 2015 at maximum phase. Next highest peak is observed during the month of October 2017 declining phase. It is clearly shows that the ascending phase of solar cycle 24 minimum compared to the maximum and declining phase. In-depth research has been done on the slowing down of solar wind pressure around solar maximum. The thermal pressure of the solar wind, along with the external pressure of the interstellar medium and magnetic field, determine the size of the heliosphere Richardson and Wang (1999).

The thermal pressure is defined as $T_{p} = n\,k_{B}\,T$, where n is the number density, T is the temperature, and k_B is Boltzmann's constant ($1.38064852 \times 10^{-23}$ m^2 kg s^{-2} K^{-1}) Gresham and DiBraccio (2020). Figure shows the greater fluctuation in thermal pressure during solar maximum compared to solar minimum, the thermal pressure variations are larger at solar maximum. The low thermal pressure flow often only occurs at low latitudes. The interplanetary magnetic field (IMF), the kinetic and thermal forces of the solar wind, and the form and position of the Earth's magnetopause are all influenced by these factors (Spreiter and Hyett 1963). Additionally monotonically growing with increasing solar wind velocity is the thermal pressure of the solar wind proton component. the velocity of the solar wind under the whole thermal pressure that the proton and electron components have created. As the speed of the solar wind rises, the temperature and thermal pressure in the plasma sheet drop. Many observers have seen elevated temperatures, magnetic field intensities, and densities upstream of fast streams (Burlaga and Ogilvi 1970). Therefore, the scenario where total plasma temperature pressure equals magnetic field pressure is the most likely.

4. CONCLUSION

According to the present study, the variation of solar cycle-24 was measured during the year from 2009-2019. The periods 2009-2012 shows the minimum phase of solar activity and maximum phase during 2013-2015 and the descending phase during 2016-2019.

- In the beginning of Solar Cycle 24, there was little activity. The solar cycle's fluctuations affect the solar wind's properties. It is abundantly obvious from this analysis that the minimum and rising phases of solar cycle 24's dynamic pressure cycles are mutually exclusive. the solar cycle's falling and minimum phases have more co-rotating streams than other phases. Due to the Sun's increased activity at solar maximum, which produces more ionised particles with higher magnetic field intensities and so-called wind speeds, these parameters may have higher values at that time. While variations in the solar cycle's properties of the plasma and magnetic field are covered by smaller-scale oscillations. This solar minimum's reduced heliosphere is likely due to lower dynamic pressure. The magnetosphere's size and form may be significantly altered by these changes because dynamic pressures are stronger during the declination phase.
- Compared to the phases of the solar cycle 24, the magnetic pressure in the solar wind is greatest at its maximum phase. At low altitudes, magnetic pressure rises and magnetic field disappears by magnetic diffusion. The lower magneto sheath zone, often referred to as the magnetic barrier region, is where the magnetic pressure then starts to dominate. The changes in the plasma heat pressure are almost usually significantly larger than the changes in the magnetic field pressure. The connection between the solar thermal and dynamic pressure from 2009 to 2014 correlates to the lowest level of sunspot activity during the ascending phase of solar cycle 24 and may be used to better understand the physical processes on the Sun and in the solar wind. Thus, a rise in dynamic, thermal, and magnetic pressure may lead to a rise in geomagnetic activity, which aids in the understanding of geoefficiency.
- High thermal pressure in the form of plasma is the pressure. The temperature is high yet the density of the plasma is low in this area. The low thermal pressure and subsequent drop in temperature are caused by the thermal energy lost during ion-neutral collisions. When the solar wind is transported into the magnetosphere as plasma, the dynamic pressure of the solar wind is more significant. The dynamic pressure in the solar wind is really significantly greater than the thermal pressure.
- The differences in thermal and magnetic pressure ratios between rapid and slow streams that are connected to the interaction zone. The density difference between the fast and slow streams was sufficiently great in the interaction zones such that the dynamic pressure of the uncompressed slow wind was greater than the dynamic pressure of the compressed fast wind. The magnetic field pressure is often equivalent to the heat pressure in situations when pressure balance is maintained. The thermal pressure is frequently greater than the magnetic pressure when pressure balance is not conserved.

- Thermal, magnetic, and dynamic pressure changes are larger in solar maximum than in solar minimum, as expected given that the majority of parameters vary more in solar maximum. When these large solar maximum instances, solar cycles still take place, but they are more intense. The declining phase, the magnetic field is open to interplanetary space, sending solar material out in a high-speed stream of solar wind that is geomagnetic storm. During solar maximum, large solar storms frequently occur.

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