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"Exploring the Solar-Cosmic Ray Connection: A Review of the Influence of Solar Parameters on Cosmic Ray Flux During Solar Cycles 23 and 24"

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ABSTRACT

The interplay between solar activity and cosmic ray flux is a complex phenomenon with profound implications for Earth's atmosphere, space weather, and climate. This review explores the influence of solar parameters on galactic cosmic ray (GCR) flux during Solar Cycles 23 and 24, highlighting the unique characteristics of each cycle. Solar Cycle 23 exhibited moderate activity, while Cycle 24 was marked by an unusually prolonged and weak solar minimum, resulting in record-high GCR flux and diminished geomagnetic activity. Variations in solar parameters, such as sunspot number, solar wind, and magnetic field dynamics, directly modulate GCR flux, creating an inverse relationship between solar activity and cosmic ray intensity. Furthermore, the impact of these changes extends to atmospheric ionization, cloud formation, and potential climate modulation. Observations of ephemeral magnetic regions, geomagnetic indices, and heliospheric dynamics provide deeper insights into the solar-cosmic ray connection, offering a framework to assess the broader implications of solar variability on Earth's environment during these solar cycles.

Key words- *galactic cosmic ray, Solar Cycle 23, Solar Cycle 24, coronal mass ejections, Solar activity*

INTRODUCTION

The 11-year cycle of rising and falling solar activity has a significant impact on modern living. Increases in the Sun's severe ultraviolet and X-ray emissions, which have a profound impact on Earth's upper atmosphere, are a sign of increased solar activity. At various spacecraft altitudes, the related atmospheric heating raises the atmosphere's temperature and density. The orbital lifespan of these precious assets can be significantly shortened by the rise in atmospheric drag on satellites in low Earth orbit (for a review, Pulkkinen, 2007). As the frequency of solar flares and coronal mass ejections (CMEs) increases, there is a greater chance that energetic particles accelerated in these events can harm sensitive instruments in space. These solar energetic particles (SEPs) can also pose a health risk to airline passengers flying high-altitude, polar routes as well as astronauts in space. The climate on Earth appears to be impacted by solar activity as well. There is strong evidence that, to some extent, the Earth's temperature warms and cools in response to variations in solar activity, even if the change in total solar irradiance appears to be too tiny to have a major impact on the climate (for a summary, Haigh, 2007). Without a doubt, the solar cycle is magnetic in nature and is created by the Sun's dynamo processes (Charbonneau, 2010 for a summary of the solar dynamo). they days, people frequently discuss solar variability, cosmic rays, and how they affect the Earth's climate, but their comprehension of the quantitative and qualitative consequences is still quite complicated and unexplained (Reid, 2000; Gray et al., 2010; Usoskin, 2012). The evolution of the magnetic field in the solar convection zone and solar evolution driven by conditions inside the Sun are the causes of solar variability. Numerous phenomena that have been observed at and above the solar surface, including sunspots, coronal mass ejections and flares, active regions, small flux tubes, and sunspots, show up as violent fluctuations in the spectral distribution, the total power of broadband electromagnetic emissions, the solar wind, and the fluxes of energetic particles and ultraviolet (UV) emission lines (Frohlich, 2006).

As a result, the Sun's electromagnetic radiation likewise rises and falls in a cycle that corresponds to the sunspot count's 11-year cycle. Remarkably, the Sun's visible light emissions barely change during this cycle; the Sun's brightness and dimness in the visible light spectrum only differ by roughly 0.1% (Wilson and Hudson, 1991; Weart, 2006). Out of the 1,368 W/m2 that reach the top of Earth's atmosphere, this translates to a shift in solar insolation of 1 or 2 W/m2 at Earth (Willson and Mordinov, 2003).

COSMIC RAYS

The solar cycle modulates the galactic cosmic ray flux at 1 AU. Electrons and bare nuclei are the building blocks of galactic cosmic rays, which are accelerated to GeV energy and beyond after supernova shocks. Neutron monitors at high-altitude observation locations can measure the cascading particle showers produced by the positively charged nuclei in Earth's upper atmosphere. Climax, Colorado, in the United States, is home to the oldest neutron monitor still in continuous operation. The period of daily observations is 1951–2006. Together with the sunspot number, monthly averages of the neutron counts are displayed as a function of time. Neutron counts decrease as sunspot numbers increase.

The heliosphere's braided magnetic field is thought to be the cause of this anti-correlation (Parker, 1965). Magnetic structures are transported outward on the solar wind during periods of intense solar activity. Incoming cosmic rays are dispersed by these structures, which lowers their flux within the inner solar system.

There has never been a solar cycle minimum like the one that resulted from the lengthy, unanticipated delay at the beginning of cycle 24. The 13-month averaged sunspot number fell to 1.7 in December 2008, the lowest since July 1913, but the smoothed number of spotless days in a month at its highest since August 1913. The galactic cosmic ray flux hit record highs (since 1953) in September 2009, but the geomagnetic aa-index fell to its lowest value ever recorded. Since then, cycle 24 has gradually increased through one peak and then another, reaching its highest smoothed sunspot number of 81.9 in April 2014. Although this behavior is out of the ordinary given living memory, it is well within the range of typical solar cycle behavior. We have observed that small cycles have a low minimum and a long cycle because they begin late (the Maximum-Minimum Effect). Additionally, it takes longer for little cycles to reach their maximum. An amplitude of around 82 for cycle 24 indicates a timeframe of 150 months for cycle 23 (147 months observed); a minimum of 0.3 for cycle 23/24 minimum (1.7 observed); and a rising time from minimum to maximum of 56 months (63 observed) in comparison to previous cycle behavior.

SOLAR ACTIVITY

Solar Activity and Solar Variability

Solar activity can signify various things. It might allude to phenomena like coronal mass ejection and solar proton events, or it can show the intensity of solar electromagnetic radiation, which is especially noticeable at wavelengths of solar x-rays and the extreme ultraviolet. The dramatic rise in temperature above the solar photosphere is caused by a wide variety of non-thermal phenomena found in the solar atmosphere, which are referred to as activity. It creates a range of distinct features at the local level, such as the complex structures of the solar corona, the emission plages and network of the chromospheres, and the black sunspots and bright faculae of the photosphere (Radick, 2004). Through the solar wind, a mixture of ions and electrons that flows away from the Sun, these changes on the solar surface and interior remotely control the Earth's atmosphere in a number of ways and on a wide range of time scales. In actuality, the Sun's outer atmosphere is so hot that it constantly evaporates despite the Sun's gravity. The solar magnetic field is carried by the departing plasma (Parker, 1957) all the way to the heliosphere's edge, when its dominance in interstellar space eventually terminates (Schwenn, 2006a, b).

Solar flares, Coronal Mass Ejections (CMEs), and their temporal and spatial recurrence are also considered manifestations of solar activity (Singh and Singh, 2003; Singh et al., 2010; Siingh et al., 2011). Only from above the Earth's atmosphere can precise radiometric measurements of the total amount of heat, light, and other radiation received from the Sun be made. A number of specialized equipment on various solar spacecraft have been maintaining this technically demanding work since it was first started on an ongoing basis in 1978.

Solar Variability and Galactic Cosmic Rays

Galactic cosmic rays (GCRs) are powerful charged particles that primarily originate outside of the solar system and flow to the Earth's atmosphere via the Milky Way galaxy. Simple protons make up around 89% of all incoming cosmic ray particles. Solar Variability, Galactic Cosmic Rays, and Climate: A Review About 1% of galactic cosmic rays (GCRs) are electrons (beta particles), with slightly less than 1% being heavier elements and approximately 10% being helium nuclei (alpha particles) (Singh et al. 22) (Mewaldt, 2010). The atmosphere is penetrated by solar protons and incoming galactic cosmic rays. One crucial factor is the energy content of GCRs. According to Wolfendale (1973), the energy densities at the Earth's surface above the energies shown are ~0.05, ~0.03, 3 x 10-3, 10-4, and 10-6 in units of Jm-3. According to Erlykin and Wolfendale (2010), the total solar irradiation is approximately 108 times higher than that of the entire GCR. According to Gray et al. (2010), the GCR flux measured in the Earth's atmosphere shows modulation of various periodicities and fluctuation in solar activity, particularly solar electromagnetic radiation, which has a long-term impact on the climate.

Since the Sun's eruptional properties greatly influence cosmic rays, which positively affect cloud cover, the solar contribution to climate change can no longer be regarded as insignificant. Another physical explanation for the impact is that the cosmic rays' secondary ions act as condensation nuclei with hygroscopic qualities, which promote cloud formation (Tinsley and Yu, 2003; Siingh and Singh, 2010). The indirect impact of the sun on the flux of Galactic Cosmic Rays (GCRs) entering the atmosphere is a significant component of its climate-influencing influence. Low cloud formation is supported by GCR, an ionizing radiation. The solar wind protects the atmosphere from GCR flux when the Sun's power rises. As a result, the climatic effect is enhanced by the decreased low cloud cover that coincides with the increased sun irradiation. Similarly, more GCR flux enters the atmosphere as solar output decreases, increasing low cloudiness and intensifying the chilling impact brought on by the decreased solar energy.

MAGNETIC FIELD

Sunspot measurements were the first to be made of the Sun's magnetic fields. Once these data spanned more than one cycle, it became clear that the solar cycle was magnetic. Even while it is now widely acknowledged that the magnetic field itself provides the greatest representation of the solar cycle, systematic daily observations have only been available since the 1970s, and they only describe the last three and a half solar cycles. However, several salient features were evident from the initial observations.

Since the middle of the 1970s, the Wilcox Solar Observatory at Stanford University has been measuring the polar fields virtually every day (Scherrer et al., 1977). Early in the 1970s, Kitt Peak National Observatory began conducting systematic, high-resolution, daily studies of the Sun's magnetic field over the visible solar disk. From early 1975 to mid-2003, synoptic maps derived from these observations are almost continuous. Similar (and even better resolution) data were later made accessible by the Synoptic Optical Long-term Investigations of the Sun (SOLIS) facility of the National Solar Observatory (NSO) (Keller, 1998). Data from the Michelson Doppler Imager (MDI) on the Solar and Heliospheric Observatory (SOHO) mission can be used to fill in the gaps between these two datasets as well as within the SOLIS dataset (Scherrer et al., 1995).

EPHEMERAL REGIONS

Small (less than 30 mm across) bipolar magnetic areas known as ephemeral regions are usually only visible for a day or two and do not frequently result in sunspot formation. According to Parnell et al. (2009), they expand the range of the bipolar active zones that normally do produce sunspots to smaller sizes. They were initially described in relation to a small, Up to 100 ephemeral zones may erupt daily with as much total magnetic flux as erupts in the bigger active regions, according to Harvey and Martin's (1973) analysis of magnetograms and Hα pictures taken during three 4-day intervals in 1970 and 1971 (after the peak of cycle 20). Additionally, they pointed out that the latitude distribution was wider than that of the active zones and proposed that the sunspot cycle had no bearing on the occurrence of ephemeral regions. However, a direct solar cycle dependence was later discovered by Harvey et al. (1975) in a bigger study that included the years 1970 to 1973. Additionally, they discovered that although the spatial orientation was nearly random, there was a slight overabundance of novel cycle orientations at the high latitudes in 1973.

These early ground-based magnetograph studies were challenging due to the small sizes and brief lifetimes of ephemeral areas. The introduction of space-based magnetographs significantly eased this issue. Using the SOHO/MDI instrument, Hagenaar (2001) investigated the characteristics of ephemeral areas and discovered a significantly higher number of (smaller) ephemeral regions that had an emergence rate fast enough to replace the quiescent Sun magnetic field in just 14 hours.

The frequency of small ephemeral zones varied in anti-phase with the sunspot cycle, according to Hagenaar et al. (2003), who expanded their data to encompass the climb from cycle minimum in 1996 to maximum in 2001. Subsequent research revealed that unipolar regions (coronal holes) have less ephemeral regions (Abramenko et al., 2006; Hagenaar et al., 2008). Since more unipolar patches are detected at cycle maximum in the examined area (within 60 of the disc center), this could help to explain part of the cycle dependence.

GEOMAGNETIC ACTIVITY

The solar cycle dependency of geomagnetic activity is more intricate than that of sunspot area, radio flux, flares, and CMEs. Numerous geomagnetic activity indices exist; the majority use modest networks of ground-based observatories to measure quick (hour-to-hour) variations in the Earth's magnetic field's strength and/or direction. Measured at three-hour intervals from a network of roughly 13 high-latitude stations, the ap index represents the range of fluctuation in the geomagnetic field (in 2 nT units). The corresponding daily amplitude Ap is the mean of the eight daily ap readings. From 1932 to the present, these indices cover the years. Similarly generated from three-hour intervals, but from two antipodal stations situated at latitudes of around 50°, the aa index goes back further (to 1868; Mayaud, 1972). There is evidence that the data itself reflects the periodic changes in the positions of these two stations (Svalgaard et al., 2004). Disturbance storm time, or Dst, is another commonly used statistic that has been constructed from measurements made at four equatorial locations since 1957.

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