

Analysis of the Motion of Solar Wind (SW) and Other Solar Activities Impacts on the Earth

Chunyu Yu ^{1,*} and Jiayin Zhou ²

¹Changjun high school international department, Changsha, China

²Ningbo Foreign Language school international department, Ningbo, China

* Corresponding Author Email: zouxian@ldy.edu.rs

Abstract. Solar wind (SW), the powerful outflow of charged particles from the Sun, has a significant impact on Earth's magnetosphere, ionosphere, and atmospheric processes. This paper examines the motion of SW and its effects on Earth, focusing on changes such as slow and fast SWs and their impacts on geomagnetic storms, ionospheric disturbances, and precipitation patterns. Observations from spacecraft, including the Solar and Heliospheric Observatory (SOHO), the Advanced Composition Explorer (ACE), and the Wind spacecraft, have provided valuable data on solar wind properties. However, there are limitations in spatial coverage and the measurement of internal SW properties. Accurately predicting SW behavior remains a challenge. Future research should focus on developing advanced observational techniques, utilizing multiple spacecraft, and improving modeling and data analysis approaches. The forthcoming expeditions, specifically the Solar Orbiter and Parker Solar Probe, are predicted to provide novel understandings into solar activity. Enhancing our understanding of solar activity and improving space weather predictions are crucial for mitigating the potential adverse effects of SW on electricity, communication, and other human activities. This research contributes to advancements in space weather forecasting and the reliable and safe operation of our technological infrastructure.

Keywords: Solar wind; solar activities; geomagnetic storms; ionospheric disturbances.

1. Introduction

Humanity has made significant progress in observing solar activity, leading to important discoveries. In 1859, solar flares were first observed and their impact on human and production activities, like their short and long term cyclical changes, were established. Subsequent observations and explorations have revealed that various forms of solar activity affect not only Earth and its organisms, but also Earth itself. The influence of solar activity and its structures, such as the corona and other solar activity, has had diverse effects on human communication engineering, man-made satellites, atmospheric composition, and Earth's magnetic field. Furthermore, the observation of solar activity has brought attention to cosmic rays, a cosmic phenomenon that affects the energy intensity and abundance of various cosmic ray components. Cosmic rays, consisting of numerous charged particles, are influenced by the magnetic field of large stars like the Sun. However, the variations that occur in space and time are still being explored. The effects of cosmic rays on the terrestrial environment and organisms after passing through the Earth's atmosphere are substantial. Thus, understanding the combined impact of cosmic ray variations and long or short-term variations in solar activity will enhance our knowledge of outer space beyond Earth and help mitigate potential catastrophes affecting both humanity and the planet.

The sun undergoes intricate physical processes, including coronal mass ejections (CMEs), SW and current sheets. Researchers have previously observed a recurring pattern of long-term solar activity changes that happens approximately every 11 years, which called the solar cycle [1]. This pattern also applies to the long-term activity of the SW and the inclination of the solar current sheet. The interaction between Earth's magnetic field and the SW, which consists of charged particles with high energy, has significant effects on various systems such as electricity and communication [1, 2]. Moreover, the periodic activity of the sun causes deflection of its magnetic poles, influencing the tilt angle of the solar current sheet, which in turn affects the drift mode of solar cosmic rays [1]. There

has also been research into short-term solar activity phenomena. Solar flares can be sudden bursts of strong SWs or coronal mass ejections. Solar cosmic ray events can temporarily boost the energy of particles, causing them to travel across the geomagnetic field and affect Earth's surface [3]. The material ejected from the solar corona during coronal mass ejections also contains a magnetic field that can block the cosmic rays from the Milky Way and affect observations of the ground [4].

Coronal mass ejection involves the emission of high-energy plasma from the sun, carrying broad magnetic field lines, that interacts with charged particles propagating in cosmic rays. This interaction leads to deflection or deceleration of particle trajectories. The plasma undergoes acceleration during the ejection process, increasing the energy of the ejected solar cosmic ray particles. As a result, collisions and interactions with galactic cosmic rays occur, causing changes in both their energy levels and composition. These differences remain present when the particles reach the atmosphere or a ground-based observation network [4]. The term SW pertains to the forceful outflow of charged particles, predominantly protons and electrons, discharged from the sun's corona into the vast expanse of interstellar space. These particles spread out near Earth's orbit at velocities ranging from 200 to 900 kilometers per second [5]. Long-term fluctuations in SW activity, corresponding to the solar cycle, have an impact on the interplanetary magnetic field and the migratory movement of cosmic ray particles within the magnetic domain [5]. Observers within the solar system witness a particle flow driven by convection in the direction of the SW speed. Additionally, cosmic ray particles within the expanding SW experience adiabatic deceleration, similar to expanding gas, resulting in changes in their energy spectra. Furthermore, the intensity and frequency of SW eruptions vary during different periods of maximum and minimum solar activity. In years with intense solar activity, the frequency of SW eruptions is higher, leading to stronger modulation effects on both incoming and outgoing cosmic rays from the Milky Way. Conversely, in extremely quiet solar activity years, the frequency of SW eruptions is lower, resulting in weaker modulation effects [5].

Solar current sheets represent surfaces where the polarity of the magnetic field within the solar system undergoes transformation. The magnetic poles of the sun flip cyclically, causing changes in the inclination angle of the current sheet. During the magnetic pole transformation process, the inclination angle reaches its maximum value, and when the magnetic pole completes rotation, the inclination angle reaches its minimum value. Depending on the arrangement of the magnetic poles and the geographical north poles, when the northern magnetic pole is located in the geographic north pole, cosmic ray particles tend to be distributed at both poles, while when the south magnetic pole is located in the geographical south pole, cosmic ray particles tend to be distributed at the equator. The distribution of cosmic ray particles is influenced by the effect of the current sheet on drift, causing changes in their distribution and propagation modes [6]. Through research on solar activity, such as the long-term and short-term phenomena described above, we can gain a deeper understanding of the laws governing solar activity and effectively respond to their effects. Additionally, studying solar activity is conducive to advances in cosmic ray research, addressing their impact on the terrestrial environment and organisms [3]. The extensive study of solar activity has focused on the SW, which constitutes supersonic plasma charged particles originating from the sun's upper atmosphere. Researchers, including those utilizing Wind Satellites, have made significant contributions to our understanding of the SW and its impact on various phenomena in recent decades [7-9]. Researchers have employed advanced technologies and instruments to monitor the SW and its properties in interplanetary space. These studies have enabled us to observe and comprehend the characteristics of the SW, such as its variations during solar cycles and its involvement in magnetic reconnection processes [8, 10]. The impact of the SW on Earth is particularly notable due to its interaction with our planet's magnetic field, which can lead to the occurrence of geomagnetic storms and disruptions in the ionosphere [11]. Understanding the SW is crucial for mitigating the effects of these phenomena on Earth's electrical systems, satellite networks, and communication infrastructure, as well as for improving our ability to predict and respond to such events [11].

Additionally, the historical progression of SW research has yielded valuable insights into the fundamental properties and dynamics of the sun, expanding our understanding of astrophysical and

plasma physics [8][10]. Furthermore, investigations into the SW contribute to advancements in space weather forecasting and our overall comprehension of the solar system's interplanetary environment [7, 9]. This article aims to investigate and summarize the definition and observation of the SW, explain certain phenomena associated with the SW, and explore its limitations and prospects for the future. By summarizing relevant research on the SW, we hope to further deepen people's comprehension of solar activity and improve their ability to respond to its adverse effects.

2. Descriptions of Solar Wind

The SW is a stream of charged particles that constantly streams out from the Sun. It is formed by two key factors, namely, the provision of energy and the source of material for its formation. The process of SW formation involves heating the solar corona, which is an important part of the SW. The heating of the solar corona in the sun occurs when different magnetic lines of force in the solar magnetic field produce shear twist, causing joule dissipation. This is an important reason for the differences in solar wind formation. The SW surrounding the Earth has been examined and found to be divided into two types in velocity, slow and fast. The characteristics of these two different types of SWs are also very different. The second one is faster and has higher proton temperature than the first one. But the number density is opposite. The helium abundance in the fast SW is mainly stable at about 4%, while the helium abundance in the slow SW varies with the peak and trough years of the solar activity, with the helium abundance being mainly stable at about 2% in the trough years, and at about 4% in the peak years, with a wide range of variations [12].

3. Observation of Solar Wind

Observing the variations in SW is essential for understanding the motion of solar activities and their impacts on Earth. Over the years, various instruments have been developed to accurately detect and measure the properties of SW. One commonly used instrument is SOHO. SOHO, a joint mission between NASA and the European Space Agency, has provided invaluable insights into SW characteristics since its launch in 1995 [13]. It is equipped with multiple detectors and instruments that enable comprehensive observations of SW. For instance, the SW Anisotropies (SWAN) instrument onboard SOHO measures the distribution and velocity of SW particles using Lyman-alpha radiation [14]. The Extreme Ultraviolet Imaging Telescope (EIT) on SOHO provides images of the Sun's outer atmosphere, also called the corona, which aid in studying the dynamics of SW [15].

Another significant spacecraft that plays a crucial role in monitoring SW conditions near Earth is ACE [16]. ACE provides real-time information about SW properties and is positioned at the L1 Lagrange point, approximately 1 million miles from Earth. ACE is equipped with various instruments, including the Solar Wind Electron Proton Alpha Monitor (SWEPAM), which measures the composition, speed, and temperature of solar wind particles [17]. Moreover, the Solar Wind Ion Composition Spectrometer (SWICS) on ACE measures the elemental and isotopic composition of SW ions [18]. Through continuous monitoring, ACE has significantly contributed to our understanding of SW behavior and its effects on Earth's magnetosphere.

The Wind spacecraft, launched by NASA in 1994, has provided valuable data on SW properties. It is positioned at the L1 Lagrange point and constantly monitors solar wind characteristics [19]. The Solar Wind Experiment (SWE) instrument aboard Wind provides measurements of SW speed, density, temperature, and magnetic field strength [20]. The 3D Plasma and Energetic Particle (3DP) instrument on Wind offers insights into the distribution of energy and composition of SW particles [21]. The combination of these instruments has facilitated detailed analysis of SW behavior and its impact on Earth's magnetosphere and ionosphere.

Through observations conducted by instruments such as SOHO, ACE, and Wind, significant findings have been obtained regarding the motion of solar activities and their consequences on Earth. For example, studies have revealed that SW speed plays a crucial role in the formation and evolution

of geomagnetic storms [22]. High-speed SW streams, often associated with coronal holes on the Sun's surface, can cause disturbances in Earth's magnetosphere, leading to phenomena such as magnetic reconnection and the enhancement of the auroral electrojet currents [10]. Additionally, SW variations have also been linked to changes in Earth's ionosphere, which can influence radio communication and satellite operations [23].

In conclusion, the examination of SW fluctuations utilizing instruments such as SOHO, ACE, and Wind has offered crucial perspectives into solar activities and their consequences for Earth. These instruments have facilitated the measurement and analysis of SW properties, resulting in an enhanced comprehension of its behavior and impact on Earth's magnetosphere and ionosphere. The resultant discoveries have illuminated the connection between SW and geomagnetic storms, as well as the influence of SW on the Earth's ionosphere. Ongoing advancements in the technology for detecting SW will assuredly contribute even more to our understanding of solar activities and their consequences for our planet.

4. Explanation and Impacts of Solar Wind

SW, which is a fundamental solar activity, can have effects on Earth due to its unique characteristics. One effect is the phenomenon of auroras, which occur when high-energy charged particles from the Sun collide with each other after reaching Earth's magnetic poles. The impact of the SW is not limited to the poles; it also affects rainfall and flash floods. Changes in SW intensity coincide with changes in regional rainfall patterns, resulting in variations in precipitation. When SW intensity is high, precipitation intensity naturally increases. This has significant implications for human activities and well-being. By observing the SW, coronal mass ejections, and other meteorological data, more accurate weather predictions can be achieved [24].

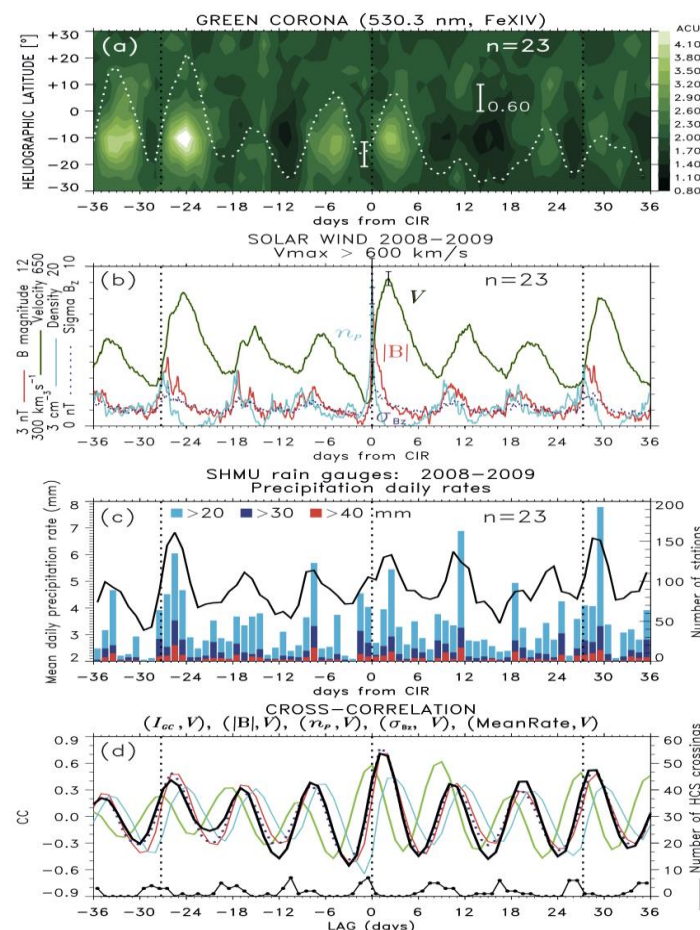


Fig. 1 Observation of the Solar Wind.

As shown in the Fig. 1, the intensity of the SW and the variation curve of the corona basically coincide with the variation curve of the daily precipitation of the place where the site is located, which reinforces the close correlation between the SW and other solar activities and the meteorology of some parts of the Earth.

5. Limitations and Prospects

Although considerable advancements have been achieved in comprehending the movement of solar activities and their effects on Earth through the investigation of SW, several limitations and challenges persist and necessitate attention. One such limitation pertains to the constrained spatial coverage of current spacecraft and instruments. Although missions such as SOHO, ACE, and Wind have furnished invaluable data, they are stationed at specific locales, primarily the L1 Lagrange point, and fail to present a comprehensive outlook of the entirety of the solar wind. A more extensive spatial coverage is imperative to capture the entire intricacy and fluctuations of solar wind phenomena. Another limitation is the difficulty in directly measuring the internal properties of the SW, such as its magnetic field strength and composition. Current instruments primarily measure the properties of SW particles and their interaction with the Earth's magnetosphere. However, understanding the internal structure and dynamics of the SW is crucial for predicting space weather events and their potential impacts on Earth. Furthermore, the prediction of SW behavior and its effects on Earth still faces challenges. While advancements have been made in forecasting solar flares and coronal mass ejections, accurately predicting the characteristics and timing of these events remains a complex task. The complex interplay between solar magnetic fields, plasma instabilities, and the evolving solar atmosphere adds to the challenge of reliable forecasting.

Several avenues for future research and advancements in the study of SW are anticipated. One such direction is the development of advanced observational techniques, including the utilization of multiple spacecraft in a constellation formation. This approach would enable a more comprehensive and continuous monitoring of SW properties, leading to a more detailed understanding of its dynamics. Furthermore, ongoing and proposed missions, like the Solar Orbiter and Parker Solar Probe, offer promise in providing new insights into the motion of solar activities and their impacts on Earth. These missions will enable closer observations of the Sun and its surrounding environment, facilitating the study of SW properties at unprecedented spatial resolutions and distances. Moreover, advancements in modeling and data analysis techniques are essential for improving our understanding of SW behavior. Sophisticated numerical simulations that incorporate the complex physics of SW interactions can enhance our predictive capabilities and help mitigate potential space weather impacts.

In conclusion, current research on solar wind motion and its impacts on Earth has provided valuable insights. However, there are still limitations and challenges that need to be addressed. Expanding the spatial coverage, improving measurements of internal solar wind properties, and enhancing prediction capabilities are crucial areas for further study. With the development of advanced observational techniques, ongoing and proposed missions, and improved modeling approaches, future research holds great potential for advancing our understanding of solar activities and their impacts on our planet.

6. Conclusion

In summary, this study investigates the motion of SW and its impacts on Earth. Through the observation and analysis of SW variations, it has been revealed that solar wind activity is influenced by various solar activities, such as coronal mass ejections and solar current sheets. SW, characterized by supersonic plasma charged particles, plays a significant role in shaping Earth's magnetosphere, ionosphere, and atmospheric processes. Its effects include geomagnetic storms, ionospheric storms, and changes in precipitation patterns. However, this research has identified certain limitations. The spatial coverage of existing spacecraft and instruments is limited, hindering a comprehensive

understanding of SW phenomena across the entire solar system. Direct measurement of internal solar wind properties also remains challenging. Accurate prediction of SW behavior and its impacts on Earth requires further advancements in forecasting techniques. Looking ahead, future research should focus on developing advanced observational techniques, utilizing multiple spacecraft, and improving modeling and data analysis approaches. The upcoming missions, Solar Orbiter and Parker Solar Probe, hold great promise for providing new insights into solar activities. These advancements will enhance our ability to predict and mitigate potential space weather impacts. In conclusion, this study contributes to our understanding of the complex motion of solar activities and their impacts on Earth. The findings provide valuable guidance for further research, space weather prediction, and efforts to mitigate the effects of solar activities on various Earth systems and human activities.

Author Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

References

- [1] Hathaway D. The solar cycle. *Living Reviews in Solar Physics*, 2015, 12(1): 4.
- [2] Reames, D. V. (2013). The two sources of solar energetic particles. *Space Science Reviews*, 2013, 175(1-4): 53-92.
- [3] Mewaldt R A, Moraal H. Cosmic Rays in the Heliosphere. *Space Science Reviews*, 2091, 215(7): 40.
- [4] Gopalswamy N, Zhang J. The solar connection to heliospheric magnetic fields. *Space Science Reviews*, 2012, 172(1-4): 397-422.
- [5] Zhang J, Richardson I G, Webb D F. Solar Wind and Coronal Mass Ejections. *Space Science Reviews*, 2018, 214(3): 46.
- [6] Rothkaehl H, Klein K L, Labrenz J. Observations of the solar current sheet. *Astronomy & Astrophysics*, 2017, 601: A72.
- [7] Bird M K, Vourlidas A, Howard R A, Socker D G. Observations of suprathermal electrons in the solar wind. *Space Science Reviews*, 2013, 175(1-4): 25-59.
- [8] Gosling J T. Solar Wind Studies: Observations and Theory. *Space Science Reviews*, 2013, 78(1-2): 277-309.
- [9] McComas D J. The Ulysses solar wind plasma experiment. *Astronomy and Astrophysics Supplement Series*, 2000, 141(1): 277-310.
- [10] Kivelson M G, Russell C T. *Introduction to Space Physics* (1st ed.). Cambridge University Press, 1995.
- [11] Gopalswamy N, Nitta N V, Akiyama S, Mäkelä P A, Xie H, Yashiro S, Michalek G. Geoeffectiveness of solar transients and quiet-time solar wind. *Space Weather*, 2020, 18(1): e2019SW002379.
- [12] He J, Tu C. Heating and acceleration of the solar wind. *Chinese Science:Earth Sciences*, 2013, 43(06): 990-1001.
- [13] Smith E J. The solar and heliospheric observatory (SOHO). *Space Science Reviews*, 2008, 136(1-4): 67-115.
- [14] Bertaux J L. SWAN: A study of solar wind anisotropies on SOHO with Lyman-alpha sky mapping. *Solar Physics*, 1995, 162(1-2): 403-424.
- [15] Delaboudinière J P. EIT: Extreme-ultraviolet imaging telescope for the SOHO mission. *Solar Physics*, 1995, 162(1-2): 291-312.
- [16] Stone E C. The advanced composition explorer. *Space Science Reviews*, 1998, 86(1-4): 1-22.
- [17] McComas D J. The solar wind electron, proton, and alpha monitor on the advanced composition explorer. *Space Science Reviews*, 1998, 86(1-4): 563-612.
- [18] Zurbuchen T H. The solar wind ion composition spectrometer. *Space Science Reviews*, 1998, 86(1-4): 257-290.
- [19] Ogilvie K W. Wind spacecraft and experiments. *Space Science Reviews*, 71(1-4), 55-77.

- [20] Lepping R P. The Wind magnetic field investigation. *Space Science Reviews*, 1995, 71(1-4): 207-229.
- [21] Lin R P. A three-dimensional plasma and energetic particle investigation for the wind spacecraft. *Space Science Reviews*, 1995, 71(1-4): 125-153.
- [22] Richardson I G, Cane H V. Near-Earth interplanetary coronal mass ejections during solar cycle 23 (1996–2009): Catalog and summary of properties. *Solar Physics*, 2010, 264(1): 189-237.
- [23] Foster J C. Effects of the January 1997 solar particle event on the ionosphere D region. *Journal of Geophysical Research: Space Physics*, 2005, 110(A2).
- [24] Prikryl P, Rušin V, Prikryl E A, et al. Heavy rainfall, floods, and flash floods influenced by high-speed solar wind coupling to the magnetosphere–ionosphere–atmosphere system, *Ann. Geophys.*, 2019, 39: 769–793.