Publication Year	2022
Acceptance in OA	2023-06-06T09:00:26Z
Title	Monitoring of the solar UV radiation at INAF Observatories
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Publisher's version (DOI)	10.36116/MEMSAIT_93N1.2022.6
Handle	http://hdl.handle.net/20.500.12386/34233
Journal	MEMORIE DELLA SOCIETA ASTRONOMICA ITALIANA
Volume	93

Mem. S.A.It. Vol. 93, 52
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Monitoring of the solar UV radiation at INAF Observatories

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Received: 15 May 2022; Accepted: 26 May 2022

Abstract. Since the start of the SARS-CoV-2 pandemic several studies have attempted to explain the geographical and temporal patterns of the COVID19 infection by the modulation of the solar UV radiation hitting the Earth's surface. Indeed, the amount of such radiation is an important parameter for the Earth's ecology. The solar UV radiation reaching the Earth's surface is estimated by using satellite data and indirect methods, as well as with direct measurements at several locations on Earth, including a few ones in Italy. In order to explore the sensitivity of direct UV measurements to environmental conditions, and provide results for further investigations of the relation between the spread of the COVID19 infection and exposure to solar UV radiation, a new UV monitoring program has been started at INAF Observatories in summer 2020. Here we present the data and methods employed, and the preliminary results achieved during a period of 20 months from September 2020 to March 2022. These results show the effects of the location, season, weather and local environmental conditions on the solar UV radiation that reached the measurements sites.

Key words. Sun: UV radiation – Methods: data analysis – Atmospheric effects – Techniques: miscellaneous

1. Introduction

The ultraviolet (UV) radiation of the solar electromagnetic spectrum extends from 100 nm to 400 nm. The amount of such radiation (hereafter referred to as solar UV) is an important parameter for the atmosphere, environment, and ecology of Earth. Indeed, as the solar UV passes through the Earth's atmosphere, it affects the composition and dynamics of the Earth's atmosphere with a potential impact on the Earth's climate (see, e.g., Ermolli et al. 2013). Moreover, once it reaches the Earth's surface, the solar UV affects the terrestrial ecosystem in many ways (e.g., Paul and Gwynn-Jones 2003). In fact, exposure to solar UV is vital for plants and humans, due to the fundamental role for the photosynthesis in plants' leaves and beneficial action in Vitamin D of individuals. However, over exposure to solar UV results in detrimental effects to many living organisms, due to e.g. the permanent DNA damage contributing to skin cancer and germicidal power on microbes. Therefore, although the solar UV represents less than 8% of the total Sun's radiative output, it has a significant impact on the Earth's atmosphere and ecology. In this light, over the past months several studies have attempted to explain the patterns of the SARS-CoV-2 pandemic by modulation of the solar UV through its impact on both the spread and mortality of the COVID19 virus.

It is worth noting that, after having travelled unaltered until the Earth's atmosphere, there the solar UV is strongly modified by absorption and scattering of various gases and particles. In particular, at atmospheric heights > 50 km the molecular oxygen (O_2) and ozone (O_3) absorb all the solar UV with wavelength below 280 nm (UVC), while lower down in the stratosphere (< 50 km height), O_3 and other atmospheric components, such as the water vapour, oxygen and carbon dioxide (CO_2), partly absorb the solar UV covering the wavelength range 280-315 nm (UVB) and that in the range 315-400 nm (UVA). In addition to the transmitted component, UVB and UVA are scattered by the molecules, water vapor, and aerosols in the Earth's atmosphere.

Since all the UVC, and ≈ 90 % of the UVB and $\approx 10\%$ of the UVA Sun's radiation are absorbed in the Earth's atmosphere, the solar UV reaching the Earth's surface is largely composed of UVA with a small UVB component. However, the amount of solar UV hitting the Earth's surface at any time (hereafter referred to as Solar Irradiance at Ground, SIG) depends on several factors, namely the Sun-Earth distance, Sun's height in the sky (zenith angle), thickness of the O_3 layer (total ozone), and other atmospheric properties, such as the presence of clouds and aerosols. Moreover, the SIG depends on environmental conditions that include the latitude and altitude of the reached surface, and ground reflection.

Figure 2 in Tanskanen et al. (2006) shows the global distribution of the clear-sky UV index, which is a quantity derived from SIG estimates on clear-sky conditions, at local noon on a given day. However, the presence of clouds can lead to large deviations between the solar UV radiation reaching the Earth's surface and that reported in the above mentioned Figure. In fact, depending on the physical properties of clouds, their interaction with the solar radiation can both strongly enhance and deeply attenuate the SIG, see e.g. Figure 3 in Tanskanen et al. (2006). Similarly, multiple reflections between the ground and atmosphere due to the Earth's surface albedo and atmospheric particulate matter can also affect the SIG.

Based on the UV virucidal power, the well established seasonal modulation of the SIG, and the observed characteristics of SARS-CoV-2 pandemic, several studies have attempted to explain the geographical and temporal patterns of the COVID19 infection by modulation of the SIG (see, e.g., Nicastro et al. 2021; Isaia et al. 2021, and references therein). These studies have revealed a significant correlation between the seasonal variability of the UV sunlight and main patterns of the pandemic spread and impact (e.g., Nicastro et al. 2020, 2021). However, there are several open questions. On one hand, most of the studies reported the effect to an average solar spectrum while the seasonal trend of the solar UV strongly affects the spectral region between 295 and 300 nm, which is of peculiar significance for the germicidal power on microbes. On the other hand, the data employed in most of the studies mainly derive from satellite measurements that may not represent the SIG accurately. In fact, the satellite data, as for e.g. the data of the NASA Ozone Monitoring Instrument (OMI; e.g., Levelt et al. 2018) and ESA Tropospheric Emission Monitoring Internet Service (TEMIS; e.g., van Geffen et al. 2005), consist of direct measurements of Earth's atmosphere tropospheric trace gases

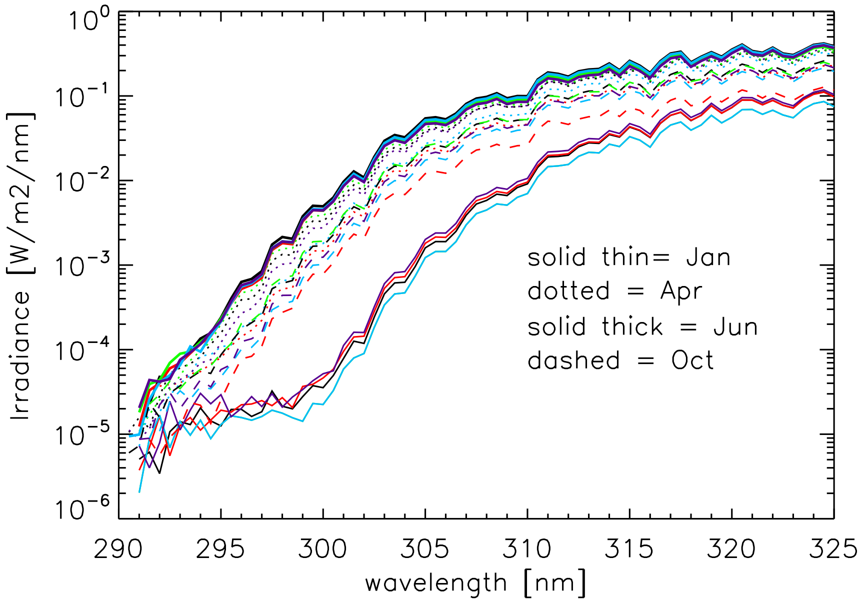

Fig. 1. Example of the solar UV irradiance spectra in the wavelength range 290-325 nm measured around noon by ARPA Valle d'Aosta on the months of January, April, June, and October 2020. The spectra reported with different colors and lines show the daily and seasonal variation of solar UV radiation hitting the measurement site, respectively.

and aerosol concentrations, and of indirect estimates of solar UV products, cloud information, and surface albedo climatologies. The latter estimates are obtained from direct measurements of the O_3 layer at local solar noon, with compensation for daily and local measured variations of the O_3, and for changes of other atmospheric components. The effects of these changes on measurements are estimated by using constant scale factors. In addition, the indirect estimates of cloud-modified UV radiation are available only for some locations on Earth. Figure 8 in Zempila et al. (2017) shows that direct SIG measurements and satellite-derived SIG data can differ by more than 100% due to cloudiness.

Routinely measurements of the SIG are available for several locations on Earth at e.g. the World Meteorological Organization (WMO) data centre (WOUDC)[1]. The UV data available at WOUDC include broadband, multiband and spectral measurements performed from 1924 to present, with several instruments in many countries. As for Italy, the WOUDC includes data sets from 9 stations, 2 of which operating at the present time. In addition to these, there are time series of SIG measurements available for a few locations in Italy from the solar UV monitoring programs performed by some institutions (e.g., Fountoulakis et al. 2013, and references therein). As an example, Figure 1 reports the solar UV spectra at ground from the UV monitoring program carried out by the Agenzia Regionale Protezione Ambientale Valle d'Aosta (ARPA VDA). The solar radiation is measured with a double monochromator in the range 290-500 nm, with a step of 0.25 nm and a resolution

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[1] WOUDC supports the Global Atmosphere Watch (GAW) program operated by Environment and Climate Change, Canada.

of 0.5 nm, on the roof of the institute, which is located in a semi-rural context slightly influenced by the anthropogenic activity (e.g., Diemoz et al. 2011, and references therein). The ARPA VDA high-quality spectral data in Figure 1 clearly show both the seasonal and daily variations of the SIG at the monitoring station. However, these data are not suitable for investigations of the impact of local and environment conditions on the SIG and SARS-CoV-2 pandemic spread.

To this aim, a new UV monitoring program has been activated at INAF with the goal of acquiring data of the solar UV under different measurement conditions. INAF with its observatories located at different latitudes and environmental conditions, and the practice of its teams in performing inter-comparison measurements campaigns, has offered the opportunity to easily explore the sensitivity of SIG to local conditions.

In this paper, the preliminary results of solar UV monitoring performed at INAF observatories across 20 months are presented to describe the qualitative and quantitative impact of location, season, weather, and other environmental conditions on SIG. In Sect. 2 the data and methods used for the UV measurements are described. In Sect. 3 the daily and seasonal trends of the UV sunlight at the INAF measurements sites are analysed, as well as the effects of local environmental conditions during measurements. Finally, in Sect. 4 the main findings and the conclusions of the new monitoring program are summarized.

2. Data and Methods

The solar radiation monitoring program has been activated at the INAF Observatories of Arcetri (OAA, 43°45′N, 11°17′E, 198 m)[2], Brera at Merate (OAB, 45°42′N, 9°26′E, 292 m), Catania (OACt, 37°31′N, 15°4′E, 0 m), and Rome at Monte Porzio Catone (OAR, 41°55′N, 12°27′E, 128 m). At the above sites, the solar spectrum is measured in the range 200-1100 nm with a step of 0.5 nm and 1 nm resolution by using StellarNet Black-Comet SR spectrometers. These are commercial devices with dual blaze 40 mm diameter concave grating optics with aberration correction and no mirrors. These characteristics allow to increase the sensitivity of the instrument and limit the stray-light in it. A fifth instrument is available for future operation at the Observatory of Catania at Serra La Nave, located on Mt Etna at 1725 m altitude. The INAF solar UV measurements sites are characterized by different environmental conditions and represent almost the full latitudinal extent of the Italian territory.

Fig. 2. Measurement set-up at the INAF OAR.

Figure 2 shows the instrument setup at OAR. The solar radiation is collected by a StellarNet CR2 cosine receptor lens coupled with the spectrometer via fiber optic cables. The receptor, which collects the sunlight within a 180 degree field-of-view, and cables are placed on a tripod pointing to the Sun. The spectrometer and laptop employed to acquire the spectral data are settled nearby. During measurements, they are sheltered from sunlight by a Mylar curtain. Laptop and spectrometer are connected with a USB2 interface cable.

The spectrometers were calibrated by StellarNet to NIST standards before their installation at the INAF Observatories. The absolute calibration accuracy certified by the company is ± 5% when using the instruments with the integration and environmental con-

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[2] Acronym used in the following, latitude, longitude, and altitude of the monitoring station.

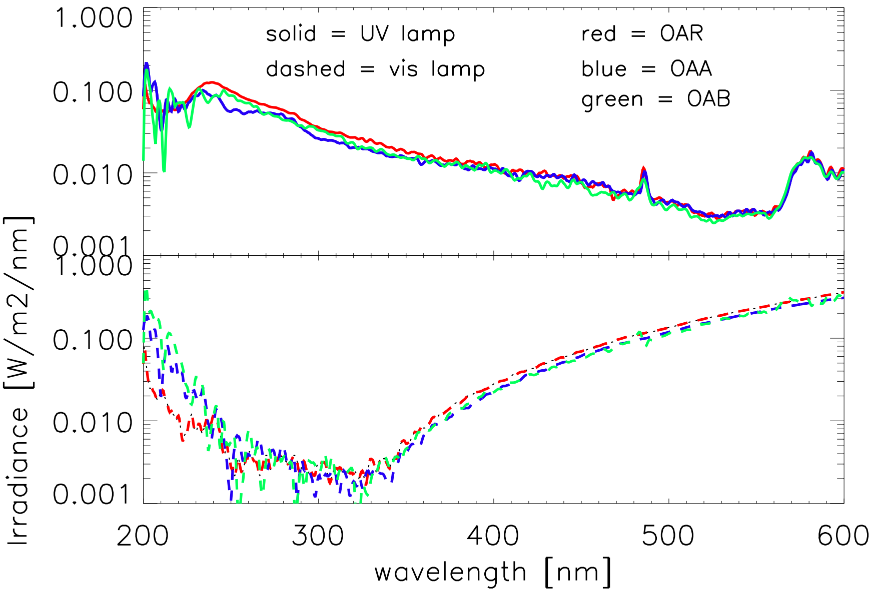

Fig. 3. Spectral responsivity of the OAA, OAB, and OAR instruments to reference standard lamps in the UV (top panels) and visible (bottom panels) ranges.

ditions employed for the calibration to NIST standards. However, in the INAF monitoring program the devices are used with different integration than the one assumed for the above calibration. In order to estimate the error in the data collected at the diverse stations, the instruments were further calibrated at the INAF OAA Astrobiology Laboratory by using standard lamps. Figure 3 displays the spectral responsivity of the OAA, OAB, and OAR instruments to two reference lamps in the UV and visible ranges available at the OAA Astrobiology Laboratory under same testing set-up. The data in the Figure show that the three instruments are characterized by a slightly different responsivity in the UVB range, and an even more significant deviation for wavelengths below 280 nm. The results of calibration measurements performed at INAF OAA suggest that the overall error in UVB and UVA measurements with the three instruments can be twice the one certified by the company under different testing conditions. In fact, the discrepancy in measurements with the three instruments ranges from ≈ 6% to 25% and from ≈ 3% to 20% in the UVB and UVA bands, respectively.

Since the arrival of the spectrometers at the monitoring stations, the solar UV was monitored rather regularly at OAB and OAR, and less often at OAA and OACt. At present, there are measurements of the solar UV acquired at OAB and OAR over a period of 20 months from September 2020 to March 2022. At these stations, the data were acquired Monday to Friday and weather permitting on a total of 224 days, with an average of 7 measurement days per month at both sites. In particular, measurements were obtained at OAB (OAR) on 94 (130) days from March 2021 (September 2020) to March 2022. The SIG was measured at OAR with a hourly cadence from approx 10 to 13 local time during days with good weather conditions, while at OAB it was monitored only at noon but independently on weather conditions. Since the start of the INAF monitoring program more than 2200 SIG measurements have been acquired at OAB and OAR under standard and different environmental conditions.

3. Results

Figure 4 shows the solar UV irradiance spectra covering the wavelength range 200-400 nm that were measured almost simultaneously at OAB (dashed line), OACt (dotted line), and OAR (solid line) at various Sun's heights in the sky on 10 March 2021. The data in Figure 4 display the effect of both the Sun's heights in the sky and local weather on the solar UV radiation reaching the measurement sites. In fact, the radiation measured under sunny weather conditions at OAR show larger variations with Sun's height than obtained from the data taken under partly cloudy conditions at OACt. In particular, the ratio of the UVA/UVB radiations measured at OAR under sunny conditions varied from 10 to 13 local time by $\approx 30\%$, and less than $\approx 15\%$ at OACt over the same interval but under partly cloudy conditions. Moreover, the UVA and UVB radiations measured at the three sites differ by up 130% when comparing data taken at almost same time under sunny and cloudy weather conditions. In particular, depending on time and weather, the radiation measured by the three instruments differs from 9% to 125% in the UVB band, and from 12% to 130% in the UVA band. It is worth noting that the above discrepancies in the measured solar UV may also derive from other environmental conditions during the acquisition of data than Sun's height and local weather. Moreover, we notice that the measurements performed in the range 200-280 nm are dominated by instrumental noise; those for wavelengths below 300 nm are characterized by higher values with respect to e.g. high-quality data from the ARPA VDA monitoring. This discrepancy is suggestive of an instrumental stray-light contribution to the values measured in that range.

The effect of local conditions on the measured solar radiation is also shown by the data reported in Figure 5. This Figure displays the UV irradiance spectra measured at OAR at four zenith angles with the standard setup employed for the solar monitoring and around noon under different environmental conditions. In particular, the measurements were performed on 3 March 2021 by using same setup at the standard location of monitoring on the terrace of the institute, at the forefront of the institute, in the park of the institute, and in the shade near the entrance door of the institute. The data in Figure 5 show that the solar UV radiations measured in all open-air locations at various Sun's heights differ by less than $\approx 30\%$, while the UV radiations measured at same elevation in open-air and in the shade differ by more than 2500%. It is also worth noting that the measurements in open-air and in the shade return a different ratio of the UVA/UVB radiations.

Figure 6 shows the solar UV irradiance spectra measured at OAR for the period from March 2021 to March 2022, during which regular measurements are available for both the OAB and OAR sites. The measurements were all acquired close to local noon. The data in Figure 6 display a clear seasonal change of the measured radiation, with daily variations that only occasionally exceed the seasonal changes. However, we recall that at OAR the solar monitoring is limited to days of good weather conditions.

In order to investigate the dependence of the measured radiation on season and weather conditions, we computed monthly averages of the UV spectra and ratios between UVA and UVB radiations for all the months of overlapping OAB and OAR measurements. At the former station the monitoring is performed independently on weather conditions. Figure 7 shows monthly averaged solar UV irradiance spectra from daily measurements performed at OAB and OAR from March 2021 to March 2022 at about noon, from 12 to 13 local time. The data in Figure 7 clearly show the seasonal course of the solar UV radiation at the two monitoring stations, with a larger variability of the radiation reaching the ground in spring and fall months than that received in summer and winter months. It is worth noting that for both stations, the averaged irradiance obtained from the data taken in spring months exceed

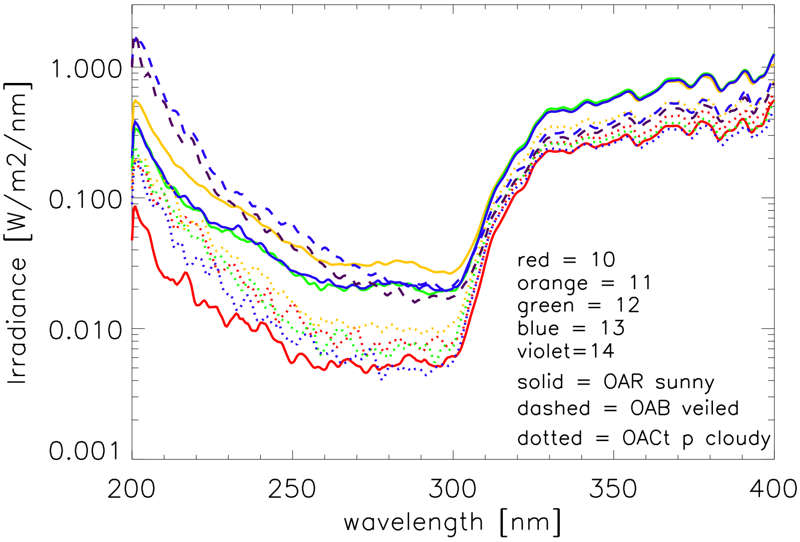

Fig. 4. Solar UV irradiance spectra measured at the INAF Observatories of Brera (OAB, dashed line), Catania (OACt, dotted line) and Rome (OAR, solid line) on 10 March 2021 from 10 to 14 local time [CET]. Measurements at different zenith angles are shown with the diverse colors specified in the Legend.

the one obtained from the measurements performed in summer months. The data in Figure 7 also clearly show that the seasonal variability of solar UV radiation measured at OAB is larger than the one reported at OAR, due to the impact of clouds and other environmental effects on measurements at OAB, as e.g. air temperature and humidity and instrumental setup. In particular, at OAR, the UV radiation at 315 nm around noon increased by ≈ 185% in the annual course, while that at 390 nm by ≈ 175%. On the other hand, at OAB, the increase of the two above UV radiations over the same period was about twice larger than the one reported for OAR. In particular, at OAB, the UV radiation at 315 nm around noon increased by ≈ 400% in the annual course, and that at 390 nm by ≈ 325%.

Finally, in Figure 8 we show the variation of the solar UV flux in the UVA and UVB bands estimated from the measurements performed at OAB and OAR at about local noon from March 2021 to March 2022, as well as the ratio of the UVA/UVB radiations at the two monitoring stations. The data in Figure 8 show a small difference between the UVB fluxes that reached the two stations during the analyzed period, and a larger discrepancy in the UVA radiations measured at the two sites. The data in the Figure do not show a clear seasonal trend, but they are suggestive of a variation of the measured fluxes on time scales exceeding the period considered in the present study. This variation may derive from climatologies of the solar UV, as well as from instrumental aging. Regular inter-calibration measurements with standard lamps available at the INAF OAA Astrobiology Laboratory can provide important data to investigate the nature of the trends in Figure 8.

4. Conclusions

The solar UV radiation reaching the Earth's surface is largely variable due to a combination of several factors, including astronomical terms and atmospheric and local environmental conditions. Given the beneficial and harmful effects of solar UV radiation on human health and living organisms, it is important to accu-

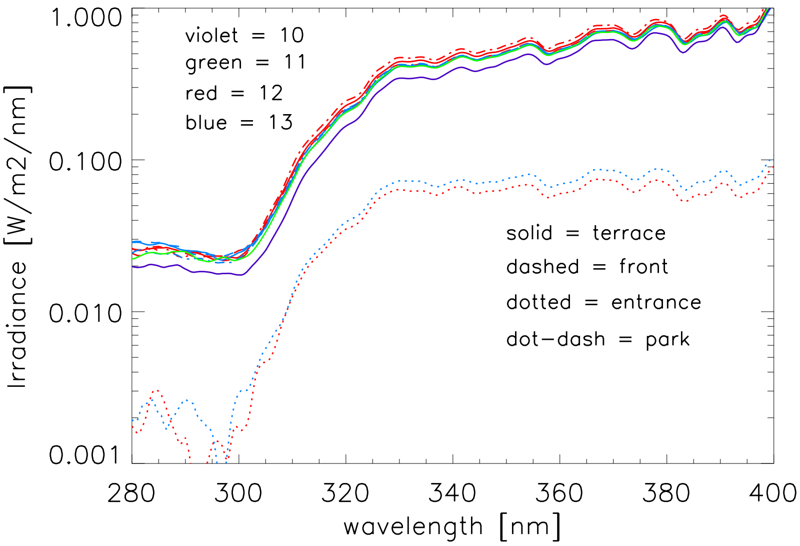

Fig. 5. Solar UV irradiance spectra measured at the INAF Observatory of Rome on 3 March 2021 from 10 to 13 local time [CET] at four elevation angles and around local noon under different environmental conditions. Solid, dashed and dot-dashed lines show measurements in open-air at the usual measurement site (terrace), forecourt (front) and park of the institute, while dotted line shows measurements results close to the institute door in the shade (entrance).

rately characterize the solar UV radiation at ground. However, for many locations on Earth the solar UV hitting the ground level is only indirectly estimated from satellite data of the Ozone in the Earth's atmosphere. Direct measurements of the solar UV radiation at ground are available for several location on Earth, including a few ones in Italy, from national and international solar UV monitoring programs. However, the latitude extension and large variety of environmental conditions in Italy make the solar UV data derived from those programs unsuitable to investigate the role of local conditions on e.g. the patterns of the COVID19 infection.

A new monitoring program of the solar UV radiation has been activated at INAF in summer 2020 with the goal of acquiring data useful to improve the understanding of the impact of climatological and local environmental conditions on the solar UV at ground. The main task is to characterize the variation of the solar UV at sites that largely differ in terms of latitude, weather, and environment.

Since the start of the INAF UV monitoring program, the solar radiation was measured at four INAF institutes, rather regularly at the Observatories of Rome and Brera and less often at the Observatories of Catania and Arcetri. More than 2200 measurements of the solar UV radiation have been acquired under standard and different environmental conditions accross a period of 20 months from March 2021 to March 2022.

The data collected by the INAF monitioring program clearly show the effects of seasons and local environmental conditions on the solar UV radiation that reached the INAF measurements sites. Intercalibration measurements performed with standard lamps show that, despite the limitations due to the characteristics of the commercial spectrometers employed

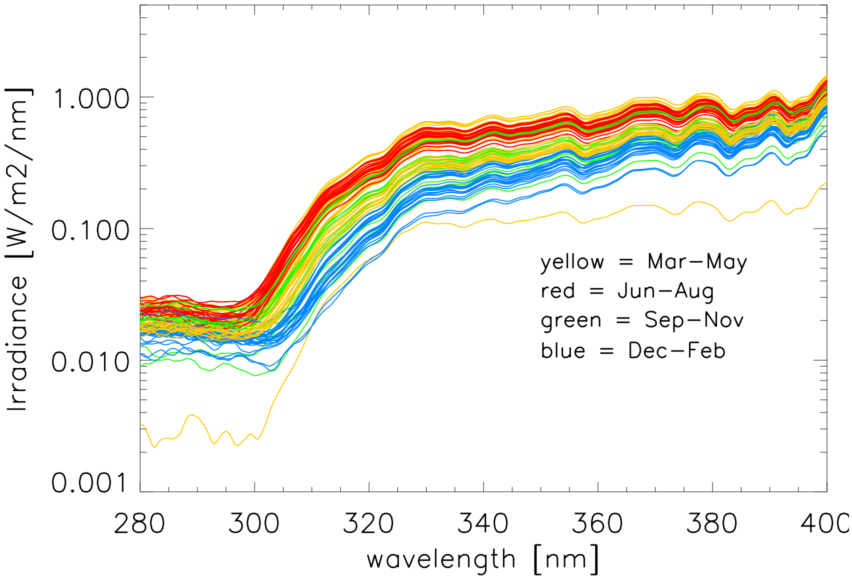

Fig. 6. Solar UV irradiance spectra measured at the OAR on clear-sky and good weather days from March 2021 to March 2022 at about local noon.

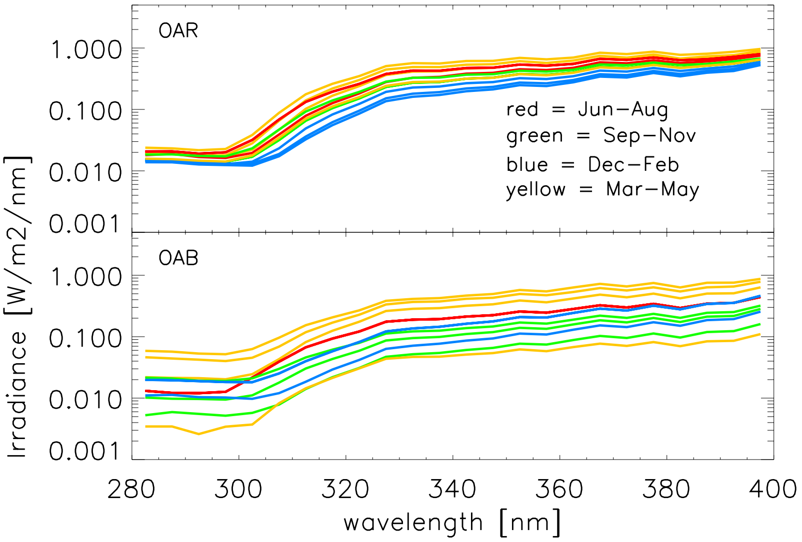

Fig. 7. Solar UV irradiance from the measurements performed at OAR (top panel) and OAB (bottom panel) from March 2021 to March 2022. We show the monthly average flux from the data taken at about local noon, from 12 to 13 local time [CET]. The data for spring, summer, fall, and winter months are shown with the colors described in the Legend. Flux values are shown in 5 nm bin steps.

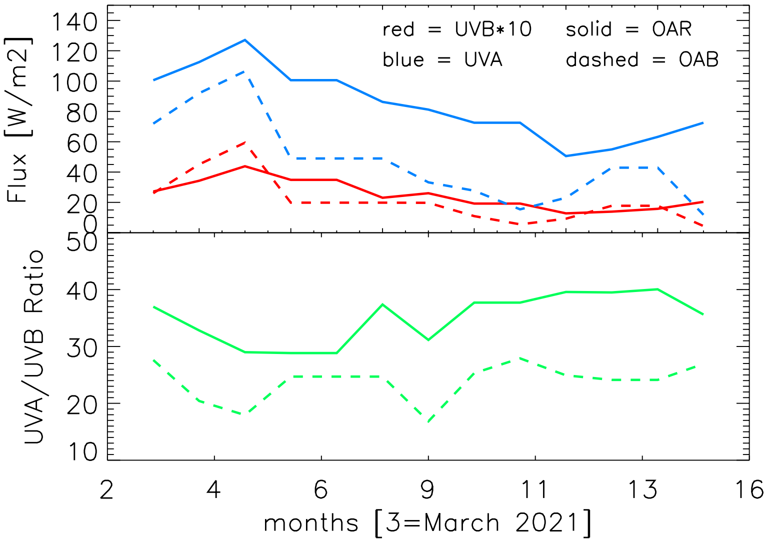

Fig. 8. Variation of the solar UV flux in the UVA and UVB bands from March 2021 to March 2021 from the measurements performed at OAR and OAB (top panel) at about local noon and annual course of the UVA/UVB ratio at the two sites (bottom panel).

for the measurements, the UV radiation measured at the INAF Observatories can be considered representative for the measurements sites within ≈ ± 10% error measurement.

The data gained by the INAF UV monitoring program can serve to characterize the solar UV radiation at ground in Italy. They can serve to further study the relation between the modulation of the solar UV and SARS-CoV-2 pandemic, as well as to characterize the biologically effective solar UV radiation. In addition, they can allow to further investigate the correlation between satellite products from the OMI and TEMIS programs and condition to local UV solar exposure in Italy.

Acknowledgements. We are grateful to the INAF Presidents Prof. Nichi D'Amico and Prof. Marco Tavani, and INAF Science Director Dott. Filippo M. Zerbi, for having fostered the INAF IVC programme. We thank Dott. Giovanni Pareschi, leader of the IVC programme, and all the researchers involved, for the many interesting discussions on the solar UV and its biological effects.

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