Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/20043
DOI URL: http://dx.doi.org/10.21474/IJAR01/20043

RESEARCH ARTICLE

MAGNETOSPHERIC DISTURBANCES IN GNEVYSHEV GAPS: CASE OF SOLAR CYCLES 20 TO 24

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Manuscript Info

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Manuscript History
Received: 10 October 2024
Final Accepted: 14 November 2024
Published: December 2024

Key words:-
High-Speed Solar Wind, Gnevyshev Gaps, Interplanetary Magnetic Field, Magnetospheric Convection Field, Geomagnetic Activity

Abstract

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Time dependence of many solar activity factors and related phenomena shows a highest double-peak structure around sunspot maximum during the maximum phase of the 11-year solar cycle. Highly variable conditions on the Sun persist throughout the phase maximum of solar activity. A distinctive minimum around this phase maximum, called the «Gnevyshev Gap» or «GG», forms a kind of separating matrix between ascending and descending phases of a solar cycle (SC). This article gives some details on the disturbances experienced by our magnetic shield (Earth's magnetosphere) during the last five complete solar cycles. Using a statistical approach, solar parameters and magnetic indices were analyzed over a discontinuous period of 125 days, having recorded the High-Speed Solar Wind (HSSW). As they pass through the interplanetary medium, highly energetic HSSW particles become hostile to all humanity and its society, which has become too technological. Our results show that solar activity is influenced by factors specific to each SC, but general structure of daily variations remains stable in GG. An asymmetry between the activity of the poloidal component of the solar magnetic field and that of HSSW was revealed over all solar cycles 20 to 24. Of these cycles, SC_22 was the most magnetically dipolar and the cycle with the most non-polar coronal holes. The time dependence of HSSW also shows two trends (increasing and decreasing). The gradually increasing HSSW trend induces North/South fluctuations in the Bz component of the Interplanetary Magnetic Field (IMF-Bz). These fluctuations are due to the emergence of new active regions of the Sun in the early morning and late night. On the other hand, rapidly decreasing HSSW trend inflicts southern stability on IMF-Bz. Whatever the period of solar cycle, IMF-Bz and E_M (convective electric field) progress inversely. This suggests that in GG, solar wind/Earth magnetosphere interaction is not responsible for magnetospheric plasma circulation. Thus, GG offers a crucial period of relative calm in the terrestrial solar system, ensuring the absence of harmful phenomena in the terrestrial environment.

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Introduction:-

Sun is not only a source of light, it also emits a stream of electrically charged particles, mainly protons and electrons, into interplanetary space. Solar wind is made up of these particles. This wind not only carries plasma, but also the magnetic field of the sun's corona. Action of solar wind modifies Earth's magnetic field and plasmas in the Earth's environment, creating a region of interface between interplanetary medium traversed by the solar wind and the Earth's upper atmosphere. As early as 1957, with the start of space age, this interface was studied and was named “magnetosphere” in 1959 (Mottez, 2018). Magnetosphere is a cavity created by the interaction between solar wind and Earth's magnetic field (Chapman and Ferraro, 1931). It is a region of space around the Earth where geomagnetic field dominates Interplanetary Magnetic Field (IMF). Magnetosphere is a highly sensitive and dynamic entity (Russell &Elphic, 1979). It is highly complex and plasma-filled, with a variety of phenomena resulting from the interaction between Earth's magnetic field, upper atmosphere and solar winds.Earth's magnetosphere is constantly evolving under the dynamic action of ever-changing solar wind.This magnetic cavity protects Earth from highly energetic and devastating particles of these solar winds. Indeed, solar winds are one of the key factors in the disturbance of the solar environment (Gnanou et al., 2022). During interaction between solar wind and Earth's magnetosphere, events are triggered in the magnetosphere’s tail, known as magnetic substorms. When solar winds are accelerated (i.e., HSSW), disturbances become more severe, affecting human life and technology on Earth. These disturbances can affect satellites, telecommunication and navigation systems, positioning, geological studies and exploitation, industry and health (Naitamor, 2011; Kanao et al., 2019; Hapgood et al., 2021). Disturbances in the magnetosphere make technological systems more vulnerable. HSSW appear to be a potential danger to Earth and space systems, especially during the maximum phase of the solar cycle, when solar activity becomes very intense.

The sunspot cycle is known to exhibit a double-peak structure highest during the period of maximum activity (Gnevyshev, 1963,1967; Antalova and Gnevyshev, 1965; Georgieva, 2011; Bazilevskaya and al., 2014). According to Karak et al., (2018), these peaks are generated due to fluctuations in the poloidal field generation process from tilted bipolar magnetic regions. Interval between the two peaks when sunspot number (SSN) decreases, is called «Gnevyshev gap» or «GG» or «Gnevyshev lacuna» (Storini&Pase, 1995). Not limited to sunspot numbers or surface data, the double-peak feature is also observed in other indicators of solar activity, such as coronal activity (Gnevyshev, 1963; Kane, 2010). Our study will focus on the double-peak structure of solar cycles 20 to 24. Although observed in previous solar cycles, double-peak feature has received particular attention in recent years, mainly because the last three solar cycles have experienced double peaks (Phillips, 2013).

M. N. Gnevyshev noted that every SC generally has two maxima, with a gap in the maximum phase of SC of 11 years in the number of sunspots (Schove, 1979). This gap is a tribute to the Russian astronomer M. N. Gnevyshev, who first drew attention to this phenomenon in the 1940s. Double-peak sunspot cycle and GG have their natural explanation in flux transport dynamo theory. According to Feminella and Storini, 1997; Storini et al., 2003; Ahluwalia and Kamide, 2005; Kane, 2005; Bazilevskaya et al., 2006; Kane, 2007; Takalo and Mursula, 2018; Takalo, 2021; SC produced by the solar dynamo inside the Sun, and therefore magnetic in nature, essentially comprises three typical phases: (i) an ascending phase characterized by an increase in the number of sunspots (SSN), their groups and surfaces; (ii) a descending phase characterized by a steady decrease in SSN;(iii) and between these two phases lies the GG (as described above), which is characterized by the maximization of SSN, groups and areas. In effect, GG is a kind of separator between two main phases of solar cycle. Note that different phases of SC are witness to various solar emissions such as coronal mass ejections (CMEs), solar flares and high-speed flows (HSSW) emanating from coronal holes.

Coronal holes are stable formations that can survive several solar rotations or Bartels’s rotations. This paper aims to examine how Earth's magnetosphere responds to HSSW in the GG of solar cycles 20-24.GG phenomenon is important because it may have implications for space weather and the understanding of the long-term behavior of sun and its terrestrial environment. Studying these fluctuations during peak solar activity can help researchers better understand the consequences of the phenomena that occur there. In the following guidelines, we will presentdata and method used to determine periods studied, database used and criteria for selecting the days, as well as the method for identifying HSSW. Statistical results and their discussion will then be described in section 2. And finally, a conclusion will be set out in the final section of this manuscript.

Data and Methodology:-

To study the phenomenon of magnetospheric convection under the influence of HSSW in GG, several data are used: geomagnetic index aa[nT]; Ey component [mV/m] of the electric field in solar wind; solar wind velocity V[km/s] and the intensity Bz[nT] of IMF. In this article, data required to analyze events in GG were extracted from «http://omniweb.gsfc.nasa.gov» and « https://isgi.unistra.fr» internet web systems. For the present work, we have limited our selection of data from the study period of 1964 (start of near-Earth solar wind observations) to the time when provisional Dst index data are available for the latest complete GG, i.e. December 2019. In this way, the complete study period extends from October 1964 to December 2019, covering the last five complete solar cycles (20 to 24).According to Norton and Gallagher (2010), GG appears more often in sunspot area data than in sunspot number data. In this work, GG is obtained by projecting the two peaks (maxima) of the phase maximum ofsolar cycles 20-24 onto the sunspot curves (https://www.spaceweatherlive.com/en/solar-activity/solar-cycle/historical-solar-cycles). We denote by GG_{20} to GG_{24}, respectively, the intervals comprising the “Gnevyshevgaps” or “GG” of solar cycles 20 to 24, extending from March 1964 to February 2014. Henceforth, this nomenclature will be used throughout this study. An overview of GG_{20}-GG_{24} is shown in Figure 1, where GG boundary per SC is indicated by the yellow vertical lines. Table 1 provides a summary of GG and their respective periods.

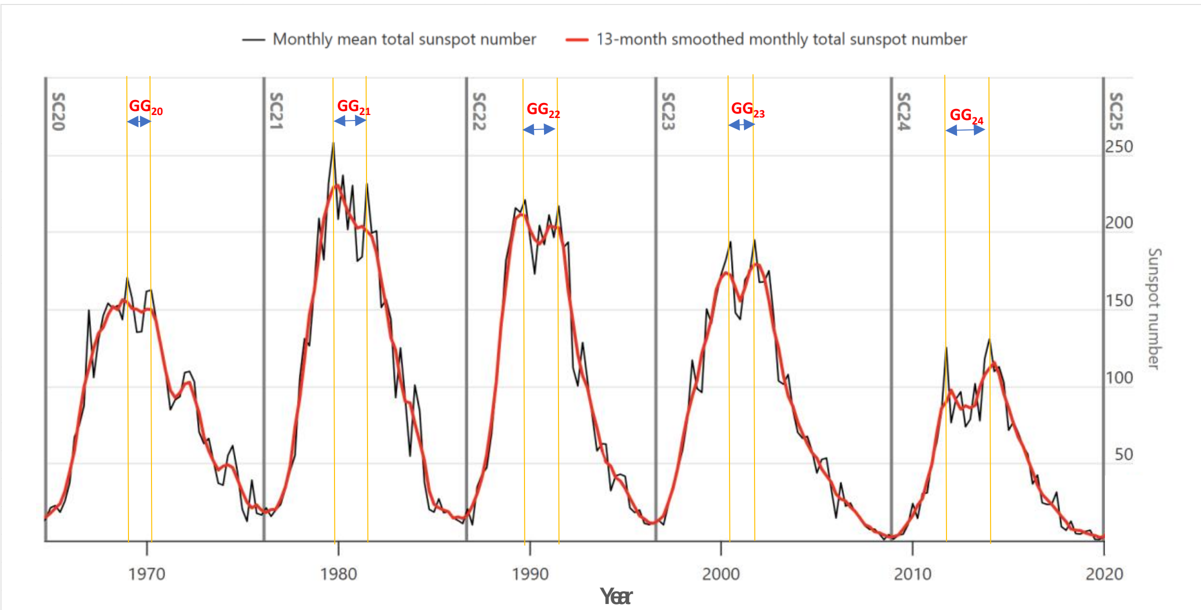

Figure 1:-Gnevyshevgaps (GG) of solar cycles 20-24.

Table 1:- Gnevyshev gaps (GG) in solar cycles 20 to 24.

Solar cycle (SC)	SCextensionperiod	Maximum phase	GG extension period	Average GG time
Cycle 20	1964 –1976	1969 – 1970	March 1969 – February 1970	12 months
Cycle 21	1976– 1986	1979 – 1982	September 1979 – May 1980	09 months
Cycle 22	1986 –1996	1988 – 1991	June 1989 – August 1990	15 months
Cycle 23	1996 – 2008	2000 – 2002	July 2000 – September 2001	15 months
Cycle 24	2008–2019	2010– 2017	November 2011 – February 2014	28 months

Solar wind electric field has also been used to monitor plasma dynamics in the Earth's magnetosphere. Solar wind electric field is, in most cases, the dominant factor determining high-latitude magnetospheric electric field structures and associated plasma convection processes. In this manuscript, to determine the magnetospheric convection electric field E_M [mV/m] at high latitudes, the field transformation law of Wu Lei et al., (1981) and Revah and Bauer (1982) was used. All aberrations in solar wind speeds and the electric field frozen into solar winds were removed. HSSW days were obtained using pixel diagrams based on solar wind speeds. These days are characterized by a solar flux velocity greater than or equal to 450 km/s over at least two consecutive solar rotations (Krieger et al., 1973; Zirker, 1977; Despirak et al., 2018). The framed cells in Figure 2 illustrate the days of HSSW emission in 2013. It is important to point out that the circled cells (again in Figure 2) representing shock days (ICME), are not considered in this study.For our specific study period, all the pixel diagrams show 125 days of HSSW, including 17 days for solar cycle 20; 06 days for cycle 21; 10 days for cycle 22; 29 days for cycle 23 and 63 days for cycle 24.

January-01	2013		332	307	302	319	308	318	354	330	336	310	314	371	417	527	460	404	399	417	428	413	368	323	297	277	338
January-26	468	464	400	373	335	314	338	448	438	374	349	322	351	425	414	378	353	362	364	379	361	354	355	326	348	378	401
February-22	390	370	337	336	326	324	333	510	563	472	436	364	319	329	314	340	322	311	315	318	320	427	444	587	541	468	486
March-21	449	400	375	409	378	375	446	428	463	546	487	430	351	313	300	270	326	339	337	347	350	426	450	404	484	402	376
April-17	336	296	291	298	283	270	291	360	463	545	501	423	397	378	419	458	407	366	376	477	522	508	480	431	393	348	348
May-14	366	384	392	389	418	377	393	400	455	417	478	573	660	670	703	536	399	359	550	717	681	585	505	480	414	425	396
June-10	371	388	422	389	335	335	324	302	279	290	352	493	588	623	533	517	445	401	398	410	514	493	429	372	360	358	340
July-07	308	312	328	421	438	423	447	386	382	364	346	428	574	526	403	383	370	338	354	539	452	445	404	372	371	350	332
August-03	314	370	518	462	415	374	397	429	406	357	372	447	513	697	677	560	469	407	456	524	505	477	408	359	363	447	368
August-30	377	416	494	429	402	452	430	400	353	378	349	339	386	379	487	520	408	364	370	433	530	472	416	393	361	388	416
September-26	342	309	280	273	263	309	571	464	383	339	310	306	328	560	451	399	374	355	407	516	496	438	372	337	307	298	328
October-23	341	333	317	294	285	282	317	337	365	363	331	359	364	329	336	358	391	502	556	501	419	381	361	342	443	477	395
November-19	385	385	342	314	332	313	314	295	300	283	296	389	492	416	394	366	343	337	331	555	460	403	355	309	292	427	499
December-16	442	401	357	360	352	340	324	300	289	300	274	288	304	344	333	384											

V (km/s)
650
600
550
500
450
350

Figure 2:-Pixel diagram of High-SpeedSolar Windfor 2013.

Results and discussions: -

High-speed solar wind in the Gnevyshev gaps of solar cycles 20 to 24: -

It is well known that speed of High-SpeedSolar Wind (HSSW) varies with distance traveled and time (Gnanou et al., 2023). To understand the temporal variability of HSSW speeds duringGG, data were averaged over 24 hours. Variations in mean HSSW velocities during GG as a function of universal time UT are shown in Figure 3 for each SC. In general terms, Figure 3 reveals little similarity in trends over the course of the day, despite some differences from one SC to the next. These differences show that solar activity is influenced by factors specific to each cycle, but the general structure of daily variations remains stable. In particular, our results show a decreasing trend in the GG for all selected cycles. Overall, correlations are significant and worth −0.70; −0.51; −0.60; −0.16 and −0.84 respectively for solar cycles 20 to 24.

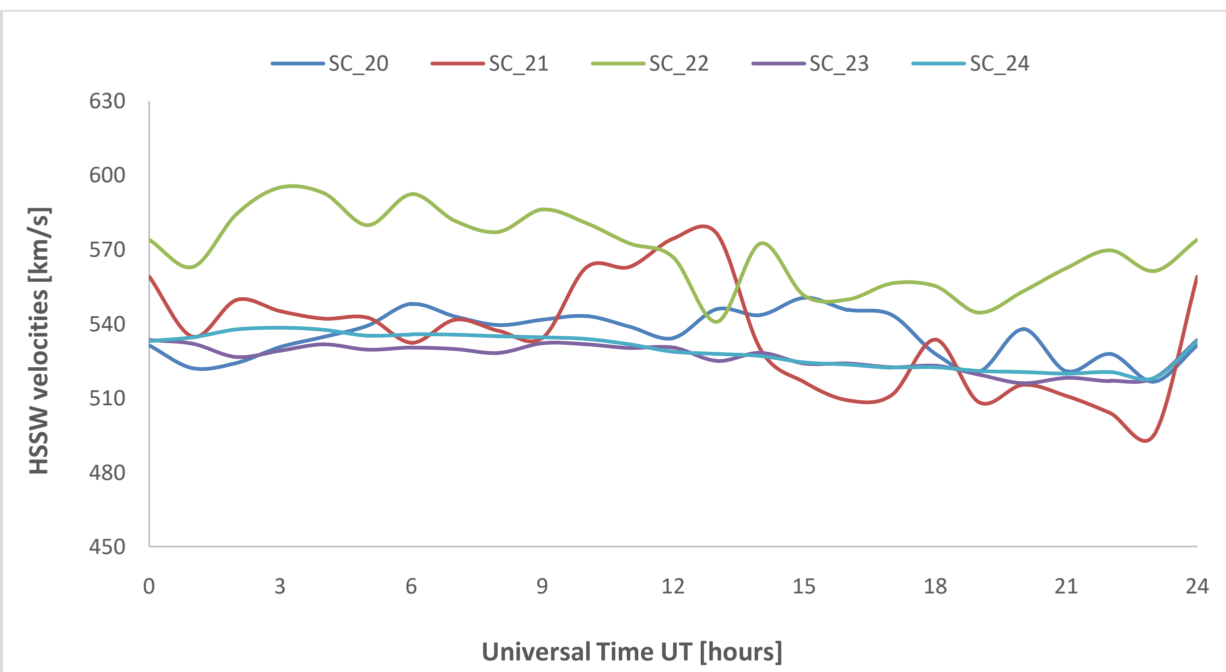

Figure 3:-Time evolution per solar cycle of HSSW velocities during Gnevyshev gaps.

However, particular attention should be paid to SC_23, which recorded a low correlation (−0.16). This weakness could be due to the fact that GG trough of solar cycle 23 (SC_23) corresponds to a period outside observation (*cf.*Amenomori et al., 2006).Another explanation could be linked to the decrease in sunspot activity in SC_23 (e.g. Lasheng et al., 2003; Toma et al., 2004; Watson et al., 2011). Of the solar cycles, SC_22 exhibited very strong fluctuations and large amplitudes of solar flux velocities. Similarly, polar field fluctuations propagating to the new toroidal field, may favor double peaks in the next SC. On the other hand, polar field fluctuations occurring outside the solar maximum generate effects in the form of peaks or troughs in the following sunspot cycle. This makes SC_22 the most magnetically dipolar cycle and the one with the most non-polar coronal holes (Kane, 2010; Gnanou et al., 2022). In a recent study, Kabore et al., (2024) showed that the majority of coronal holes are located in polar regions, whatever the phase of the SC. Further on in their study, they showed the predominance of non-polar coronal holes during the maximum phase of SC_24. Our results are partly corroborated by this recent study.

As shown in previous section, the selected solar cycles showed a clearly visible pattern of highest double peaks. However, this feature seems to be more pronounced from SC_22 to SC_24, with a decrease in their overall progression. At present, we do not know why this feature is more pronounced over the period indicated above. However, a large-scale statistical study of the most powerful solar events (with ground-level reinforcements) using data from different sources could be carried out in the GG in the near future. The monthly mean sunspot number curve during SC_20 and SC_21, shows small peaks and valleys (less pronounced double peaks). We believe that these may be caused by the emergence of one or more active regions or, conversely, by their absence, and are not identified as GG phenomena (Obridko et al., 2024). Norton and Gallagher (2010) supported this idea by showing that no GG phenomena are apparent in the total sunspot record when they are not apparent in at least one of the hemispheric records.In a solar flux study (SFI), Takalo J., (2023) showed that the most active eruption cycles during the period 1944-2020 are SC_19 and SC_21. He also showed that SC_20 can be compared with SC_23 and SC_24 due to its low eruptive activity, although it lies between the most active SFI cycles. Our results are corroborated by those of Takalo J., (2023). For the last three cycles (SC_22 to SC_24), SSN's first peak is much higher than that of the last two, as shown in the revised version of SSN in Figure 1. Probably, we think this could be due to the fact that the polarity reversal of solar magnetic field is asynchronous in both hemispheres. Generally speaking, the structures that appear in each data set around the solar maximum from SC_20 to SC_24, illustrate no close association between SSN and HSSW (the linear correlation, not shown here, between SSN and HSSW is 0.21). This argument suggests that activity of the poloidal component of the solar magnetic field (coronal hole activity) is therefore not symmetrical to that of SSN activity.This result is in perfect harmony with the work of Kabore et al., (2024). Also, as suggested by Richardson and Cane (2012), solar wind clearly shows a weak correlation with solar activity levels. According to the latter authors, there is an unclear trend towards local minima of solar wind speed in the GG near solar maximum. To better track the evolution of HSSW in the GG, we have plotted in Figure 4, the daily variation of HSSW velocities across the GG from SC_20 to SC_24.

High-speed solar wind (HSSW) cause storms that are triggered gradually (Obridko et al., 2013). According to Figure 4, HSSW show three general trends, one decreasing (10:00 to 23:00 UT), and two increasing (00:00 to 10:00 UT then 23:00 to 24:00 UT). Speeds range from 521.86 km/s to 550.47 km/s, with an average of around 540 km/s. The decreasing trend suggests a gradual slowdown of the HSSW in GG. This may be due to the reduction in size or disappearance of coronal holes, darker, less active regions of the Sun where the magnetic field opens out to space, allowing the acceleration of energetic solar wind particles. Coronal holes are often associated with HSSW (Cranmer, 2009; Zerbo and al., 2012; Poletto G., 2013; Maghradze et al., 2022). As these holes diminish in size or disappear, the amount of accelerated plasma decreases, and the speed of solar winds naturally weakens.In GG, the increase in HSSW velocity in the early morning and late night could be due to the emergence of new active regions of the Sun. Zhao et al., (2009) justified the probable cause of this increase by other solar plasma-accelerating phenomena such as magnetic reconnection. According to several works (Dungey, 1961; Gonzalez et al., 1994; Lilensten and Blelly, 2000), process of magnetic reconnection represents the efficient engine for transferring energy from solar winds to the Earth's magnetosphere. The vertical component (Bz) of IMF plays a crucial role. In addition, dawn-to-dusk component of the interplanetary electric field ($Ey = V_{sw} \times Bz$), where V_{sw}, HSSW velocity, plays a central role for ring current injection during geomagnetic storms (Burton et al., 1975; Kan & Lee, 1979; Rawat et al., 2010). In the following section, we will discuss the morphology of IMF-Bz in GG in order to understand its influence on magnetospheric plasma dynamics.

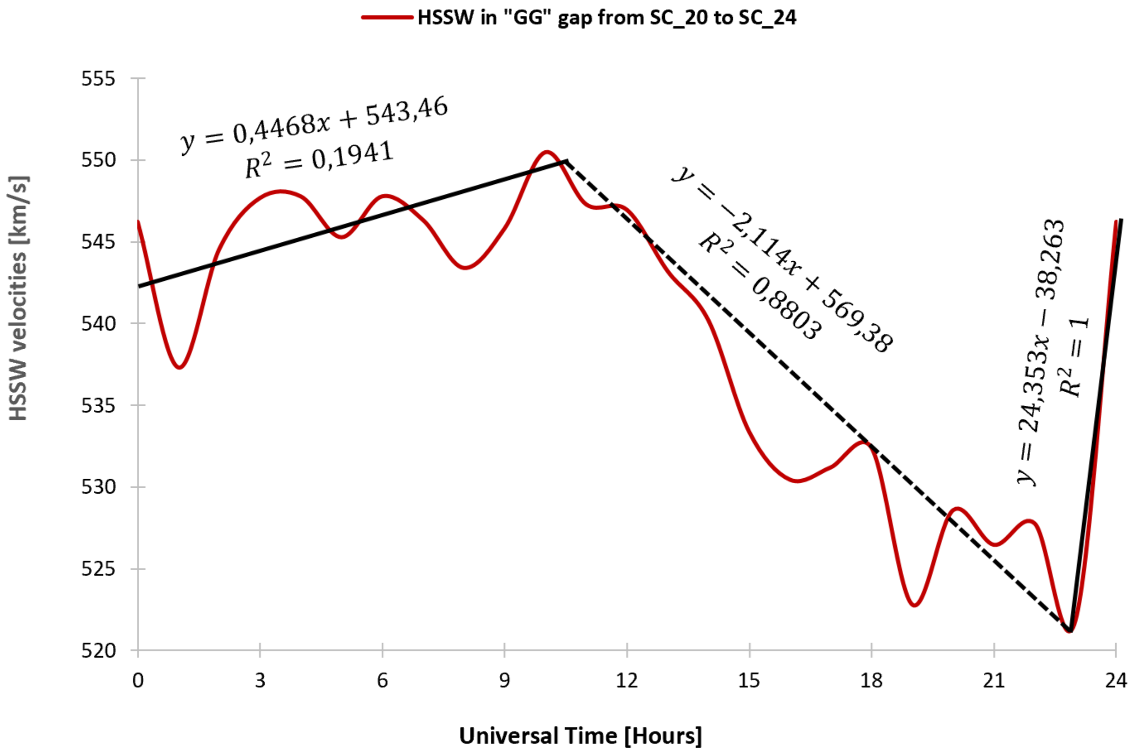

Figure 4:-Evolution of HSSW velocities as a function of time during the Gnevyshev gaps of cycles 20-24.

Interplanetary magnetic field and magnetospheric dynamics in the Gnevyshev gaps of solar cycles 20 to 24: - Having elucidated the variability of HSSW velocities from the near present to 1964 in the previous section, we now investigate how the magnetic and electrical structures of the near-Earth solar wind parameters have varied in the GG over more than four solar cycles. Figure 5 illustrates the variations of IMF-Bz and magnetospheric convection electric field E_M in GG of all selected solar cycles. The highly significant Pearson correlation between these two quantities is −0.997.

According to Figure 5, as convection decreases, IMF-Bz tends to increase, and vice versa. The decreasing phases of E_M field are due to the change in IMF-Bz from South to North, which leads to a limitation of magnetic reconnection, and therefore to a weakening of convection of HSSW particles in the Earth's magnetosphere (Kelly &al., 1979). These phases could be associated with reduced geomagnetic storms or periods of magnetospheric calm.In particular, geomagnetic storms can lead to the appearance of aurora borealis or aurora australis at latitudes where they are not normally visible. As a result, aurora progressively loses strength and brightness. According to McPherron et al., (2007), magnetic reconnection between the north-facing IMF-Bz lines and those of the geomagnetic field could indicate a calm period. Magnetic reconnection becomes less likely in this case, limiting the development of magnetic storms, and auroras tend to diminish in brightness and intensity. On the other hand, increasing phases of E_M field correspond to the change in direction of IMF-Bz from North to South. Thus, geomagnetic activity becomes highly excited when IMF near the Earth turns southwards. Each time the IMF-Bz turns southward, magnetospheric field strength gradually increases. This increase implies a magnetic reconnection that will enable energetic HSSW particles to induce intense geomagnetic activity: substorms (see, for example, Akasofu et al., 1985; Gonzalez and Tsurutani, 1987).Research by Gnanou et al., (2022) examining the cross-relationship between $E_M$field and Bz during solar cycles 20-23 on 03-hour increments, also confirms this result. Here, the strong correlation recorded between E_M field and Bz is justified by the fact that no solar flux parameter can be dissociated from the interaction between fast currents (HSSW) and the Earth's magnetosphere. Clearly, HSSW cannot independently control ring current, IMF vertical component, their velocity or even electric field of the solar flux. According to several studies (Sheeley et al., 1976, 1977; Richardson et al., 2001; Tsurutani et al., 2006), passage of HSSW beyond the Earth enhances geomagnetic activity. Generally speaking, increased geomagnetic activity is associated with improvements in the y-component of the convective electric field of solar winds, and hence in the magnetospheric convective electric field.

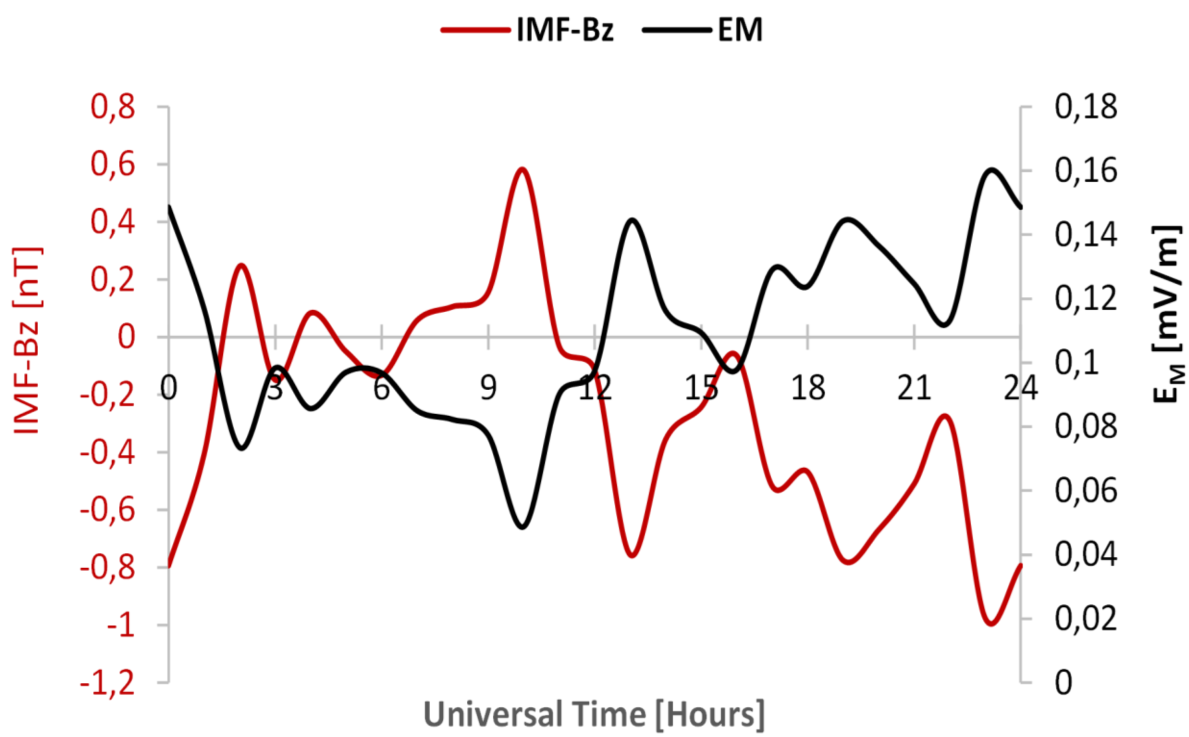

Figure 5:-Variations of IMF-Bz and E_M convection electric field in GG from SC_20 to SC_24.

These enhancements lead, on the one hand, to improved reconnection between solar winds and magnetospheric fields, and on the other, to increased energy deposition in the Earth's magnetosphere (O'Brien and McPherron, 2000; Ji and al., 2010).Thus, magnetic reconnection and/or energy deposition favors a southern orientation ofIMF-Bz. In the GG of each SC, IMF-Bz, with low intensities ranging from −0.97 nT to 0.58 nT, shows both southern (South) and northern (North) orientations from 00:00 to 10:00 UT (*cf.* red curve in Figure 5). However, from 10:00 to 24:00 UT, IMF remains predominantly south-facing (Bz<0). A north-facing IMF tends to reduce its interactions with the Earth's magnetic field, since the Earth's magnetic lines and those of the solar wind are parallel and do not reconnect directly (Gonzalez et al., 1994). On the other hand, IMF southerly orientation produces a magnetic reconnection on the day and night sides of Earth's magnetosphere (Dungey, 1961). In addition, low IMF amplitudes may indicate stable magnetic conditions. Amplitude variations observed in the GG could be linked to solar activity specific to each SC, impacting solar wind dynamics and interactions with the Earth's magnetic field. This argument suggests that magnetic and electric fields of solar origin, are relatively weak in HSSW regions around phase maximum (Richardson & Cane, 2012).

Furthermore, in high-speed currents, intermittent southward intervals of the IMF-Bz seen from 00:00 to 10:00 UT in Figure 5, are associated with Alfvénic fluctuations away from the Sun. This leads to geomagnetic activity that can persist for several days as a current passes in front of the Earth, reappearing at the solar rotation period. Large changes in southward direction of the IMF-Bz had already been linked to large variations in the Dst geomagnetic index by Saiz et al., (2008, 2013). Although many other geomagnetic indices have also been used as indicators of terrestrial disturbances, Dst index represents one of the most widely used tracers due to its clear physical meaning. For a sample covering data obtained over a 10-year period, Saiz and colleagues have shown that there could be a transfer of energy from the solar wind to the magnetosphere, not only due to the arrival of a Southern IMF at the nose of the magnetopause and by reconnection leading to a subsequent large-scale convection flow towards the tail, but also due to fluctuations in IMF-Bz.These results indicate that contributions other than those of$E_M$field may be involved in the injection function of HSSW into Earth's magnetosphere. In general, plasma convection on a global scale is a fundamental feature of the planetary magnetosphere. Dungey's cycle explains that steady-state convection in the closed part of the magnetosphere relies on magnetic reconnection in magnetospheric tail on the night side.

However, time-dependent models of Dungey's cycle suggest an alternative scenario in which magnetospheric convection may be driven solely by magnetic reconnection on the diurnal side.

Conclusion:-

Above results lead us to conclude that Gnevyshevgaps reflect the behavior of Earth's magnetosphere. The presence of the GG in sunspot data is masked by non-global structures across the selected cycles. Although no significant correlation was found between SSN and HSSW in GG, analysis of the velocities of fast currents showed increasing and decreasing trends characterized respectively by the emergence of new active regions of the Sun, and by the reduction in size or disappearance of coronal holes. Variability of HSSW and IMF-Bz observed in GG is the result of the variability of processes in the Sun and its corona, with the ultimate source being the convection zone with its dynamo. Decreasing trend inIMF-Bz (increasing E_M field) leads to enhanced magnetic reconnection, enabling energetic HSSW particles to induce substorms, while the increasing trends characterize the period of magnetospheric calm. This calm, characterized by intense magnetic storms and auroras, is moderate despite the interaction of HSSW with the magnetosphere.It's tempting to conclude that GG corresponds to a unique moment in the solar cycle that allows easy penetration of solar wind particles into the magnetosphere, while maintaining a magnetic calm. It thus ensures a balance between magnetic reconnection and a relative calm in terms of geomagnetic activity. The results obtained in this study have either been confirmed by previous work, or are original. However, the main limitations of our research are linked not only to the high time steps (01 hour) and small sample size (05 solar cycles), but also to the non-uniform average duration of the GG (varying from 09 to 28 months, *cf*. Table 1) selected. These limitations make it difficult to generalize our results to other solar cycles. We believe that a large-scale extension (over several cycles) of this study to GG of similar length could yield more significant results.

Acknowledgements:-

We are grateful to OMNIWeb(http://omniweb.gsfc.nasa.gov/)and ISGI (http://isgi.unistra.fr/) space data centers for the availability of solar wind parameters. We also thank SpaceWeahtherLive centers for sunspot numbers data.

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