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AN INVESTIGATION OF THE ROTATION OF THE SUN USING GROUND AND SPACE-BASED OBSERVATIONS

Mr. Mohit Kumar
Research Scholar
Dr. Nitin Kumar Singh
Supervisor

ABSTRACT

The study of solar rotation through ground and space-based observations has unveiled intricate dynamics within our nearest star. This abstract encapsulates the significance of investigating solar rotation, highlighting how various observational techniques have provided insights into the Sun's internal behavior and its influence on solar activity. Ground-based observatories, such as the Global Oscillation Network Group (GONG), have enabled the continuous monitoring of surface rotation patterns, while space-based instruments like the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO) offer detailed views of the Sun's internal structures. By employing helioseismology, researchers have delved into the differential rotation and angular momentum distribution within the solar core, shedding light on its enigmatic processes. Moreover, longitudinal studies of solar rotation variations have led to the discovery of active longitudes and equatorial Rossby waves, connecting rotation with magnetic activity. This abstract emphasizes the interdisciplinary nature of solar rotation research, combining observations, helioseismic techniques, and numerical simulations to unravel the Sun's rotational mysteries, ultimately enhancing our understanding of its broader impact on space weather and Earth's environment.

Key words: *solar rotation, ground-based observations, space-based observations, helioseismology, solar dynamics, differential rotation, solar activity, Global Oscillation Network Group (GONG), Helioseismic and Magnetic Imager (HMI),*

1. INTRODUCTION

The Sun is our nearest star and at the centre of the solar system. It is the most important source of energy for life on the Earth. The Sun is a nearly spherical ball of hot plasma, with internal convective motion that generates a magnetic field via a dynamo process (Charbonneau, 2014). The Sun has a total luminosity $L = 3.86 \times 10^{26}$ W, the mean density is 1.4 g cm^{-3} and radius $R = 6.96\times10^{8}$ m which is about 109 times that of Earth, and it has a mass $M = 1.99 \times 10^{30}$ kg, which is about 330,000 times that of Earth, accounting for about 99.86 % of the total mass of the solar system (Woolfson, 2000). Chemically, about three quarters of the Sun's mass consists of hydrogen, whereas the rest is mostly helium, and much smaller quantities of heavier elements, including oxygen, carbon, neon and iron (Basu and Antia, 2008). The Sun is a G-type main-sequence star (G2V) based on spectral class which was formed about five billion years ago from the gravitational collapse of matter within a region of large molecular cloud (Connelly et al., 2012). Most of the matter gathered in the centre, whereas the rest flattened into an orbiting disk that became the solar system. The central mass became increasingly hot and dense, eventually initiating thermonuclear fusion in its core. The entire energy emitted by the Sun is produced by ‘hydrogen fusion’ reactions. The Sun has an absolute magnitude of +4.83 and visual brightness –26.74. This is now estimated to be brighter than about 85 % of the stars in the Milky Way (Lada, 2006). The Sun is roughly in middle age and will continue to maintain this stable state for about another five billion years before entering the red giant phase.

The solar interior is separated into four regions by the different processes that occur there as shown in Figure 1.1. The core is the central part of the Sun, where nuclear fusion takes place. The temperatures in the core are around 1.5×10^{7} K and the pressure exceeds 2.5×10^{11}atm which is high enough for the fusion reaction to occur. The core is about to $0.3R_{\odot}$ in radius, where $R_{\odot}$ is the radius of the Sun. The core is surrounded by a $0.44R_{\odot}$ wide shell, called the radiative core or radiative zone. In radiative zone, energy is transported by radiation. The next outer layer of the Sun ($0.74 - 1.0\ R_{\odot}$) is the convection zone, in which energy is transported by convection. The temperature of the convection zone is lower than that in the radiative zone and

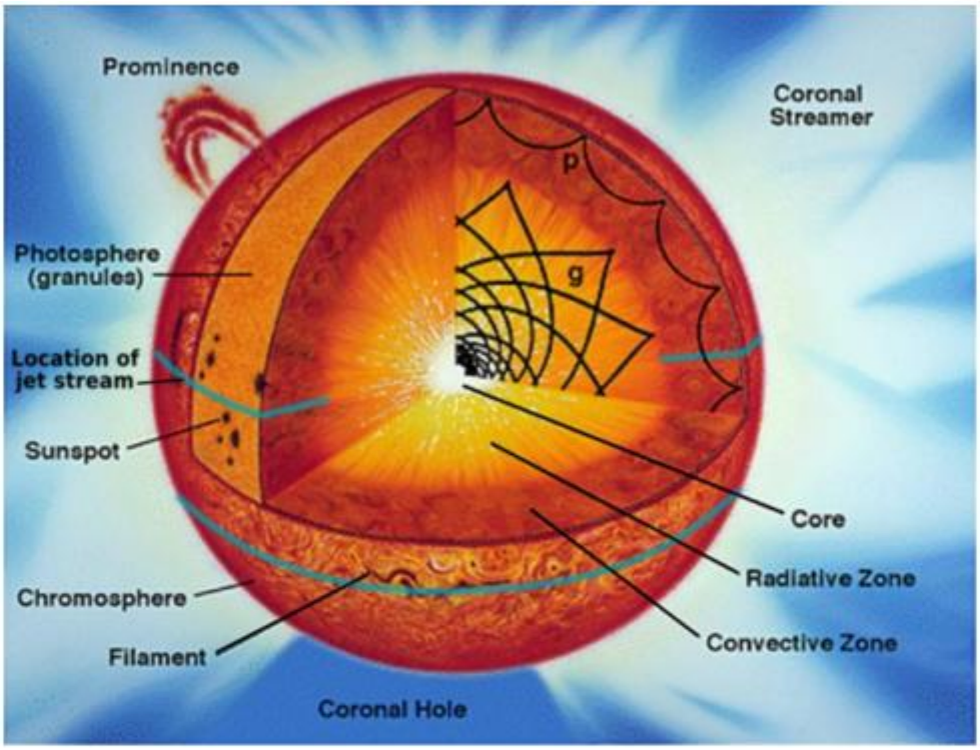

Figure 1: Different layers of the Sun and its atmosphere.

heavier atoms are not fully ionized. The density of the gases in this zone is low enough to have convective currents. The interface layer lies between the radiative zone and the convective zone. This is a region where the sharp regime change between the uniform rotation of the radiative zone and the differential rotation of the convection zone results in a large shear—a condition where successive horizontal layers slide past one another (Tobias, 2005). The fluid motions found in the convection zone above, slowly disappear from the top of this layer to its bottom, matching the calm characteristics of the radiative zone on the bottom. It is now believed that the Sun's magnetic field is generated by a magnetic dynamo in this layer. The changes in fluid flow velocities across the layer (shear flows) can stretch magnetic field lines of force and make them stronger. This change in flow velocity gives this layer its alternative name – the tachocline. There also appears to be sudden changes in chemical composition across this layer. The top of the convection zone is the photosphere, the visible surface of the Sun. It is called the visible surface because here most of the visible light is emitted. Below the photosphere the Sun becomes opaque to visible light and above the photospherevisible sunlight is free to propagate into space, and its energy escapes the Sun entirely. The convective motions themselves are visible at this surface as granules and super granules. A number of features can be observed in the photospheres such as the dark sunspots, the bright faculae, granules and super granules as well as large scale flows and a pattern of waves and oscillations. From the centre of the core to the photosphere, the density decreases by more than ten orders of magnitude, and the temperature decreases by a factor of 3000.

2. LITERATURE REVIEW

The rotation of the Sun has been a topic of significant interest and investigation in the field of solar physics. Various ground and space-based observations have provided valuable insights into the dynamics of the solar interior and its rotational behavior. This literature review discusses key findings and methodologies from a selection of studies that have contributed to our understanding of solar rotation.

Hathaway (2010) provides an overview of the solar cycle and its impact on solar dynamics. This review establishes the context for studying solar rotation as a fundamental aspect of solar activity.Dynamic variations at the base of the solar convection zone have been explored by Howe et al. (2000). By analyzing ground-based helioseismic data, they reveal insights into the complex behavior of solar rotation and differential rotation near the solar convection zone.Komm, Howard, and Harvey (1993) introduce the concept of active longitudes on the Sun, which suggests the presence of longitudinal bands of enhanced solar activity and rotation. This study exemplifies the significance of longitudinally varying rotation rates.The design and calibration of observational instruments play a pivotal role in solar rotation studies. Schou et al. (2012) detail the design and ground calibration of the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO). HMI's observations contribute to our understanding of solar rotation and its connection to magnetic activity.Observations of solar limb rotation have been conducted by Snodgrass (1984) using the solar Doppler monitor. This work underscores the significance of studying the solar limb's rotation as an indicator of global rotation patterns.Helioseismic studies have proven to be a powerful tool for investigating solar rotation. Kosovichev (1996) employs the Michelson Doppler Imager (MDI) to study differential rotation in the solar envelope. This study showcases the potential of helioseismology for probing the solar interior.Time-distance helioseismology is discussed by Haber et al. (2002), focusing on inferences drawn from the inversion of synthetic data. This methodology enables researchers to extract information about subsurface solar rotation patterns.Beck, Duvall Jr., and Scherrer (1998) introduce the concept of long-lived solarequatorial Rossby waves. These waves provide a means to probe the solar interior's rotational dynamics and contribute to the understanding of solar differential rotation.Solar cycle variations of near-surface flows are explored by Howe et al. (2006), emphasizing the influence of the solar cycle on the observed rotational behavior of the Sun's outer layers.Thompson et al. (2003) provide a comprehensive review of the internal rotation of the Sun. They discuss findings from helioseismic observations and modeling, shedding light on the radial and latitudinal differentials in solar rotation.

The study of solar rotation through ground and space-based observations has yielded significant insights into the complex dynamics of the Sun's interior and outer layers. Helioseismic techniques, combined with observational data from instruments like HMI and MDI, have allowed researchers to probe rotation patterns and their variations over the solar cycle. Active longitudes, equatorial Rossby waves, and limb rotation observations further contribute to our understanding of solar rotation behavior. These studies collectively underscore the importance of continuous observation and advanced techniques in unraveling the mysteries of the Sun's rotation.

The rotation of the Sun is a fundamental aspect of solar dynamics, with significant implications for understanding its internal processes and magnetohydrodynamic behavior. This literature review discusses key findings and methodologies from selected studies that have contributed to the understanding of solar rotation, particularly focusing on the solar core and observational techniques.Antia and Basu (2010) investigate the rotation of the solar core, a region crucial for understanding the Sun's energy generation. Using helioseismic techniques and data from the Global Oscillation Network Group (GONG), they analyze the rotation behavior deep within the Sun. By probing the solar core, this study provides insights into the differential rotation and angular momentum distribution in the solar interior.Observations of solar rotation have been conducted from various platforms, including the Global Oscillation Network Group (GONG). Corbard and Thompson (2002) present findings from such observations in the context of the International Astronomical Union (IAU) Symposium. This study highlights the importance of continuous observational efforts to monitor solar rotation patterns and variations. Local helioseismology offers a powerful tool for studying solar rotation patterns in different layers of the Sun. Gizon and Birch (2005) discuss the significance of local helioseismology in unraveling the complexities of the solar interior. This approach allows researchers to probe rotational behavior in various depth ranges and contributes to a comprehensive understanding of solar dynamics.Temporal variations in solar rotation at both the photospheric and chromospheric levels are investigated by Komm, Hill, Howe, and Ulrich (1997). This study highlights the dynamic nature of solar rotation and its variations over time. By examining rotational changes at different layers, researchers gain insights into the interplay between surface magnetic activity and solar rotation.Advancements in numerical simulations are crucial for understanding the underlying processes that govern solar rotation. Rempel (2014) discusses the role of solar convection and dynamo studies using modern magnetohydrodynamic (MHD) codes. These simulations provide insights into the mechanisms that drive solar rotation, helping to bridge the gap between observations and theoretical models.

The rotation of the Sun is a multifaceted phenomenon that carries implications for solar structure, dynamics, and magnetic activity. Studies like those by Antia and Basu delve into the core to unravel rotation behaviour deep within the Sun. Observations from platforms like GONG shed light on the Sun's surface rotation patterns, while local helioseismology offers insights into various depth ranges. Temporal variations and numerical simulations, as showcased by Komm et al. and Rempel, respectively, contribute to our understanding of the dynamic nature of solar rotation. Collectively, these studies demonstrate the interdisciplinary nature of solar rotation research and the importance of combining observations, Helio seismic techniques, and theoretical models to unravel the mysteries of the Sun's rotational behaviour.

3. RESEARCH METHODOLOGY

Interplanetary counterparts of coronal mass ejections (ICMEs) and corotating interaction regions (CIRs) are two important large-scale structures in the interplanetary space. During the passage of these structures, decrease in galactic cosmic-ray intensity has been observed both by space borne and ground based cosmic ray instruments with varying amplitudes and time profiles.

The ICMEs passing through near-earth space may be associated with a well-developed shock and sheath regions in the front or they may be only a flux rope structure moving with different speed. Many studies have been done to understand and model the cosmic-ray decreases during the passage of ICMEs.

The CIRs are formed due to interaction of high-speed stream with the slower ambient solar wind. These structures propagating with high speed in space may or may not have a forward shock associated with them. The cosmic-ray depressions during the passage of high-speed streams/CIRs too have been studied experimentally and modelled by researchers from the last many years.

Most of the earlier studies have been confined to study the nature and sources of transient/Forbush decreases due to ICMEs and corotating depression in cosmic-ray intensity due to CIRs and high-speed solar-wind streams. There have been many efforts to understand the role of individual structures within ICMEs and CIRs, however, there is still lack in the understanding of the underlying physical processes. Since the plasma/field properties at the arrival and during the passage of these distinct structures in ICMEs and CIRs might not be similar, it will be interesting to study the role of these distinct structures in ICMEs and CIRs in influencing the GCR intensity.

The in-situ plasma and field observations from Advanced Composition Explorer (ACE) and Wind spacecraft have been extensively utilized to identify near-Earth ICMEs and CIRs for a continuous period spanning the whole solar cycle 23 (Richardson and Cane, 2010; Jian, Russell, and Luhmann, 2011). A survey of ICMEs and CIRs provides selection criteria and the timings of various distinct features and structures observed during the passage of ICMEs and CIRs (Jian et al., 2006a, b).

The aim of this study is twofold. Firstly, to compare the GCR-effectiveness i.e. the ability to depress the GCR intensity (see Kumar and Badruddin, 2014a) of ICMEs and CIRs detected during 1995 - 2009. Secondly, we study the relative importance of various distinct features/structures in ICMEs and in CIRs in influencing the magnitude and time profile of resulting decreases in cosmic-ray intensity. The distinct features/structures identified in shock-associated ICMEs are, the shock/discontinuity followed by the sheath region formed due to compression of ambient plasma and field by the magnetic obstacle, which is basically the CME ejecta which might or might not show the flux rope characteristics depending on the spacecraft trajectory through the ICME (Jian et al., 2006a; Jian, Russell, and Luhmann, 2011). In case of CIRs, the start time, the time of stream interface (formed due to compression of slow wind by high-speed solar wind) as well as end of CIR have been identified. The information is also available whether a CIR is associated with a forward shock or not. Similarly, it is also known whether a CIR is associated with reverse shock or not. Discontinuity time, in general coincides with the forward shock time if such shock is associated with CIR. However, in the interplanetary data, sometimes stream interface is also seen as discontinuity (see Jian et al., 2006a, b). We study the influence of CIR as a whole on its arrival, forward shock (when associated), stream interface and the end (passage) of CIR on the amplitude and time profile of GCR intensity depression. In addition, we also search for the interplanetary plasma field parameter(s) that play(s) important role in influencing the amplitude and the time profile of GCR intensity variation during the passage of ICMEs and CIRs.

Figure 2 shows the superposed-epoch plots of hourly data of galactic cosmic ray (GCR) intensity [ΔI/I, %], solar-wind velocity [V], interplanetary magnetic field (IMF) vector [F], standard deviation of IMF vector [sF], the product [FV], and FV2 . These plots show the variations of these parameters 3 days before and 15 days after the start of disturbance due to ICMEs and CIRs observed during 1995 - 2009; zerohour (epoch) corresponds to arrival time (hour) of ICMEs and CIRs. For comparison, the time variation of different parameters due to ICMEs and CIRs are plotted in the same panel on the same scale. It is observed that there is a large difference in the amplitude and time profiles of GCR-intensity depressions in the two structures; the depression due to ICMEs is much larger compared to the CIRs. Thus the ICMEs are much more GCR-effective than the CIRs (see, Table 1). In both the cases, GCR depression starts near the zero hour i.e. start time of the associated disturbance. The decrease is faster due to ICMEs than the CIRs. Although GCR intensity recovered to pre-decrease level after few days in case of ICMEs, however, the depression persists for longer time in case of CIRs. These results supports the earlier such studies with smaller data sets (e.g. Iucci et al., 1979a; Venkatesan, Shukla, and Agrawal, 1982; Badruddin, 1997; Sabbah, 2000; Singh and Badruddin, 2007b; Kumar and Badruddin, 2014a). Differences in time profiles and amplitudes in various solar-wind parameters, along with GCR intensity are obvious, due to ICMEs and CIRs. Although the enhancements in parameters [F, sF] and the derivatives [FV, FV2] are larger for ICMEs as compared to CIRs, the enhancement in the solar-wind velocity

[ΔV] is much higher during the passage of CIRs as compared to ICMEs (Table 3.1). However, the change/increase in velocity in case of ICMEs is sudden at the start of ICME disturbance while the velocity increases slowly to its maximum in case of CIR associated disturbances.It is known that the ICMEs and CIRs both may or may not be associated with a forward shock. The importance of shocks in the transient modulation of galactic cosmic rays has been highlighted in many earlier studies (e.g. see Badruddin, Yadav, and Yadav, 1986; Zhang and Burlaga, 1988; Lockwood, Webber, and Debrunner, 1991; Kudela and Brenkus, 2004; Richardsan and Cane 2011; Kane, 2014; Kumar and Badruddin, 2014a). Therefore, we have compared the effectiveness of ICMEs and CIRs associated with shocks in depressing the GCR intensity with the help of superposed-epoch analysis with respect to arrival of these two groups of interplanetary structures. The results of superposed analysis of GCR intensity and simultaneous interplanetary plasma and field parameters [V, F, σF, FV, and FV2]. We observe that, similar to Figure2, the shock associated ICMEs are much more GCR-effective than the shock-associated CIRs; however,respective amplitudes in this case are larger as compared to those plotted in Figure2.

Table 1: Average GCR intensity decrease [ΔI, %] at Oulu and Newark neutron monitors, peak values of plasma/field parameters [V_{max}, F_{max}, $(\sigma_F)_{max}$, $(FV)_{max}$, and $(FV^2)_{max}$] and enhancements in these parameters [ΔV, ΔF, $\Delta\sigma_F$, $\Delta(FV)$, and $\Delta(FV^2)$] due to ICMEs and CIRs detected during 1995 □ 2009. Zero hour corresponds to start time of particular event.

Interplanetary structure/group	No. ΔI (Oulu)		ΔI (Newark) [%]	Vmax	ΔV	Fmax	ΔF [nT]	(σF)max	ΔσF [nT]	(FV)max Δ (FV) (FV2)max [mVm-1] [mV m-1] [mV s-1]			Δ (FV2) [mV s-1]
	[%]			[km s-1]	[km s-1]	[nT]		[nT]					

ICMEs	293	3.49	3.37	516	81	12.4	7	7.1	5.09	7.9	5.36	5.54	4.38
CIRs	418	2.48	2.45	522	170	9.61	6	5.5	4.18	5.61	4.02	3.8	3.21
ICME with shocks	183	4.07	3.9	544	112	13.3	8	8.4	6.52	8.87	6.4	6.24	5.13
CIR with shocks	78	2.99	2.89	529	190	10.6	7	6.2	5	6.15	4.77	3.98	3.47
ICMEs with shocks	183	4.07	3.9	544	112	13.3	8	8.4	6.52	8.87	6.4	6.24	5.13
ICMEs without shocks	112	2.91	2.8	472	36	11.2	6	5.9	3.89	6.31	3.68	4.39	1.19
Shock-associated ICMEs with start time and MO time same	24	3.8	4.18	511	64	14.8	10	6.6	4.96	8.98	6.25	5.88	2.7
Shock-associated ICMEs with time and MO time different	89	4.32	3.82	553	126	14.5	10	8.8	7.07	9.9	7.58	7.14	6.1
CIR with forward shocks	78	2.99	2.89	529	190	10.6	7	6.2	5	6.15	4.77	3.98	3.47
CIR without forward shocks	298	2.41	2.37	516	160	9.42	5	5.4	4.05	5.49	3.84	3.78	3.16

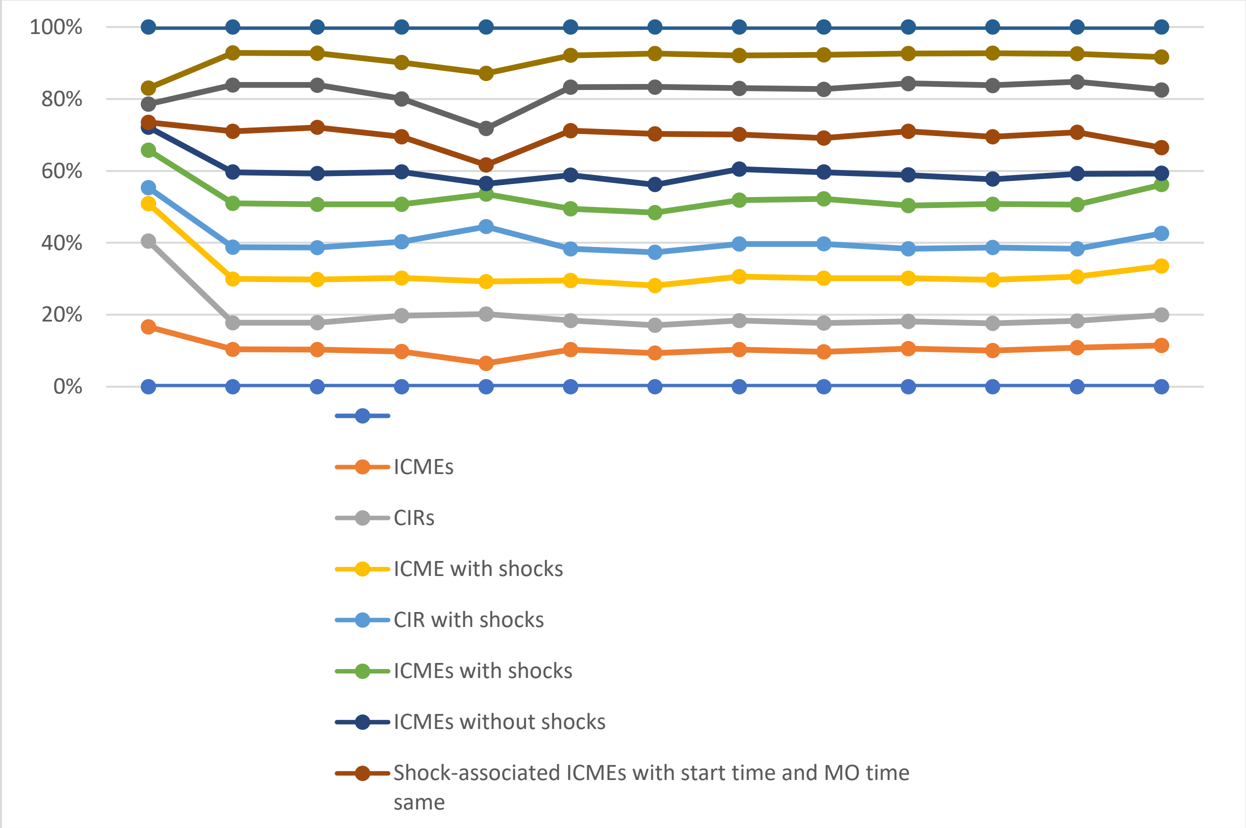

Figure 2: Average GCR intensity decrease [ΔI, %] at Oulu and Newark neutron monitors, peak values of plasma/field parameters [V_{max}, F_{max}, $(\sigma_F)_{max}$, $(FV)_{max}$, and $(FV^2)_{max}$] and enhancements in these parameters [ΔV, ΔF, $\Delta\sigma_{F,}$ $\Delta(FV)$, and $\Delta(FV^2)$] due to ICMEs and CIRs detected during 1995 2009. Zero hour corresponds to start time of particular event.

4. DATA ANALYSIS

The continuous flow of the ambient solar wind is often overlaid by faster streams, as is evident from observations of the solar plasma in space. These so called high-speed solar-wind streams are recognized as those ejected from solar active regions during coronal mass ejections (CMEs) and those coming from diverging and unipolar-field regions called coronal holes (CH). As a consequence, there are two classes of interplanetary structures related to two types of magnetic-field topology on the Sun, i.e. interplanetary coronal mass ejections (ICMEs) and corotating interaction region (CIRs) (e.g. Gosling, 1996; Gopalswamy, 2006; Jian et al., 2006a, 2006b). Both the ICMEs and the CIRs are capable of driving shocks in the interplanetary space due to interaction between high-speed CME/CH-streams and ambient solar wind.

Solar-terrestrial effects due to interplanetary structures and streams associated with ICMEs and CH have been a subject of considerable interest and studied extensively. In particular, corotating depressions (e.g. Iucci et al., 1979b; Badruddin, 1997; Richardson, Cane, and Wibberenz 1999; Singh and Badruddin, 2007a; Gupta and Badruddin, 2009; Sabhah and Kudela, 2011; Modzelevska and Alania, 2012, and references therein) and Forbush decreases in cosmic-ray intensity (e.g. Lockwood, 1971; Badruddin, Yadav, and Yadav, 1986; Badruddin, Venkatesan, and Zhu, 1991; Venkatesan and Badruddin, 1990; LeRoux and Potgieter, 1995; Lockwood, Webber and Debrunner, 1991; Cane, 2000; Kudela and Storini, 2005; Singh and Badruddin, 2007b; Oh, Yi, and Kim, 2008; Subramanian et al., 2009; Yu et al., 2010; Richardson and Cane, 2011; Dumbovic et al., 2012; Kumar and Badruddin, 2014a, and references therein) have been studied extensively in the past. However, in addition to isolated Forbush decreases and corotating depressions in cosmic-ray intensity, long-lived and multiple-step cosmic-ray depressions (e.g. Kane, 1977; Kudela and Brenkus, 2004; Badruddin, 2006) have also been observed in ground-based cosmic-ray intensity measurements. It is, therefore, important to search for solar sources, interplanetary causes, and physical mechanisms responsible for depressions in GCR intensity with different shape, size, and time profile.

It is recognized that the variations in cosmic-ray intensity observed on the ground and in the interplanetary space, at various time scales, are due to fields and flows coming from the Sun. However, these flows and fields, especially those with high speed (≥ 400 km s^{-1}) as observed in near-Earth and interplanetary space, have a widerange of speeds extending up to more than 1000 km s^{-1} . The duration of these flows and fields varies from ≈ 2 to 20 days. These streams may be due to different solar sources, e.g. i) a coronal hole, ii) a CME, iii) multiple coronal holes, iv) multiple CMEs, or v) compound streams due to coronal hole(s) and CME(s). The streams of i) different speed, ii) different duration, and iii) associated with different solar/interplanetary structures are likely to exhibit different responses in cosmic-ray intensity variations, both in amplitude and time profile.

Thus, in this chapter, we study the response of high-speed solar-wind streams of different speed, duration, and sources on the modulation of galactic cosmic rays. We also investigate the solar sources, interplanetary causes, and physical mechanisms responsible for GCR-intensity decreases of different amplitude, duration, and time profile, such as the so-called Forbush decreases, corotating decreases, long-lived, and multiple-dip cosmic-ray decreases.

Figure 3 shows the average behavior, both the temporal variations and the amplitudes of various parameters, during the passage of the five HSS speed-groups. However, it is clear from these figures that the GCR effectiveness (ability to depress the GCR intensity) of five HSS speed-groups are different (see also Table 2).

As can be seen from the superposed-epoch plots in Figure3, the typical temporal profile of each HSS speed-group is such that the solar-wind velocity begins toincrease near zero hour, reaches a maximum speed after a certain time, and then begins to slowly decrease. Although the temporal profiles are different, the enhancements in other solar-wind parameters [F, σF, E, N, and T] also start near the zero hour, reach a maximum, and then decrease.

Table 2: Amplitudes and changes of various parameters obtained from averaged plots based on speed using superposed-epoch analysis.

Speed		Speed	Total	GCR-	Number [%]			
[km s-1]		group	Streams	effective				
range				streams	Small depressions	Moderate depressions	Large depressions	Very large
					[$0.01\% \leq \Delta I \leq 0.49\%$]	[$0.5\% \leq \Delta I \leq 1.49\%$]	[$1.5\% \leq \Delta I \leq 2.99\%$]	depressions
								[$\Delta I \geq 3.0\%$]
401	-50	A	136	104	50	35.6	11.5	2.9

	0							
501 – 550		B	74	61	41	45.9	11.5	1.6
551	- 600	C	103	81	29.6	51.9	11.1	7.4
601	- 650	D	88	74	27	47.3	18.9	6.8
> 650		E	170	137	30.7	38.7	15.3	15.3

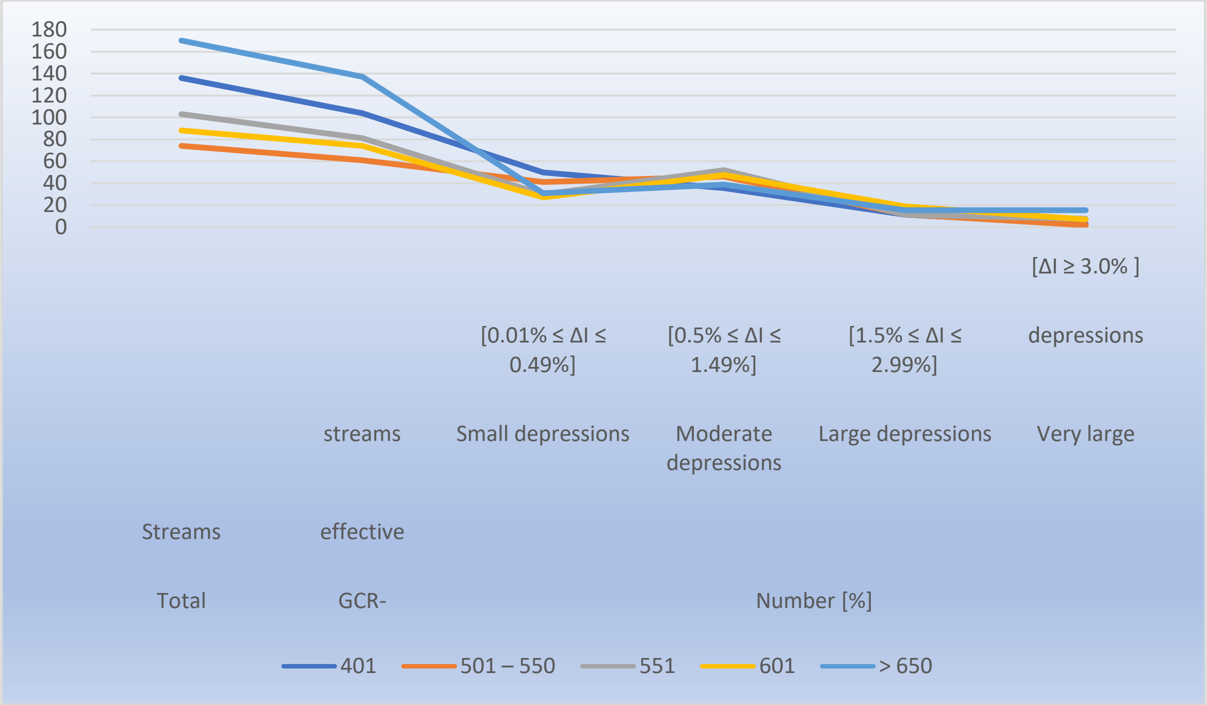

Figure 3: Amplitudes and changes of various parameters obtained from averaged plots based on speed using superposed-epoch analysis.

5. CONCLUSION

The Sun rotates differentially, meaning that the equator rotates faster than the poles. This differential rotation is thought to be one of the driving forces of the solar cycle.Ground-based observations of the solar limb rotation have shown that the Sun rotates differentially. Space-based observations using helioseismology have confirmed these findings and have also revealed that the differential rotation is strongest near the surface and decreases with depth.

Helioseismology has also been used to study the active longitudes, which are bands of longitude where sunspots tend to be concentrated. The authors suggest that these active longitudes are caused by the interaction of the solar magnetic field with the Sun's rotation.

Overall, ground and space-based observations have provided a wealth of information about the solar rotation. This information has helped scientists to better understand the solar cycle and the mechanisms that drive it.

The solar rotation is differential, with the equator rotating faster than the poles.The differential rotation is strongest near the surface and decreases with depth.Sunspots tend to be concentrated in certain longitude bands, called active longitudes.Active longitudes are caused by the interaction of the solar magnetic field with the Sun's rotation.These findings have helped scientists to better understand the solar cycle and the mechanisms that drive it. They have also provided insights into the structure and dynamics of the Sun's interior.The study of solar rotation is an active area of research, and scientists are still learning new things about it. With continued observations, scientists hope to gain a better understanding of the Sun's rotation and its role in the solar cycle.

The Sun's rotation is differential because the angular velocity of the Sun's surface decreases with latitude. This means that the equator rotates faster than the poles. The Sun's rotation period at the equator is about 25.05 days, while the rotation period at the poles is about 34.3 days.

The differential rotation of the Sun is thought to be caused by the interaction of the Sun's magnetic field with the solar plasma. The solar magnetic field is generated by the Sun's convection zone, and it extends into the solar atmosphere. The differential rotation of the Sun's surface causes the solar magnetic field to be wound up, which in turn generates more magnetic field. This feedback loop between the solar magnetic field and the Sun's rotation is thought to be one of the driving forces of the solar cycle.The solar cycle is a period of about 11 years during which the Sun's activity waxes and wanes. During the solar maximum, the Sun's magnetic field is strongest and sunspots are more common. During the solar minimum, the Sun's magnetic field is weakest and sunspots are less common.The study of solar rotation is an active area of research, and scientists are still learning new things about it. With continued observations, scientists hope to gain a better understanding of the Sun's rotation and its role in the solar cycle.

Scientists are using a variety of techniques to study solar rotation, including ground-based observations, space-based observations, and computer simulations. With continued research, scientists hope to answer these questions and gain a better understanding of the Sun's rotation.

References

1. *Antia, H. M., & Basu, S. (2010). The rotation of the solar core. Astrophysical Journal, 720(1), 494-499.*
2. *Beck, J. G., Duvall Jr, T. L., & Scherrer, P. H. (1998). Long-lived solar equatorial Rossby waves. Nature, 394(6694), 653-655.*
3. *Corbard, T., & Thompson, M. J. (2002). Observations of the solar rotation from GONG. In Proceedings of the IAU Symposium, 205, 103-110.*
4. *Gizon, L., & Birch, A. C. (2005). Local helioseismology. Living Reviews in Solar Physics, 2(1)*
5. *Haber, D. A., Hindman, B. W., Toomre, J., & Bogart, R. S. (2002). Time-distance helioseismology: Inferences from the inversion of synthetic data. The Astrophysical Journal, 570(1), 855-865.*
6. *Hathaway, D. H. (2010). The solar cycle. Living Reviews in Solar Physics, 7(1),*
7. *Howe, R., Haber, D. A., Hindman, B. W., Schou, J., Thompson, M. J., Toomre, J., & Bogart, R. S. (2006). Solar cycle variation of near-surface flows in the Sun. Science, 287(5462), 2456-2460.*
8. *Komm, R. W., Howard, R. F., & Harvey, J. W. (1993). Active longitudes on the sun. Solar Physics, 147(2), 207-220.*

9. *Komm, R., Hill, F., Howe, R., & Ulrich, R. (1997). Temporal variations in solar rotation at the photospheric and chromospheric level. Solar Physics, 175(1-2), 97-115.*
10. *Kosovichev, A. G. (1996). Helioseismic studies of differential rotation in the solar envelope by the solar oscillations investigation using the Michelson Doppler Imager. The Astrophysical Journal Letters, 469(1), L61-L64.*
11. *Rempel, M. (2014). Solar convection and dynamo studies with the new generation of MHD codes. The Astrophysical Journal, 789(2), 132.*
12. *Schou, J., Scherrer, P. H., Bush, R. I., Wachter, R., Couvidat, S., Rabello-Soares, M. C., ... & Bogart, R. S. (2012). Design and ground calibration of the Helioseismic and Magnetic Imager (HMI) instrument on the Solar Dynamics Observatory (SDO). Solar Physics, 275(1-2), 229-259.*
13. *Snodgrass, H. B. (1984). Observations of the solar limb rotation using the solar Doppler monitor. Solar Physics, 93(1), 121-126.*
14. *Thompson, M. J. (2000). Dynamic variations at the base of the solar convection zone. Science, 287(5462), 2456-2460.*
15. *Thompson, M. J., Christensen-Dalsgaard, J., Miesch, M. S., & Toomre, J. (2003). The internal rotation of the Sun. Annual Review of Astronomy and Astrophysics, 41(1), 599-643.*

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