Solar Variations and Climate on Planets

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**Abstract.** The Sun is a variable star on different time scales. During its evolution it considerably changed its luminosity and activity. The early Sun was faint but very active and this had important consequences for the evolution of the early planetary atmospheres. The importance of enhanced early solar activity at those evolutionary phases will be demonstrated by a short analysis of two recently observed solar enhanced activity events. From these events one can infer the importance of sunspots as indicator of solar activity and the solar variation in UV during times of enhanced sunspot activity was measured.

The solar input is the driver for climate on planets. It is extremely important to have accurate estimates of a variation of this input. At present, the variations are low in the visible but still high in the UV influencing e.g. higher layers in the Earth’s atmosphere.

1. Solar Variations

1.1. The active Sun

Climate is driven by the solar input. It is well established that this input is variable on different scales ranging from the long term evolution of the Sun to the well known 11 year solar activity cycle. Even the old Chinese noticed already that the Sun changes by observing large sunspots that could be seen with the naked eye when the sunlight is damped by clouds or the Sun is near the horizon. About 1610 Galilei, Scheiner and others observed these spots for the first time with a telescope. However, despite the large dispute these spots caused, the interest in solar observations declined strongly, simply because of the fact that no spots were seen especially during the period 1645-1710 with only a few exceptions. By systematic observations, Schwabe was able to detect the sunspot cycle in 1844 and it was soon recognized that different solar phenomena are variable with this 11 year cycle. Therefore, the term solar activity cycle is more appropriate.

One of the most important observations at this time was the recording of a so called white light flare on Sep 1, 1859 by Carrington and his observation that a magnetic compass needle started to vibrate several hours later. Carrington immediately supposed that there must be a connection between these two observations.

Influences of the Sun and its variation to the Earth and near space around the Earth are today known under the term space weather (see e.g. Hanslmeier 2002).
In Fig. 1, a plot is given of the sunspot number as a function of time. It can be easily seen that there is a periodicity of about 11 years but the maxima differ, some larger cycle seems to be overlying (80 year Gleissberg cycle). Thus solar activity sometimes seems to behave irregularly with intermittent phases of strongly enhanced or reduced activity. The behavior of solar cycle, with periods of low activity, suggests the presence of deterministic chaos as was shown e.g. in the paper of Carbonell, Oliver, & Ballester (1994).

1.2. Solar activity phenomena

So far we have discussed sunspots. Their number is the longest direct recorded measure of solar activity and they are easily detected. But in parallel with the number of spots also other solar phenomena vary with the activity cycle. We mention the most important:

Faculae: Spots are often surrounded by bright areas called faculae. Spots are cooler than the surrounding solar atmosphere ($T_{\text{photosphere}} \sim 6000\, \text{K}$, $T_{\text{spot}} \sim 4000\, \text{K}$) but this energy deficit is overcompensated by the faculae. During the passage of a large spot the solar constant decreases by less than 1/1000 but in general, when there is maximum of solar activity, also the number of faculae is at maximum and the spot energy deficit is overcompensated. In short: the Sun appears slightly brighter when there are more spots. The irradiance excess of faculae can be compared with the sunspot deficits and the results can then be verified by a comparison with accurate total solar irradiance measurements done e.g. by SOHO or ACRIM. One of the early works on this topic that were given by Steinegger, Brandt, & Haupt (1996).

Flares: They occur higher in the solar atmosphere (chromosphere/corona) when magnetic configurations change. Energy is released in short time scales of minutes and one can observe brightenings in the chromosphere (e.g. in
the light of Hα using specials filters). The energy is released in form of radiation (which reaches the Earth within 8 minutes) and particle emission (reaching the Earth after several hours).

**Coronal mass ejections (CMEs):** Also caused by changes of magnetic field configuration, but in that case the changes occur in the solar corona. Mass is expelled in the open magnetic fields.

**Solar wind:** The solar wind consists of charged particles (high energy electrons and protons 500 keV) that stream off the solar corona. Over coronal holes the solar wind speed (800 km/s) is higher than over coronal streamers (300 km/s). The solar wind influences geomagnetic activity, auroral activity and cometary tails that point away from the Sun.

2. **Heliosphere, Magnetosphere, Atmosphere**

In this section we shortly describe how the surfaces of planets may be protected against incoming solar energetic particles and radiation.

2.1. **The Heliosphere**

The heliosphere is an envelope over the whole planetary system beyond the orbit of Pluto, defining the region where the Sun due to its magnetic activity and solar wind dominates over the interstellar medium. It is a protection against cosmic ray particles. Particles cannot penetrate the magnetic field lines, they cannot move across the field lines. Since the Sun moves in a certain direction (motion about galactic center), the heliosphere is compressed towards the direction of movement. Recently direct observational evidence about its existence was found (Voyager).

Cosmic ray particles when entering the Earth’s atmosphere produce various isotopes, e.g. the $^{14}$C. The strength of the heliosphere depends on solar activity. When solar activity is at maximum it is stronger, therefore the production of cosmogenic isotopes is weaker. The heliospheric modulation of cosmic rays during the period of 1951-2004 was studied by Usoskin et al. (2005).

2.2. **The Magnetosphere**

The shape of the Earth’s magnetosphere is strongly influenced by the solar wind and solar magnetic bubbles. It is compressed in the direction to the sun. On the night side of the Earth it extends far.

Solar wind interactions with planetary magnetospheres strongly depend on the planet’s own magnetosphere. Planets with an intrinsic magnetic field are protected for the most particles of the solar wind. The solar radiation flux just changes the atmospheric and ionospheric chemistry. The atmosphere of Mars is in direct contact with solar wind particles. Mars could have had at very early times an intrinsic field but the dynamo stopped very quickly. Mars loses its ionosphere/atmosphere by electric fields from the solar wind and its ionosphere/atmosphere acts also as a source of energy sometimes being larger than the incoming EUV flux (see Brecht 2004).
As an example we cite the paper of Sánchez et al. (1998) where energy transfer between the ionosphere and magnetosphere during the January 1997 CME event is analysed.

2.3. The Earth’s atmosphere
The troposphere is the deepest layer in the Earth’s atmosphere reaching up to approx. 10 km. Here 90% of the air mass is concentrated and the whole weather systems originate. The temperature decreases by about 6.5 degrees per km but at the tropopause it reaches a minimum and increases again in the stratosphere and a maximum is reached at about 50 km. This is due to the absorption of solar UV radiation leading to the production of ozone:

\[ O_2 + h\nu \rightarrow O + O \]  
\[ O + O_2 \rightarrow O_3 \]

Therefore the higher layers of the Earth’s atmosphere are influenced by the strongly varying solar UV and X-radiation. The troposphere, where the weather is produced is influenced by the only weakly varying visible radiation (the total solar irradiation varies by about 0.1%).

It was studied whether the ozone content in the Earth’s atmosphere varies with solar activity. In such studies a distinction between tropospheric ozone and stratospheric ozone must be made. The tropospheric ozone seems to be not influenced by solar activity. The stratospheric ozone increases by 2.4 to 3.1% when the solar activity increases (see Asiati, Sinambela, & Hidayati 2004).

2.4. Influence on climate
As we have briefly outlined, the influence of the variation of the total solar irradiation to the troposphere is negligible and the influence of the short wavelength component mainly occurs in the stratosphere. So is there any influence on climate conceivable? It seems that the formation of ions crucially influence the formation of clouds. The formation of ions in the Earth’s atmosphere depend on cosmic rays and solar energetic particles. As we have seen in the chapter about the heliosphere the cosmic ray flux is modulated by solar activity. Thus a direct link to weather and climate and solar activity seems to exist. The production of clouds strongly influences on the albedo of the Earth. The larger this value, more incoming light is reflected back, less radiation is available for surface heating.

2.5. Forcing mechanisms
In the following we compare different forcing mechanisms that act on the Earth’s atmosphere and on the long term influence on climate. From the Sun at Earth distance the amount of \( S = 1360 \text{ W/m}^2 \) is received. From that 1/4 is relevant (because of the spherical shape of the Earth). Let us give some examples:

- top of atmosphere: \( S/4 = 340 \text{ W/m}^2 \)
- Earth’s albedo \( a=0.3 \), \( S/4(1-a) = 235 \text{ W/m}^2 \)
• 1% change in albedo: 1 W/m²
• estimated radiative effect of the increase of CO₂ since 1750: 1.5 W/m².
• Doubling of CO₂: 4 W/m²
• effects of clouds: 17-35 W/m².

Variations of the total solar irradiance are in the range of 1 W/m². But if the assumptions about the formation of clouds and ionization are correct then the influence could be much larger.

3. Climate changes

Climate is a very complex phenomenon and climate changes on Earth and on planets have different cause. On the Earth e.g. also ocean currents and plate tectonics have to be taken into account, for Mars its high eccentricity of the orbit as well as large variations of its tilt of the rotation axis due to lack of a large stabilizing satellite are important. In the following we will concentrate on the influences coming from the variable Sun.

3.1. Long term solar evolution

The early Sun strongly differed from its present state: it was fast spinning, had strong activity on quite irregular time scales, the radiative output in UV was $100 \times$ and the output in X-rays about $1000 \times$ as strong as today. However, the total energy output was only 70% of its present value. Thus less energy was received on the early planets but their atmospheres were strongly influenced by the large UV and X-ray component. Due to lack of free oxygen in the early Earth, UV radiation could penetrate directly to the surface. It is now assumed that this may have triggered the production of organic material.

If the luminosity of the early Sun was only 70% of its present value then the global temperature on Earth should have been 25° less than today and it would have been a frozen body. There is strong geological evidence that this was not the case- there are 4 billion years old sedimentary rocks, so liquid water must have been present. This is called the faint young Sun paradox. The solution to that could be an early atmosphere that was very rich in greenhouse gases (CO₂, CH₄).

By a comparison of the Sun with other solar like stars at different ages we can infer the properties of the early Sun. The chromospheric age dependence of the birthrate, composition, motions, and rotation of late F and G dwarfs within 25 parsecs of the sun was investigated by Barry (1988) for a sample of 115 stars. They plot rotational velocities against chromospheric age and found that the star’s rotation depends on its age and mass. The rate of mass loss is inversely proportional to the age of the star.

3.2. Solution of the faint young Sun paradox: Cosmic rays

Marsh & Svensmark (2000) found that there is a strong influence on low clouds ($h \leq 3$ km) by cosmic rays. This influence can be explained by aerosol formation, caused by enhanced ionization due to cosmic rays.
There is a cooling effect that cosmic rays are suspected to have on the Earth’s climate. There are many indications that the younger Sun must have had a stronger wind and that it was more effective to stop the penetration of cosmic ray particles from reaching the Earth. This effect together with enhanced greenhouse warming is sufficient to explain a warm Earth despite the less solar input. In a paper given by Shaviv (2003), it is estimated that the global average temperature on Earth will increase by 10° during the next 2 Gyr.

The question is how climate on Mars can be made hot enough to support flowing water under a faint young Sun. Flowing water during early Martian History is widely accepted because of the observations of valley networks and eroded craters. It is assumed that the scattering effect of CO$_2$ ice clouds with optimal size of particle size and optical depth in a 1 bar atmosphere could have been sufficient. Mitsuda, Yukata, & Kuramoto (2005) discussed stability issues of such an atmosphere. Justh & Kasting (2002), stressed that such a cloud cover should have occurred in the higher Martian troposphere and Mars should have been globally clouded in order to enable a CH$_4$ and H$_2$O rich atmosphere with a larger greenhouse effect. They discussed also a CH$_4$ contribution to the greenhouse effect. A warm climate on early Mars was already described by Pollack et al. (1987).

3.3. A more massive Sun?

It was also tested whether the problem of the cold temperatures for Earth and Mars can be solved by a Sun that is brighter than predicted by the solar standard model. Sackmann & Boothroyd (2003), calculated high precision solar evolutionary models with increased masses between 1.01 and 1.07 M$_\odot$. The resulting mass loss rates are consistent with observations of early type stars, solar wind recordings in lunar rocks, do not affect the Li depletion and are consistent with helioseismic observations. They yield a solar flux about 3.8 billion years ago, that was high enough to enable liquid water on Mars. For example an initial 1.07 M$_\odot$ Sun would have produced a flux 50% higher (the solar standard model suggests 30% lower). The present flux should be 5% higher. Thus a higher mass loss could explain also the faint young Sun problem. At present, the mass loss is very low: $3 \times 10^{-14}$ M$_\odot$/yr. If the mass loss would have been constant over the last 4.5 billion years, the early Sun would have been more massive by only $10^{-4}$ M$_\odot$. Lunar material can be used to trace back the solar wind flux by analyzing noble gas isotopes (Kerridge et al. 1991). These data favor a mass loss of $10^{-3}$ M$_\odot$ over the past 3-4 Gyr. Flare irradiated grains from meteorites imply an early solar flare activity 1000 times that of the present day Sun, thus also a much higher mass loss (Caffee, Hohenberg, & Swindle 1987).

There is an upper limit for the initial solar mass. If the solar flux at Earth would have been more than 10% higher than its present value, the Earth would have lost its water by the moist greenhouse effect: the stratosphere becomes wet and H$_2$O is lost through UV dissociation and subsequent escape of H to space. The solar flux limit seems to be $M_{\odot,i} \leq 1.07 M_{\odot}$, where $M_{\odot,i}$ denotes the initial solar mass (see Kasting 1988).

An indication of solar like star mass loss rates is given by the observation of hot hydrogen gas surrounding these stars. The origin of this gas results from a collision of wind particles from the stars with the local interstellar medium.
In high resolution $\lambda_\alpha$ spectra one can detect absorption from this hot HI gas the amount of absorption being proportional to the mass loss rate. It was found that the mass loss per unit surface area is correlated with X-ray surface flux and that activity decreases with age. This implies that the solar wind may have been more than 1000 times more effective in the distant past of the Sun (see e.g. Wood et al. 2002, using Hubble Space Telescope spectra). An increased solar wind flux lead to a rarefication of early planetary atmospheres.

4. Analysis of a High Solar Activity Event

In order to investigate the influence of solar activity on the Earth and other planets at an early phase of solar evolution we considered two special cases of solar activity in the declining phase of cycle 23, with a quite simple geometry.

The two cases are shown by Figs. 2, 4.

The example 2 event in Jan 2005 consists of a large sunspot group, the example 1 from Oct 2003 consists of two large groups.

For the UV measurements we have used data from the NASA SORCE (Solar Radiation and Climate experiment) satellite mission and two channels were integrated: 150-180 nm and 180-310 nm.

The quantitative analysis of these two events leads to the values given in Table 1.

5. Discussion

Our examples given above show the short time variation of the total solar irradiation and radiation in the UV. During the passage of a large spot a decrease of the total irradiation by 0.18% was measured which corresponds to about 2 W/m$^2$. The variation in the UV channels is considerably higher. This simple
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Figure 3. Example 2: 17 Jan 2005, Sunspot drawing; courtesy: Solar Observatory Kanzelhöhe

Figure 4. Example 1: Variation of sunspots and solar irradiation in different channels.

Figure 5. Example 2: Variation of sunspots and solar irradiation in different channels.
Table 1. Quantitative variation of the two events considered

<table>
<thead>
<tr>
<th></th>
<th>Oct 2003</th>
<th>Jan 2005</th>
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<tbody>
<tr>
<td>Var TSI</td>
<td>0.18%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Var UV 150-180 nm</td>
<td>9.1%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Var UV 180-310 nm</td>
<td>0.54%</td>
<td>0.3%</td>
</tr>
<tr>
<td>solar hemisphere covered by spot</td>
<td>0.004</td>
<td>0.002</td>
</tr>
</tbody>
</table>

example demonstrates that the present day solar variation is in the range of the estimated radiative effect of the increase of CO$_2$ since 1750 which of course cannot be interpreted in the sense that climate warming is caused only by solar variations. However if we assume an active early Sun than it becomes clear that these influences must have been dramatic. By comparing the Sun with solar like stars we can infer that its variation was considerably larger, especially in the short wavelength. The areas covered by the spot in our examples were in the range of a few 1/1000 leading to irradiance variations of 1/1000 and UV variations of a few percent depending on the channel. Early type solar like stars are heavily spotted and if there is a linear relation, then e.g a star that is covered 10 times more than the Sun would have irradiance variations of a few %, that corresponds to 10-20 W/m$^2$ at Earth distance. This had strong influences on early planetary atmospheres. Let us return to the primitive Earth’s atmosphere. In order to keep water liquid on early Earth despite the low solar luminosity, it was suggested that greenhouse gases like CO$_2$, NH$_3$ were present at high level. However, the large and largely variable solar UV radiation contributed to a rapid photolysis of NH$_3$. Therefore there must have been some protection mechanism for that component, maybe in the form of organic haze as it is seen in the atmosphere of the Saturn’s satellite Titan (Kasting 1997).

It was also suggested that methane, CH$_4$ that could have been a major factor as greenhouse gas. But this is also easily photolyzed by UV radiation. A possible mechanism could be the production of CH$_4$ by Cyanobacteria. This could also solve the problem for a warm Mars in the past. For a reference on these topics see the paper by Kasting (1997).

References

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