Influence of Solar Activity Cycles on Earth's Climate

ESA ITT AO/1-4618/NL/AR

Task 1 – Literary Survey on Sun-Earth Connections

WP 101 – Solar Variability

Technical Note

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January 28, 2005

Document status sheet

ISSUE	REVISION	DATE	REASON FOR CHANGE
0	0	January 7, 2005	First draft.
0	1	January 28, 2005	New front page, figures 1-4 included,
			section 3.1 extended.

Summary

Solar variability originates from the solar interior. One aspect of solar variability is linked to solar evolution driven by nuclear conditions in the core. This is a relatively slow process with changes on time-scales of the order of several million years and above for parameters such as mass, radius, and luminosity. Another aspect of solar variability is related to solar magnetic fields generated below the convective zone in the Sun's interior. The evolution of magnetic fields results in many manifestations, on time-scales in the range of hours to several hundred years, such as the well-known sunspot cycle and its longer-period modulations, solar wind structures, and coronal mass ejections. A third aspect of solar variability deals with periodicities due to orbital conditions such as solar rotation, changes in Earth's orbit, or inclination of rotational axis with respect to the ecliptic plane. A summary of different kinds of solar variability with their corresponding operational time-scale and observational parameters is presented in Table 2.

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1 Introduction

Our Sun is a G2 star currently on the main sequence in its stellar evolutionary track, where it will reside for a few billion years to come. A dynamo action located below the convective layer in the solar interior is generating a magnetic field. This field is further affected by differential rotation and turbulent convection, responsible for the structure and evolution of the resulting surface magnetic field, resulting in prominent features such as sunspots, plages, filaments, flares, and coronal mass ejections. A small fraction of the magnetic field is driven out into the heliosphere together with atmospheric particles becoming the solar wind with its imbedded interplanetary magnetic field. The most well-known period of solar variability is the 11-year solar cycle with its characteristic periods of low and high solar activity. Most solar activity phenomena follow this 11-year cycle as a modulation of variations occurring on shorter time-scales, probably below the temporal resolution of the most refined instruments operational today. There are also modulations of the 11-year solar cycle that probably are related to the solar dynamo, resulting in cycles with above average solar activity or extended periods with below average solar activity.

A literary survey has been carried out, locating reports on periodicities in solar activity and indicators of the periodicities. The time-scale of solar activity variabilities has been divided into long-term changes, intermediate-term changes, and short-term changes. A section has also been included summarizing the observational techniques used to observe the different solar activity phenomena. A compilation of all references presented in this report is stored at the Swedish Institute of Space Physics.

2 Solar Variability

2.1 Definition

Solar variability, as we experience it, can be of two kinds: intrinsic variability such as the solar sunspot cycle or variations as a result of changes in orbital parameters such as the Earth's solar orbit. Furthermore, we divide solar variability into three classes according to the underlying nature of the variation and its typical time-scale. The Sun experiences long-term changes due to its evolution as a star with changes in fundamental parameters such as luminosity, mass, and radius. The Earth's rotational axis and elliptical orbit around the Sun undergoes slow variations changing the conditions for a solar-terrestrial interaction. Time-scales for these orbital changes and for the solar evolutionary changes are of the order of several thousand years or more and will be included in the first class. The second class of solar variability is concerned with effects directly causing or resulting from the solar dynamo originating below the convective layer (*Schüssler*, 2002). Typical time-scales range from about one year to multiples of the solar cycle period. The final class can be categorized as changes due to a relatively short-lived surface and heliospheric phenomena with time-scales ranging from hours up to several months.

2.2 Indicators

There are several different kinds of indicators of solar variability (see *Rabin et al.*, 1991). One deals with the radiant energy from the Sun such as high-energetic X-rays, gamma-rays, or radio flux emitted from the solar corona, total solar irradiance which is a measure of the total radiant power received by the Earth, or UV-radiation originating from the chromosphere and upper photosphere. Another indicator of solar variability is solar surface phenomena. Examples in this category are sunspots, faculae, and plages, with the former being the most commonly used with several derivatives like the sunspot number, the group sunspot number, and the sunspot area index.

There are also non-solar phenomena that are modulated by the Sun such as the galactic cosmic ray intensity modulated by the interplanetary magnetic field or the subsequent modulation of cosmogenic isotopes stored in the biomass of trees or in ice cores. Particles and electromagnetic fields that are able to directly interact with the Earth's environment are another class of solar variability indicator. Examples are the solar wind with its accompanying interplanetary magnetic field, solar energetic particle events, and interplanetary coronal mass ejections.

Below is a short list of the indicators described above. A more extensive description of solar activity indicators relevant for this study will be presented in WP 201 of Task 2.

2.3 Long-term changes

The Sun is presently on the main sequence in its evolutionary track, burning hydrogen in its core, with very small changes in luminosity, radius, or mass. In approximately 1.1 Gyr from now, a

Radiant energy
Total irradiance
X-rays and gamma–rays
UV-radiation
Radio flux
Surface phenomena
Sunspot number
Group sunspot number
Sunspot area index
Interplanetary phenomena
Solar wind
Coronal mass ejections
Solar energetic particle events
Solar flares
Solar modulations
Galactic cosmic ray intensity
Cosmogenic isotopes

Table 1: A brief summary of solar activity indicators found in the literature.

solar luminosity increase from its present 1.0 $L_\odot$ to 1.1 $L_\odot$ will cause a moist greenhouse effect on Earth with water vapor circulating higher up in the atmosphere (*Kasting*, 1988). After an additional 2.4 Gyr, the luminosity will reach 1.4 $L_\odot$ (*Sackmann et al.*, 1993) resulting in a runaway greenhouse effect with total evaporation of the terrestrial oceans (*Kasting*, 1988).

The Earth's gravitational interaction with other objects in the interplanetary space creates a 100,000-year cycle in eccentricity of the Earth's elliptical orbit. Net results are periods when the Earth's orbit is somewhat more elliptical, increasing the Sun-Earth distance at aphelion and shortening the distance at perihelion. The increased eccentricity also makes the Earth move more slowly near aphelion. A second orbital variation is the change in the tilt of the Earth's rotational axis relative to the ecliptic plane. This obliquity has a period of about 41,000 years causing small but still important changes for solar activity interaction with the Earth, specially for solar irradiation but also for solar wind interaction with the geomagnetic field. Superimposed on this obliquity is a precession of the rotational axis with a period of 23,000 years. These three periods related to orbital and axial conditions create variations of solar forcing on Earth's climate with a subsequent glaciation cycle with a main period of 100,000 years with 41,000- and 23,000-year modulations superimposed (*Hays et al.*, 1976; *Imbrie et al.*, 1993; *Gildor and Tziperman*, 2000; *Berger et al.*, 2003; *Raymo and Nisancioglu*, 2003).

2.4 Intermediate-term changes

Originating from dynamo action in the solar interior, the solar magnetic field is constantly evolving on many different temporal and spatial scales. One of the most well-known solar magnetic variabilities is the 11-year sunspot cycle (*Schwabe*, 1844), resulting from active region migration,

evolution, submerging, and annihilation (see Figure 1). Although the period is 11 years on average, this sunspot cycle is varying in both length and amplitude. As a result of this cycle, the global solar magnetic polarity is reversed approximately every 11 years, giving a total solar magnetic cycle period of 22 years. *Mursula et al.* (2002) showed that a 22-year period is evident in the group sunspot number while *Cliver et al.* (1996) detected a 22-year signal in solar wind induced geomagnetic activity.

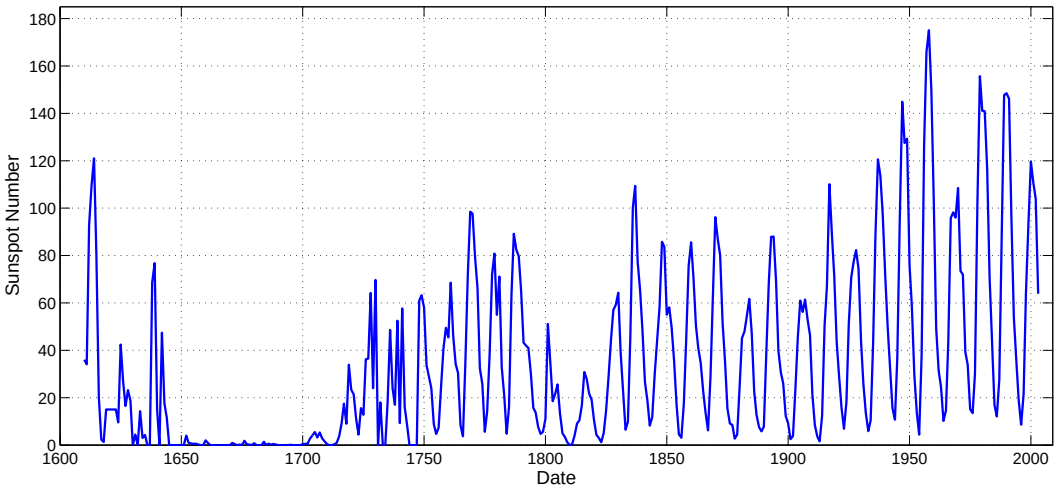

Figure 1: Smoothed yearly sunspot number for the period 1610 to 2003. The clear 11-year sunspot cycle is modulated with a 88-year Gleissberg cycle with the distinct Maunder Minimum (1645-1715) with almost no visible sunspots.

Galactic cosmic rays are high energy charged particles striking the Earth at high speeds. These particles are partially deflected by the interplanetary magnetic field embedded in the solar wind, causing an anti-correlation between cosmic-ray intensity observed on Earth and solar activity (*Forbush*, 1937). This effect is most pronounced in the overall 11-year variation (*McCracken et al.*, 2004) and the superimposed 22-year cycle (*Webber and Lockwood*, 1988; *Mavromichalaki et al.*, 1998), but can also be seen in individual interplanetary events like coronal mass ejections (*Cliver et al.*, 2003) causing intensity changes on an hourly to daily basis.

Modulating the 11-year sunspot cycle is the Gleissberg cycle with a period around 88 years (see Figure 1). The Gleissberg cycle has been detected in sunspot data (*Frick et al.*, 1997; *Ogurtsov et al.*, 2002), solar cosmic ray activity (*McCracken et al.*, 2001), and in solar energetic particle events (*Reames*, 2004). By using cosmogenic isotopes it has been shown that the Gleissberg cycle is valid for extended time spans (*Peristykh and Damon*, 2003; *Usoskin et al.*, 2004). Solar cycles with even longer periods have been proposed, such as the 205-year de Vries cycle (*Beer*, 2000; *Wagner et al.*, 2001) and the 2,100-year Hallstatt cycle (*Damon and Jirikowic*, 1992).

Helioseismic data reveal changes in the rotation of the Sun near the bottom of the solar convection zone (*Howe et al.*, 2000). With a period of 1.3 years at low latitudes, these rotational changes are probably a result of the differential rotation of the Sun responsible for the generation of the 22-year solar magnetic cycle (see Figure 2). This rotational periodicity is seen in the photospheric magnetic field (*Boberg et al.*, 2002) and most definitely linked to the earlier detected 1.3-year modulation of the solar wind speed (*Richardson et al.*, 1994) and of geomagnetic activity (*Paularena et al.*, 1995).

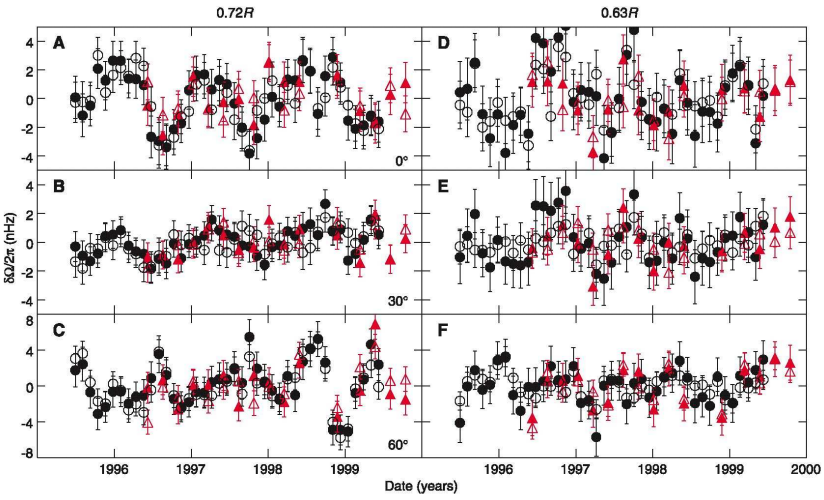

Figure 2: Variation in rotation rate at radii $0.72R_\odot$ and $0.63R_\odot$ for latitudes of 0°, 30°, and 60°. The residuals close to the equator show distinct oscillations with a period of about 1.3 years. See *Howe et al.* (2000) for more details.

2.5 Short-term changes

There is an annual cycle in solar activity effects observed on Earth due to the 7° tilt in the solar rotational axis in combination with the current 23.5° tilt in the Earth's axis relative to the ecliptic plane. As the Earth orbits the Sun, the magnetic topology condition will change on a semi-annual basis with best conditions for a solar wind interaction with the magnetosphere at the equinoxes in March and September (*Russell and McPherron*, 1973).

Rieger et al. (1984) found that solar flares have a tendency to occur in groups with a mean spacing of about 154 days. Sub-harmonics of this period have also been detected with periods ranging from 33 to 129 days (*Bai*, 2003). It has further been proposed, by studying variations in sunspot areas and sunspot numbers, that this 154-day period is the third harmonic of the 1.3-year period found in the solar interior (*Krivova and Solanki*, 2002). This 154-day periodicity can also be seen in the 10.7 cm radio flux (*Lean and Brueckner*, 1989) and the interplanetary magnetic field magnitude measured at 1 AU (*Cane et al.*, 1998). Furthermore, *Temmer et al.* (2004) reported a 24-day periodicity in solar Hα flares and suggested a origin related to periodic emergence of new magnetic flux.

Solar rotation leads to distinct modulations to a number of solar parameters with a dominating 27-day period together with a quasi-periodic 13.5-day variation (*Donnelly et al.*, 1983; *Pap et al.*, 1990; *Mordvinov and Plyusnina*, 2000; *Kane*, 2002; *Boberg et al.*, 2002) (see Figure 3). These periodicities can also be traced out to the solar wind from recurring high-speed solar wind structures originating from coronal holes (*Fenimore et al.*, 1978) and into the Earth's magnetosphere (*Mursula and Zieger*, 1996).

Coronal mass ejections (CMEs) are huge plasma clouds ejected from the Sun. The CME rate depends on the phase of the solar cycle; during solar minimum the rate is around 0.5 day^{-1}

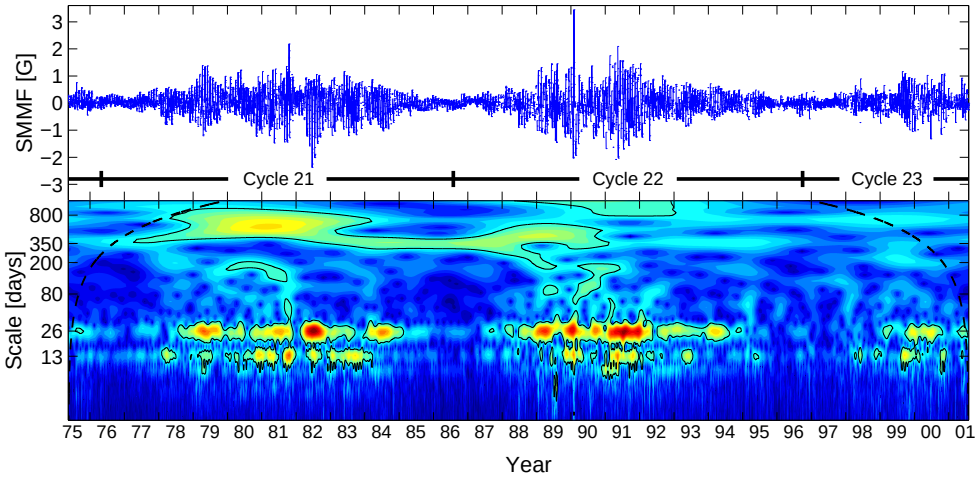

Figure 3: A wavelet power spectrum of mean magnetic field observations at the Wilcox Solar Observatory (*Scherrer et al.*, 1977) from 1975 to 2001. The dominating 27-day period, together with a 13.5-day harmonic, due to solar rotation is clearly seen for the different solar cycles. From *Boberg et al.* (2002).

(*Gopalswamy et al.*, 2004) whereas during solar maximum and during the declining phase of the solar cycle the rate reaches 2-5 day^{-1} on average (*St. Cyr et al.*, 2000; *Gopalswamy et al.*, 2004). An interplanetary disturbance due to a CME reaching the magnetosphere have an geoeffective duration between 10 and 60 hours (*Cane and Richardson*, 2003). Furthermore, solar energetic proton (SEP) events, accelerated by shock waves, have an energy spectra in the MeV range compared to a few keV for typical solar wind particles and lasts from several hours to a few days (*Reames*, 2004).

Other geoeffective interplanetary structures are high speed solar wind originating from coronal holes and co-rotating interaction regions formed when high speed solar wind catch up with slower moving wind (*Gonzalez et al.*, 1999). These structures are generally somewhat less dramatic than interplanetary CMEs, but they are more common and lasts longer, typically between 4 and 6 days (*Mavromichalaki and Vassilaki*, 1998).

3 Observational Techniques

3.1 Helioseismology

Helioseismology is the science studying wave oscillations in the solar interior. These waves are excited by processes in the convective layer of the Sun and appears as oscillations on the solar surface and measured using Doppler shifts of certain spectral lines. The Sun acts as a resonant cavity between the surface with its large density drop and the solar interior with a sound speed increase refracting waves towards the surface (see Figure 4). By comparing the resulting surface standing waves with theoretical solar models, we get information on parameters such as temperature, magnetic field, density, and pressure in the solar interior (*Harvey*, 1995).

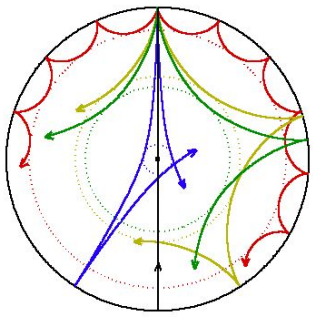

Figure 4: Diagram of ray paths of different acoustic (pressure) waves inside the Sun.

There are currently two major projects observing the structure and dynamics of the solar interior using helioseismology. One is the SOI/MDI project onboard the Solar & Heliospheric Observatory (SOHO) (*Scherrer et al.*, 1995), that in 1996 began to produce velocity and continuum intensity maps from 20 solar images every minute with a $4''$ resolution. The other project is the Global Oscillation Network Group (GONG), which started in 1995 and include observations from six identical instruments located around the Earth (*Harvey and the GONG Team*, 1998). These instruments together produce continuous full-disc images of the Sun every 1/60 second that produce acoustic mode data promptly available to the public.

3.2 Calculating the sunspot number

The sunspot number is obtained by counting the number of sunspot groups g and individual sunspots s from white-light images of the Sun, using the formula $R = k(10g + s)$ where k is a scaling factor (usually < 1) that accounts for observing conditions and the type of telescope. R is know as the Wolf sunspot number or the Zurich sunspot number and has been calculated since 1848 and reconstructed as far back as 1610 based on drawings of the solar disc. This makes the sunspot

number one of the oldest direct measures of solar activity (*Waldmeier*, 1961). To reduce the effects of corrections for observer differences and the difficulty to see the smallest sunspots, *Hoyt and Schatten* (1992) constructed a group sunspot number derived from the number of sunspot groups alone.

3.3 Measuring solar radiation

Total solar irradiance (TSI) is a measure of the radiation received at the top of our atmosphere, integrated over all wavelengths. The measurement technique is often based on heat flux absorbed in a cavity using an electrically calibrated heat flux transducer. TSI monitoring begun in 1978 with a steady improvement in accuracy due to calibration procedures and comparison of data from different instruments. So far, six experiments on different space missions have measured the TSI: Nimbus 7/HF (*Hoyt et al.*, 1992), SMM/ACRIM I (*Willson*, 1984), ERBS/ERBE (*Lee III et al.*, 1987), UARS/ACRIM II (*Willson*, 1994), SOHO/VIRGO (*Fröhlich et al.*, 1997), and ACRIM-Sat/ACRIM III (*Willson*, 2001).

Solar flux at radio wavelengths originates from the solar chromosphere and lower corona and has been recorded routinely by radio telescopes since 1947 (*Covington*, 1969). Due to a historical coincidence the observational wavelength was set to 10.7 cm, which is now regarded as a typical wavelength for the entire radio spectrum. The 10.7 cm solar flux correlates well with other indices of solar activity such as sunspot number and total sunspot area, with the advantage over those indices that the measurements are completely objective, and can be made under almost any weather conditions.

Solar ultraviolet (UV) radiation is located in the wavelength band between 120 and 400 nm and originates from the upper photosphere and the chromosphere. It comprises less than 1% of the total solar irradiance but has a strong direct impact on Earth's atmosphere and a considerable sunspot cycle variation of up to 10-20%. Early measurements of solar UV irradiance were made using rocket experiments (*Lean*, 1987). The observational confidence level and technique were steadily improved starting in the early 1980 using satellite observations, such as the NOAA weather satellites (*Cebula et al.*, 1998) or the SOLSTICE spectrometer (*Woods et al.*, 1993; *Rottman*, 2000).

The solar extreme ultraviolet (EUV) comprises the band 10-120 nm and originates from the chromosphere and the transition region. The EUV constitutes 10 ppm of the total solar energy but is important due to its ionizing effect and its significant variability. A large number of experiments measuring the solar EUV have been carried out, starting in the 1960s (*Kreplin*, 1970). Today we have full disk images in the EUV range from the SOHO/EIT (*Moses et al.*, 1997) and SOHO/CDS (*Thompson and Carter*, 1998) experiments.

X-ray ultraviolet (XUV) radiation has wavelengths below 10 nm and originates from the solar corona. Recent spacecraft measurements in the XUV region include the GOES XRS (*Garcia*, 1994), GOES SXI (*Hill et al.*, 2001), Yohkoh SXT (*Acton et al.*, 1999), SNOE SXP (*Bailey et al.*, 2000), and SOHO CELIAS/SEM (*Judge et al.*, 1998). Variations in the XUV spectra are mainly caused by solar flares, solar rotation, active region evolution, and the 11-year sunspot cycle.

3.4 Solar wind measurements

Solar wind parameters have been observed in situ beginning in 1963 with the Interplanetary Monitoring Platform No. 1 (IMP-1) (*Ness et al.*, 1964; *Paularena et al.*, 1997). Other important solar wind instruments are the WIND spacecraft (*Smith et al.*, 1998; *McComas et al.*, 1998), the three International Sun-Earth Explorer (ISEE) spacecrafts (*Ogilvie et al.*, 1989), the Advanced Composition Explorer (ACE) (*Lepping et al.*, 1995; *Ogilvie et al.*, 1995), and the CELIAS/MTOF experiment onboard SOHO (*Ipavich et al.*, 1998). For solar-terrestrial relationships, the most important parameters are the plasma density, the flow speed and the interplanetary magnetic field vectors.

3.5 Cosmic ray monitors

Cosmic rays are energetic particles, with galactic as well as solar origin, that filter through our atmosphere. The primary cosmic ray particles interact with the atmosphere and generate secondaries, some of which will reach the surface of the Earth. When the secondary cosmic rays enter the neutron monitor they disintegrate into charged particles and neutrons (*Simpson*, 2000). The neutrons are moderated and counted and then used as a measure of the primary cosmic ray infall. Cosmic rays in the 500 MeV to 20 GeV portion of the primary cosmic ray spectrum have been detected by ground-based neutron monitors regularly since 1953 (*Simpson*, 2000).

3.6 Cosmogenic records

Solar variability can be traced several hundred thousand years back in time using cosmogenic isotopes like ^{14}C and ^{10}Be (*Muscheler et al.*, 2003). These isotopes are radioactive and are produced by the interaction of galactic cosmic rays with atmospheric atoms, where the galactic cosmic ray infall is modulated by the solar wind. ^{10}Be interacts with aerosols and is subsequently removed from the atmosphere by wet deposition, making it measurable in natural archives such as ice cores (*Beer et al.*, 1990). ^{14}C is produced mainly by the interaction of thermal neutrons with atmospheric nitrogen and shows up in tree ring measurements (*Stuiver et al.*, 1998). ^{10}Be, with a half-life of 1.5 million years, is more suitable to reconstruct solar activity over very long time periods, compared to ^{14}C with a half-live of 5730 years. Furthermore, ^{14}C can provide global signals but is less reliable due to influences from natural carbon cycles.

4 Conclusion

The Earth is a magnetized body located inside a highly active and variable environment, known as the heliosphere. The heliosphere consists of fast flowing charged particles, radiation in all wavelengths, and an interplanetary magnetic field. These phenomena show spatial and temporal variabilities on a wide range of scales and the focus of attention in the literary study presented here is to locate and present those solar variabilities that can influence or interact with the Earth's environment. The results of this literary study are summarized in Table 2 with a plausible origin, corresponding time-scale, and observational indicators.

Time-scale	**Origin**	**Observables**
$\sim 10^9$ years	solar evolution	nearby G2V-stars, HR diagram
100,000 years	eccentricity of Earth's orbit	cosmogenic isotopes
41,000 years	obliquity in Earth's rotational axis	cosmogenic isotopes
23,000 years	precession of Earth's rotational axis	cosmogenic isotopes
2,100 years	solar dynamo?	cosmogenic isotopes
205 years	solar dynamo?	cosmogenic isotopes
88 years	solar dynamo	sunspots, solar cosmic rays, solar energetic protons, cosmogenic isotopes
22 years	solar dynamo	sunspots, galactic cosmic rays, solar wind parameters, photospheric magnetism
11 years	solar dynamo	sunspots, 10.7 cm radio flux, solar UV, galactic cosmic rays, solar wind parameters, photospheric magnetism
1.3 years	internal solar rotation	photospheric magnetism, solar wind parameters
6 months	Earth's orbital motion	geomagnetic activity
154 days	internal solar rotation?	solar flare activity, solar wind, 10.7 cm radio flux
13.5/27 days	solar rotation	sunspots, solar wind parameters, 10.7 cm radio flux
24 days	magnetic flux emergence	Hα flare occurrence
4-6 days	coronal holes, corotating interaction regions	solar wind parameters
10-60 hours	coronal mass ejections, solar energetic proton events	solar wind parameters, galactic cosmic rays

Table 2: A summary of major solar variabilities with corresponding time-scales, origins, and observables found in the literature.

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