The Response of the Ionosphere and Magnetosphere to Solar Wind Variability During 2002-2010

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ABSTRACT

Understanding the Sun's processes and how they affect the Earth allows us to better understand climate change, main sequence stars, and aids in the understanding and prediction of space weather. The need for accurate space weather forecasting increases as our dependence on satellite communication and electric power grids grows. This work examines magnetospheric and ionospheric response to solar wind drivers during solar cycles 23 and 24 (years 2002 - 2010). To date, no studies on Sun-Earth coupling during this period have considered both ionospheric and magnetospheric response to various solar drivers. In this study several satellite data sets were used to examine solar parameters, relativistic and energetic electrons, nitric oxide (NO) infrared radiation and auroral power (A_p). Yearly time series, correlations, and trends in periodicities were examined for the entire period. Active years (2002 and 2003) and inactive years (2008 and 2009) were contrasted in attempts to develop an understanding of the underlying physical processes and relationships among solar, magnetospheric, and ionospheric parameters. Relativistic and energetic particles had the highest correlation with solar wind speed in general, especially during the extended solar minimum when high speed streams (HSS) were present (2008). Periodicity analysis showed dominance of the 27-day solar rotational period for the declining phase of cycle 23, and more prominent 7, 9 and 13.5-day periodicities for the solar minimum. These findings support previous work, and combine two areas of research to reveal a more complete view of Sun-Earth dynamics over this time period.

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1. Introduction

Solar activity, and in particular solar wind variability, directly affects the earth by inducing fluctuations of charged particles in geospace. High flux and high energy particle streams can disrupt satellite operations, communication and navigation systems, and damage power grids which may result in power outages. It is therefore extremely important to improve our ability to accurately forecast space weather so that precautionary measures (such as reducing power grid loads) can be taken to safeguard against potential risks during geomagnetic storms. Identifying problematic solar conditions can be challenging. The sun, with its complicated magnetic field configuration, differential rotation, and complex transient processes, is still being researched extensively.

The solar wind varies during each solar cycle according to physical processes that occur in the Sun, but no two cycles or phases are identical. Solar cycles are defined by sunspot number (SSN), which are associated with active regions on the Sun. However, Gibson et al., [2009] showed that SSNs are not always a good indicator of magnetic activity and structure of the Sun. New research shows that solar wind speeds and the direction of the Interplanetary Magnetic Field (IMF) may be a better indicator of magnetic activity and solar structure. Solar wind high speed streams (HSS) can come from either coronal mass ejections (CMEs), solar flares, or from coronal holes (CHs). HSS from CMEs and solar flares are associated with active regions in the Sun which tend to occur at solar maxima and the early declining phase of the solar cycle, while CH HSS tend to occur near the solar minima. HSS interaction with the magnetosphere has been shown to significantly alter the Earth’s atmospheric chemical and particle composition and affect auroral power [Li et al., 2011; Lei et al., 2008; Reeves et al., 2010; Emery et al., 2011] by altering geomagnetic activity. As such, even at solar minima and during declining phases of each solar cycle, the Sun’s processes can have a significant impact on Earth.

CHs exhibit open magnetic field lines (Figure ??) which give rise to HSS that carry lower density ionized plasma to the earth. Two sorts of coronal holes exist: polar and low latitude, with the former the most prominent at solar minimums and the latter occurring during the declining phase of the solar cycle [Lei et al., 2008]. Solar minimum and declining phase polar coronal holes can extend toward the solar equator, and emit HSS [Reeves, et al., 2011, Lei et al., 2010] with typical speeds of 500-800 km s$^{-1}$ [Lei et al., 2008]. Low-latitude CHs also cause HSS that affect the earth [Emery et al., 2011, Gibson et al., 2009, Gibson et al., 20011].
Solar wind speed affects the rate at which the solar wind impacts Earth’s Magnetosphere which in turn affects the density and energy of charged particles in the ionosphere and magnetosphere. The IMF is essentially the Sun’s magnetic field orientation carried by the solar wind which determines how extensively solar winds will affect the Earth. Li et al., [2011] found a nonlinear relationship between the log of energetic [MeV] electron flux and solar wind speed. The relationship is complex, and in addition to solar wind speed, the southward component of the IMF enhances energetic electron flux. Relativistic electrons (>1MeV) are also affected by solar wind velocity, though a non-linear correlation was found showing a velocity dependent lower limit and velocity independent upper limit on flux [Reeves et al., 2011]. In addition to relativistic electron flux, CO and NO infrared emissions [Mlynczak et al., 2008], as well as thermospheric neutral densities [Lei et al., 2008] are also related to solar wind speed.

This work examines solar wind variability and its effects on the magnetosphere and ionosphere during solar cycles 23 and 24 (years 2002-2010). The solar minimum of cycle 24 was compared to the early declining phase of cycle 23 in order to better understand and validate recent studies on Sun-Earth coupling processes and ultimately to improve our understanding of space weather and ability to forecast geomagnetic storms. Though studies have been done with regard to the effects of high speed solar winds emanating from CHs on the earth during solar minima, none have yet included both magnetospheric and ionospheric effects from multiple sources. Ionospheric and magnetospheric parameters such as NO infrared radiometry, energetic electron flux, and auroral power ($A_p$) are considered, and correlations among these parameters in relation to solar wind velocity ($V_{sw}$), IMF, Interplanetary Electric Field (IEF), and geomagnetic ($K_p$) index are analyzed.

2. Methods and Procedure

To determine the effect of solar wind variability on the magnetosphere and ionosphere, several data sets from multiple satellites were used including measurements from NOAA’s Geostationary Operational Environmental Satellites (GOES) and Polar Orbiting Environmental Satellites (POES) in addition to the Sounding Acoustic Broadband Emission and Radiometry (SABER) instrument on-board NASA’s Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, and the Advanced Composition Explorer (ACE).
In this study, GOES and POES electron flux data were used. The Medium Energy Proton Electron Detector (MEPED), Total Energy Detector (TED), and two Space Environment Monitors (SEMs) on-board NOAA’s POES satellite detect charged particles with energies between 20 eV and 1 MeV. The GOES satellite contains an Energetic Particle Sensor (EPS) that measures protons, electrons and alpha particles with relativistic energies \( \geq 0.6 \text{ MeV} \). For this study, data from the \( \geq 2 \text{ MeV} \) channel were used.

ACE measures solar wind parameters and solar energetic particles. Solar wind and IMF data from ACE were used. SABER is a passive acoustic monitoring instrument that observes atmospheric infrared backscatter over a broad altitude and spectral range. It measures the vertical distribution of gases by observing solar radiation and emission of infrared heat. For this work, SABER NO infrared emission data were used for the nine-year period 2002-2010. Geomagnetic index (\( K_p \)) data were taken from mid-latitude ground magnetometers.

Yearly time series plots for 2002-2010 were made for \( V_{sw} \), \( K_p \) index, NO infrared and auroral power, and daily integrated values for POES and GOES electron flux. Linear regression was used to find correlation coefficients between \( A_p \), GOES and POES electron flux, versus VBz, IEF and two solar coupling functions. A time delay for GOES electrons was taken into account because geosynchronous electron flux has a delay of up to several days after a HSS, CME or other flux-inducing event [Reeves et al., 2011]. The two coupling functions that were chosen to test were \( \frac{d\Phi}{dt} \) and \( \epsilon \) [Newell, et al, 2008]. These two functions are dependent on the magnetic field of the Sun, \( V_{sw} \), and the IMF clock angle, \( \theta \), and are given by the following equations:

\[
\frac{d\Phi_{MP}}{dt} = V_{sw} B_T^2 \sin^2 \left( \frac{\theta_c}{2} \right) \tag{1}
\]

\[
\epsilon = V_{sw} B_T^2 \sin \left( \frac{\theta}{2} \right) \tag{2}
\]

with \( \frac{d\Phi_{MP}}{dt} \) being the best predictor of magnetospheric response found by Newell et al. [2007], and referred to hereafter as the Newell coupling function.

Lomb-Scargle spectral periodograms were also made for each year to determine trends in periodicity. 2003 and 2008 were chosen for closer examination. 2003 saw a large amount of solar activity including several X-class solar flares (during the Halloween Storms). 2008, on the other hand, occurred during the long solar minimum of solar cycle 24. Despite solar minimum conditions, there were still HSS present in 2008 so this year was chosen to observe effects of HSS resulting from CH. Carrington maps with ballistic mapping were made to validate assumptions of the anatomy of the sun during two Carrington Rotations (CRs) in the year 2003 (CRs 2009 and 2010) and one CR in the year 2008 (CR 2068).

3. Results

While examining time series plots, correlation coefficients, and periodograms, aspects related to the phase of the Sun during each year were considered. For example, we know that during solar active periods and into declining phases of the solar cycle there are active regions and some CHs, while during quiet times and the extended solar minimum we expect to see mostly CH activity [Gibson et al., 2009]. These assumptions are validated with synoptic maps, shown in Figures 2, ??, and ?? and were considered when analyzing solar, ionospheric and magnetospheric parameters and their relationships. Figures 2, and ?? show CRs 2009, 2010, and 2008. CR 2009 and CR 2010 occurred during October and November 2003 respectively. The missing data in CR 2009 indicates the point at which ACE instrumentation malfunctioned due to the large geomagnetic storms that occurred during this time. It is evident that many of the streams emanate from bright (active) regions on the Sun’s surface. There are also HSS evident in CR 2009 and CR 2010 that appear to be coming from equatorial CHs (CHs are shown as the darker regions on the map). In CR 2068 it appears that most of the HSS are coming from borders of CHs. Because the CHs are more spread out it is a bit more difficult to decipher the origin of the HSS, but we know CHs dominate HSS during minimum conditions represented in CR 2068. Note the very few active sites on the Sun’s surface, especially when compared to the synoptic maps for the early declining phase of cycle 23 in 2003 (CRs 2009 and 2010).
Fig. 2. Synoptic map with overlaid ballistic mapping of for CR2009. The black line represents the projection of the ACE satellite’s position on the Sun, which measures charged particles velocity and direction. That information was then used to trace particles back to the surface of the Sun. Colored lines indicate the trace back from the measurement location (ACE) and the dots show the footprint of the approximate location where the particle came from. The dashed blue line represents the heliospheric current sheet—the location where the polarity of the Sun changes. The red line at the top of the plot indicates where the polarity is negative and the blue where the polarity is positive.

Fig. 3. Similar synoptic map of $V_{sw}$ for CR2010.
Fig. 4. Synoptic map of $V_{sw}$ for CR2068.

a. Time Series

Yearly time series plots were made for 2002-2010 for solar wind speed, $K_p$, auroral and NO power, and GOES and POES electron flux. Solar wind speed showed tremendous variation throughout the 8-year period and time series plots demonstrated such variability for each phase of the cycle. High velocities were more apparent in the declining phase of the solar cycle (years 2002-2007) than throughout the solar minimum and into the ascending phase of solar cycle 24. Figures ?? and ?? illustrate the differences in $V_{sw}$ characteristics nicely. HSS were evident in the early declining phase (years 2002 and 2003), when SSNs were highest. When SSNs are lower there are still HSS present, but they diminish as the sun moves into the extended minimum (2008-2009).

$A_p$ and NO Power exhibited similar characteristics with power increasing in 2003 and staying elevated through 2005 and into 2006. The average values for NO power during the declining phase were around 250 GW in 2003 with peaks over 1000 GW, while $A_p$ showed a yearly average of about 50 GW and peaks up to 230 GW in 2008. GOES electrons increase from 2002-2005 then decrease significantly in 2007 as the Sun approaches its minimum. POES electrons showed similar behavior, with significant decline halfway through 2008. To illustrate these parameters at different periods of the solar cycle, figures ?? and ?? are shown.

Relativistic and energetic electrons (shown in the bottom panel of figures ?? and ??) showed the least contrast for the selected years. Both electron fluxes showed smaller values in general for 2008, but especially for the energetic POES electron flux. Relativistic electron flux showed similar values to 2003 in 2008 until about halfway through the year when their flux fell significantly and continued to do so into 2009 through the remainder of the solar minimum. POES energetic electron flux showed significant increase in 2003, and thus POES electron flux was larger than the GOES relativistic electron flux.
Fig. 5. From top to bottom panel: Daily solar wind speed values, Kp, NO infrared power and Ap, and POES and GOES energetic electron flux are plotted for 2003. Note the top panel $V_{sw}$ plot with high speed streams (HSS) shown in red and low speed streams (blue).
Fig. 6. From top to bottom panel: Daily solar wind speed values, $K_p$, NO infrared power and $A_p$, and POES and GOES energetic electron flux are plotted for 2008. Note the top panel $V_{sw}$ plot with high speed streams (HSS) shown in red and low speed streams (blue).

$K_p$ index time series showed highest values in the declining phase of solar cycle 23, around 2004 and 2005 (not shown). Shown here for consistency and contrast in figures ?? and ?? is 2003 (again, during the
early declining phase of cycle 23) and 2008. The Kp index rises to nearly 10 and averages around 3.5 in 2003, while in 2008 there are peaks of at most 6 and the average is lower, at around 2.

b. Correlation

Studying correlations allow us to better understand the relationships among the Sun and Earth parameters. Figures 7 - 10 show correlations between A_p, NO infrared power, POES and GOES electron flux and solar parameters V_sw, V_Bz, IEF, and the two coupling functions ε and Newell for 2002-2010. A_p showed highest correlation with the IEF, and also has fairly high correlation with the coupling function ε except during 2003 when the Sun had several violent solar flares. NO infrared power, as seen in figure 7 showed similar correlations, with the IEF being the highest and the coupling function ε a close second, having an average correlation coefficient of 0.733 over the duration of the study and continuously high correlation coefficient values except in 2006 when the correlation dropped to 0.46.

![Auroral Power Correlations for 2002–2010](image)

**Fig. 7.** A_p correlated with V_sw, V_Bz, IEF, and two coupling functions ∂ϕ/∂t (Newell), and ε for 2002-2010.
POES electron flux (Figure ??) showed a more complex relationship with solar parameters than $A_p$ and NO infrared power. Highest correlation was observed between POES electron flux and $V_{sw}$ with an average coefficient of 0.71 for the time period. There was also high correlation for POES flux with the Newell coupling function, with an average coefficient of 0.67, and also with the IEF and $\epsilon$, except during 2003 when both coefficients were very low. GOES electron flux (Figure ??) showed high correlation with $V_{sw}$ and also a high correlation with the Newell coupling function $\frac{d\phi}{dt}$, and unlike POES electron flux did not show high correlation with the IEF or $\epsilon$. 

**Fig. 8.** NO infrared correlated with $V_{sw}$, $V_{Bz}$, IEF, and two coupling functions $\frac{d\phi}{dt}$ (Newell), and $\epsilon$ for 2002-2010.
Fig. 9. POES energetic electron flux correlated with $V_{sw}$, $V_{Bz}$, IEF, and two coupling functions $\frac{d\phi}{dt}$ (Newell), and $\epsilon$ for 2002-2010.
To summarize, the highest correlations between $A_p$, NO infrared power, GOES and POES electrons and $V_{sw}$, $V_B$, IEF and the $\epsilon$ and Newell functions are shown in figure 10. NO infrared power was found to have a strong correlation with the IEF especially during the declining phase of cycle 23 (2002-2005). $A_p$ also showed high correlation with the IEF, with lower coefficient values until the later half of the declining phase of cycle 23, and had highest correlation coefficients with IEF in 2008. Figure 10 shows highest correlations for NO infrared and auroral power, and energetic electron flux. The highest correlation pairs of all examined parameters are shown.
Fig. 11. Correlation coefficients between magnetospheric and ionospheric parameters, (Auroral Power (Ap), NO Power, energetic electrons (POES) flux, and relativistic electrons (GOES) flux), and solar parameters $V_{sw}$, $V_{Bz}$, IEF, and two coupling functions: the Newell coupling function, and $\epsilon$ were calculated. This plot shows the highest correlations among these parameters for 2002-2010.

c. Periodicity

Figures 12, 13, and 14 show Lomb-Scargle Periodograms for the $B_y$ and $B_z$ components of the IMF, $B_T$, $V_{sw}$, IEF, $K_p$, $A_p$, NO infrared power, and GOES and POES electron flux for 2003, 2005 and 2008. Three years are shown here to illustrate the changes in periodicity from the descending into the minimum phases of the solar cycle. In 2003, periodograms showed dominance of the 27-day solar rotational period, and random counts in the periodogram. During this phase in the solar cycle there were many solar flares and CMEs occurring, and these are one-time events. They occur, the effects are received by the Earth through solar wind and then they disappear. This explains the random counts in the spectrogram and the prominence of the 27-day solar rotation period. We see this smooth out in 2005 then return in 2008 along with higher 9 and 13.5 day periodicities. In 2008, coronal holes dominate solar activity, and these features persist for several rotations. Thus their effects are seen periodically and predictably as prominent 9, 13.5 and 27-day periodicities.
**Fig. 12.** Lomb-Scargle Periodograms for 2003.

**Fig. 13.** Lomb-Scargle Periodograms for 2005.
4. Discussion and Conclusions

This work reaffirms previous work on magnetospheric and ionospheric response to solar wind speeds. High correlation coefficients between both energetic and relativistic electron flux with solar wind velocities were demonstrated as in Paulikas and Blake [1979], and its follow up paper by Reeves et al. [2011] which found that while relativistic electron flux shows a $V_{sw}$ dependence, the relationship is complex. In this study, the correlation between relativistic electron flux and solar wind speed also confirmed this complex dependence in analyzing correlations, which were highest during 2008 when CH activity dominated. Similar correlation was seen for energetic electron flux. Additionally, time series plots showed significantly lower NO infrared power as we head into solar cycle 24 and the extended minimum, which supports the recent work by Mlynczak et al. [2011].

It would be beneficial to study these correlations over a full cycle. SABER was launched in 2002 on-board TIMED. As such, there is not yet a full cycle of data available for analysis, but in the future additional analysis including a full cycle should be considered for a more complete view of the solar influence on geospace. This would lend itself to a more complete look at the Sun-Earth relationship. Solar cycle 24 exhibited a deep solar minimum, the quietest the sun has been in almost a century. Thus, it would also be beneficial to observe the next minimum. The more we know about the Sun and how it affects the Earth, the more we can relate that information to space weather and continue build a solid knowledge base about our planet and its processes.
References


