UV RADIATION IN THE SOLAR SYSTEM

A. HANSLMEIER\(^1\) and M. VÁZQUEZ\(^2\)

\(^1\) Institut f. Physik; Geophysik, Astrophysik und Meteorologie, Univ. Graz, Austria
\(^2\) Instituto de Astrofísica de Canarias, IAC, La Laguna, Tenerife

UDC 523-74
Conference paper

Abstract. The source of UV radiation in the solar system is mainly the Sun. The influence of its various compounds as well as the variability is discussed here. It is summarized on which time scales the solar UV radiation is variable and by which processes it influences the atmospheres of planets. UV radiation on solar like stars that may be surrounded by planets plays an important role in the extension of habitable zones in these systems.

Key words: Sun - UV radiation - variability - planetary atmospheres

1. Introduction

UV radiation in the solar system is mainly related with radiation form the Sun. Since the Sun is variable on different time scales it has to be taken into account that as a consequence, also the UV part was variable. The changing conditions in the space environment of the Earth on larger time scales (at least several 10\(^2\) years) is nowadays called the space climate. Space weather effects were discussed in the textbook of Hanslmeier (2002) and also in the paper of Hanslmeier (2003).

Here we concentrate on the UV radiation from the Sun. First we give an overview of the UV radiation from the Sun then we discuss its influences on the Earth’s atmosphere on different time scales before we also address the problem of UV radiation and interaction with other planetary atmospheres. Finally, some consequences for solar like stars will be discussed.
2. Solar UV Radiation

Considering radiation from the Sun, we must remember that the origin of different parts in the electromagnetic spectrum is related to different heights in the solar atmosphere. Whereas practically 99% of the visible part of solar radiation comes from the photosphere, radiation on shorter wavelength scales emanates from higher solar atmospheric layers. The sources of solar UV radiation are mainly found in the chromosphere and the transition region layer of the Sun. Here the temperatures are high enough to excite the emission of hydrogen Lyman lines or lines of highly ionized atoms. This is shown in Figure 1. The upper image shows a part of the Sun with a sunspot group in white light (photosphere), the image in the middle the Sun at a wavelength of 160 nm (chromosphere) and the lower image the Sun in X rays (corona). It is clearly seen how magnetic features from spots reach from the photosphere to the corona. Magnetic fields dominate the flow of plasma in these layers.

The Sun is variable, especially in those layers where UV radiation comes from, on different times scales:

- hours to days: this is to be seen with solar active regions. The variation can be quite high, depending on the wavelength. The related processes on the Sun are flares, CMEs.

- \( \sim 10^1 \ldots 10^2 \) years; such variations are related to the solar cycle. The variation is at least higher than in the visible part of the solar spectrum (the total irradiance variation is in the order of 0.4%, see e.g. as a general overview Pap et al., 1994).

- Variation during the evolution of the Sun.

An example of the solar UV spectrum is given in Figure 2.

That figure shows that spectral lines appear in absorption up to about 200 nm but then at shorter wavelengths they are emission lines because of their origination in the higher (hotter) chromosphere.

The solar irradiance variation and its estimation is given in Figure 3. This estimation shows that during the Maunder Minimum, a reduction of 0.2% for the total solar irradiance and of 0.7% of the irradiance between 120 to 400 nm occurred. The variation in the UV is about twice than the total solar irradiance variation.
Figure 1: The Sun seen in different wavelength bands. Courtesy: TRACE, K. Schrijver.
Figure 2: The solar UV spectrum. Adapted from Scheffler and Elsässer (1974).

Figure 3: Simulation of solar irradiance in different spectral wavelengths (Courtesy of J. Lean, Naval Research Lab.)
3. UV Radiation and Ozone

3.1. General Remarks

Passing through the Earth’s atmosphere, solar UV undergoes absorption and scattering. The most important processes of absorption are:

- CO\(_2\): peak absorbance at 190 nm, radiation below 200 nm is attenuated.

- Ozone: increasing ozone concentrations result in lower irradiances in the UV-B range.

- Molecular oxygen.

Whereas UVC rays (wavelengths of 100 to 280 nm) are absorbed by the atmospheric ozone, most radiation in the UVA range (315 to 400 nm) and about 10% of the UVB rays (280 to 315 nm) reach the Earth’s surface. Both UVA and UVB are of major importance to human health. Small amounts of UV are essential for the vitamin D production of humans, yet overexposure may result in acute and chronic health effects on the skin, eye and immune system.

In general the UV radiation on the Earth’s surface depends on: cloud cover (UV-A, UV-B Mie scattering due to water droplets), ozone in the stratosphere, oblique angle of sunlight reaching the surface, aerosols in the troposphere (smoke, dust absorbing UV-B), water depth in oceans, reflection (snow). NASA’s TOMS (Total Ozone Mapping Spectrometer) estimates UV-B irradiance at the Earth’s surface based on ozone abundance measurements.

In biological systems, UV radiation causes photochemical reactions and these interactions result in temporary or permanent alterations. The most important target in cells is the DNA- the absorption maximum is about 260 nm. It can be stated that solar UV radiation has been a driving force for the evolution of life on Earth by acting as a mutagen by its DNA-damaging capacity and as a selective agent (Rettberg and Rothschild, 2002). Organisms on Earth have developed protection mechanisms such as DNA repair enzyme activities. Biological strategies for protection and avoidance of UV radiation are discussed by Wynn-Williams and Edwards (2002).
Solar UV radiation influences the upper parts of the Earth’s atmosphere. The most well known example is the ozone layer. The maximum of ozone reactions by the solar UV absorption occurs at a height of about 50 km. In this context we have to take into account that the amount of UV radiation is variable, dependent on the solar activity cycle. The variations are given in Table I.

Remote sensing techniques in planetary atmospheres use transitions ranging from microwaves to UV. For Mars, UV radiation < 200 nm can penetrate to the surface and can act as a source of gas composition variations.


Table I: Percentage change solar UV flux solar maximum to solar minimum (Huang and Brasseur, 1993)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150-159</td>
<td>20</td>
</tr>
<tr>
<td>159-170</td>
<td>14</td>
</tr>
<tr>
<td>170-185</td>
<td>10</td>
</tr>
<tr>
<td>185-190</td>
<td>9</td>
</tr>
<tr>
<td>190-200</td>
<td>7.6</td>
</tr>
<tr>
<td>200-208</td>
<td>6.6</td>
</tr>
<tr>
<td>208-266</td>
<td>3</td>
</tr>
<tr>
<td>266-270</td>
<td>0.6</td>
</tr>
<tr>
<td>270-277</td>
<td>2</td>
</tr>
<tr>
<td>277-282</td>
<td>6</td>
</tr>
<tr>
<td>282-303</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Ozone is formed by the reactions

\[
\begin{align*}
O_2 & \rightarrow O + O & \lambda < 200 \text{ nm} \\
O + O_2 & \rightarrow O_3
\end{align*}
\]

(1) \hspace{1cm} (2)

Ozone is destructed by

\[
\begin{align*}
O_3 & \rightarrow O_2 + O & < 200 \text{ nm } \lambda < 300 \text{ nm} \\
O + O_3 & \rightarrow O_2 + O_2
\end{align*}
\]

(3) \hspace{1cm} (4)
3.2. OZONE VARIATIONS AND THE SOLAR CYCLE

Paetzold et al. (1972) gave a review on stratospheric ozone variations over solar cycles from 1951 - 1972.

Several studies were made to estimate the influence of UV radiation on ozone. Rozanov et al. (2002) e.g. showed that ozone and temperature in the Earth’s stratosphere are sensitive to solar radiation between 220 and 200 nm. For that wavelength interval they found a positive correlation. In the upper stratosphere and mesosphere the solar flux variability in the Lyman $\alpha$ and Schumann-Runge band were found to be important.

Seasonal variations of ozone in the Martian atmosphere were discussed by Shimazaki and Shimizu (1979) utilizing data for atmospheric temperature, pressure, and water vapour abundance observed by the Viking satellite mission. The results indicate that a high ozone density is not produced near the winter solstice but is in rather late winter, when the amount of water vapour is still small and the solar radiation can penetrate more deeply.

Highly relativistic electron precipitation events during the May 1992 event were studied by Pesnell et al. (2000) (electrons with $>100$ keV) caused ozone depletions up to 20% because of HO$_x$ reactions.

Thus a change during solar maximum and minimum in the total ozone content can be found (see e.g. Sekiyama et al., 2004). Using a three dimensional chemical transport model (CTM), they found the following trends:

- Peak differences of ozone concentration between solar maximum and minimum are calculated as approximately 4% in the stratosphere.
- Solar cycle changes of temperature also show altitudinal, latitudinal, and longitudinal variations from -1.0 K to +0.8 K in the stratosphere.
- There is a high correlation (0.8) between the two horizontal distributions in the lower stratosphere and a strong but negative correlation (-0.7) in the upper stratosphere.

3.3. LONG TERM VARIATION

It is well known, that from the early phase the luminosity of the Sun has been increasing by about 30%.

Terrestrial planets have secondary atmospheres. The early Earth must have had a non reducing atmosphere like that we find today on Mars and
Venus (mainly CO₂, N₂). As a basis for the origination of the atmospheres of Venus, Mars and the Earth the present outgas products of terrestrial volcanoes (80% H₂O, 17% CO₂,...) can be considered (see also Vázquez and Hanslmeier, 2005, Chap. 6). But why are the so big differences between e.g. Venus and Earth? If we assume that Venus started with the same amount of water as the Earth, early Venus could have lost its water by the action of the more intense solar UV radiation by the following process:

\[ \text{H}_2\text{O} + \text{UV} \rightarrow \text{H}_2 \uparrow + \text{O}_2 \]  \hspace{1cm} (5)

The light H₂ escaped (Kasting, 1988). Other processes in the atmosphere of Venus are discussed in the book of Vázquez and Hanslmeier (2005).

4. UV Radiation and Planetary Atmospheres

Table II gives an overview on the solar irradiance on the planets (adapted from Vázquez and Hanslmeier, 2005).

UV radiation has a high energy and therefore it is the main regulator of the photchemistry in planetary atmospheres. Some basic reactions have been described by Wildt (1937).

\[ \lambda < 180.0 \text{ nm} : \quad \text{H}_2\text{O} + h\nu \rightarrow \text{OH} + \text{H} \]
\[ \lambda < 180.0 \text{ nm} : \quad \text{CO}_2 + h\nu \rightarrow \text{CO} + \text{O} \]
\[ \lambda < 120.0 \text{ nm} : \quad \text{CO} + h\nu \rightarrow \text{C} + \text{O} \]
\[ \lambda < 170.0 \text{ nm} : \quad \text{NH}_3 + h\nu \rightarrow \text{H} + \text{NH}_2 \]

Here, h\nu denotes the energy of a UV photon. Such processes are called photolytic. As can be seen from these basic reactions, photons with \( \lambda < 180.0 \text{ nm} \) are capable for example, of splitting H₂O molecules into OH and H.

Photochemistry on giant planets was mainly investigated by Moses (2000).

The detection of extrasolar planets is at present limited to giant objects orbiting close to the central star. These extrasolar giant planets receive high fluxes of stellar far UV radiation.

When considering planetary atmospheres in our solar system we have to make a distinction between the terrestrial planets and giant planets.
Table II: Solar irradiance (W/m²) and semi-major axes of planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Solar irradiance (W/m²)</th>
<th>Solar irradiance (Earth = 1.00)</th>
<th>Semi–major axis (10⁶ km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>9126.6</td>
<td>6.673</td>
<td>57.91</td>
</tr>
<tr>
<td>Venus</td>
<td>2613.9</td>
<td>1.911</td>
<td>108.21</td>
</tr>
<tr>
<td>Earth</td>
<td>1367.6</td>
<td>1.000</td>
<td>149.6</td>
</tr>
<tr>
<td>Mars</td>
<td>589.2</td>
<td>0.431</td>
<td>227.92</td>
</tr>
<tr>
<td>Jupiter</td>
<td>50.50</td>
<td>0.037</td>
<td>778.57</td>
</tr>
<tr>
<td>Saturn</td>
<td>14.90</td>
<td>0.011</td>
<td>1433.53</td>
</tr>
<tr>
<td>Uranus</td>
<td>3.71</td>
<td>0.0027</td>
<td>2872.46</td>
</tr>
<tr>
<td>Neptune</td>
<td>1.51</td>
<td>0.0011</td>
<td>4495.06</td>
</tr>
<tr>
<td>Pluto</td>
<td>0.89</td>
<td>0.0007</td>
<td>5869.66</td>
</tr>
</tbody>
</table>

The atmospheres of the giant planets (Jupiter, Saturn, Uranus and Neptune) are supposed to have been formed together with the planet out of the solar nebula and reflect mainly the solar composition.

The atmospheres of the terrestrial planets (Mercury, Venus, Earth and Mars) are mainly secondary atmospheres. Let us consider the Earth. It had a primary atmosphere, now supposed to have had a composition mainly of CO₂, CO, H₂, N₂.... For the Earth several factors came into play to change this atmosphere: evolution of life and geologic variations.

4.1. Terrestrial Planets

Effects of solar UV radiation on the Earth’s atmosphere have been already discussed. Here we concentrate on Venus and Mars.

The primary constituent in the atmosphere of Venus as well as in Mars is CO₂. Due to UV absorption the following reactions are important:

Photodissociation: \( \text{CO}_2 + h\nu \rightarrow \text{CO} + \text{O} \)

Recombination: \( \text{CO} + \text{O} + \text{M} \rightarrow \text{CO}_2 + \text{M} \)

On Venus also the airglow due to oxygen which is formed by the photolysis of CO₂ is important. The ionosphere of Venus is formed by photoioniza-
Table III: UV radiation photochemistry on giant planets

<table>
<thead>
<tr>
<th>Photolyzed molecule</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia, NH₃</td>
<td>λ &lt; 230 nm</td>
</tr>
<tr>
<td>Methane, CH₄</td>
<td>λ &lt; 160 nm</td>
</tr>
<tr>
<td>H₂S</td>
<td>λ &lt; 371 nm</td>
</tr>
<tr>
<td>Phosphine, PH₃</td>
<td>160 &lt; λ &lt; 235 nm</td>
</tr>
</tbody>
</table>

tion of neutral CO₂ and O. Since the solar EUV varies with activity cycle, the extension of the ionosphere also varies- at maximum the ionosphere of Venus extends to its highest altitudes.

For Mars, the UV photoionization processes are similar to those of Venus. On Earth, protection against UV radiation is provided by ozone and solar UV radiation λ < 300 nm does not reach the surface. Since CO₂ is the main constituent of the atmosphere of Mars, UV radiation with λ < 200 nm is absorbed and does not reach the surface. Also ozone plays a minor role for high latitude regions in winter. Cockell (2002) discussed the past and present UV radiation environment for Earth and Mars.

The biological response of organisms depends strongly on the energy and thus the wavelength of incident radiation. DNA has a peak absorption near 260 nm and it decreases by a factor of 6 towards 290 nm.

For the giant planets the the UV chemistry of several molecules is summarized in Table III.

4.2. GIANT PLANETS

In the upper troposphere of Jupiter and Saturn, NH₃ photochemistry is important. Ammonia is photolyzed by radiation 190 < λ < 220 nm. Thus complex molecules like PH₂, N₂H₄, P₂H₄, NH₂PH₂ are formed. Longer UV radiation penetrates deeper producing e.g. H₂S (see Lewis and Prinn, 1984). In the stratosphere CH₄ and its photolysis dominates. Long lived hydrocarbons are synthesized. They slowly diffuse downward the deeper hotter and denser atmospheric regions. There they thermally decompose and by a reaction with H₂ they form again methane. The colour bands seen on Jupiter and Saturn are explained by break up of H₂S molecules by UV photons.
This leads to sulphur $\text{S}_8$ (yellow), ammonium polysulphide, $(\text{NH}_4)_x\text{S}_y$ (orange) and hydrogen polysulphide $\text{H}_x\text{S}_y$ (brown).

Precipitation of charged particles and magnetic fields result in aurorae. On Earth, the aurorae are controlled by the interaction of the Earth’s magnetic field with the solar wind, on Jupiter they are controlled by particles from its satellite Io and on Saturn we have an intermediate case interaction with solar wind and particles from inner satellites.

4.3. Meteorites and comets

The surface of meteorites is fully exposed to solar UV radiation. It was found that complex molecules can be formed. Polycyclic aromatic hydrocarbons (PAHs) are a very widespread class of organic molecules. The UV processing of PAHs in meteoritic $\text{H}_2\text{O}$ ice was investigated e.g. by Bernstein et al. (2002).

On comets hydroxyl radicals are formed in the coma by UV radiation that splits up water. The following reactions are important:

\begin{align*}
\text{H}_2\text{O} + h\nu & \rightarrow \text{OH} + \text{H} \quad (6) \\
\text{H}_2\text{O} + h\nu & \rightarrow \text{O} + \text{H} + \text{H} \quad (7) \\
\text{H}_2\text{O} + h\nu & \rightarrow \text{O} + \text{H}_2 \quad (8)
\end{align*}

where $h\nu$ denotes a UV photon.

Friedson et al. (2003) modelled this complex photochemistry and also the evolution of the planetary atmospheres as the giants migrate toward their central star.

4.4. UV Radiation on Satellites

Here we consider only satellites of planets that have an atmosphere.

The icy objects like Pluto and satellites of the Solar System are exposed almost unprotected to UV radiation from the Sun. This radiation drives photochemistry on the icy surfaces of planets like Pluto, Jupiter’s moon Europa, and Saturn’s moon Tethys. On Europa radiolytic products like hydrogen peroxide and molecular oxygen are produced. Ganymede contains $\text{O}_2$ in its atmosphere because of the photolysis of $\text{H}_2\text{O}$. Coloured regions
on the surfaces of icy objects may consist of organic material produced by radiation and when the surface is exposed to electrical energy.

The largest satellite of Saturn, Titan deserves special attention. Its atmosphere consists of up to 95% of nitrogen N₂ and about 2% of methane. The surface of Titan is formed by the photolysis of methane in the stratosphere - the products precipitate out of the atmosphere, and the CH₄ vapour pressure is reduced. On Jan 14th, 2005, the ESA Huygens probe made a successful descent and landing on Titan’s surface. The texture on the surface resembles wet sand or clay composed of a mixture of dirty water ice and hydrocarbon ice.

Acknowledgements

A. H. thanks the Austrian Academy of Sciences for financing the exchange of scientists.

References


A. HANSLMEIER AND M. VÁZQUEZ: SOLAR UV RADIATION

Scheffler, H. and Elsässer, H.: 1974, Physik der Sterne und der Sonne, Bibliographisches Institut, Fig. I.6.
UV ZRAČENJE U SUNČEVU SUSTAVU

A. HANSLMEIER\textsuperscript{1} i M. VÁZQUEZ\textsuperscript{2}

\textsuperscript{1} Institut f. Physik; Geophysik, Astrophysik und Meteorologie, Univ. Graz, Austria
\textsuperscript{2} Instituto de Astrofísica de Canarias, IAC, La Laguna, Tenerife

UDK 523-74
Izlaganje sa znanstvenog skupa

\textbf{Sažetak.} Izvor UV zračenja u Sunčevu sustavu je uglavnom Sunce. Ovdje se razmatra utjecaj raznih sastavnica UV zračenja kao i promjenljivost tog zračenja. Ukratko se prikazuje na kojim vremenskim skalama je UV zračenje promjenljivo i na koji način utječe na atmosfere planeta. UV zračenje zvijezda sličnih Suncu koje bi mogle biti okružene planetima ima važnu ulogu u protezanju naseljivih zona u takvim sustavima.

\textbf{Ključne riječi:} Sunce - UV zračenje - promjenljivost - planetarne atmosfere