Solar UV and EUV Irradiance and Solar Indices

Linton Floyd[1], Jeff Newmark[2], Lynn Herring[1], John Cook[2], and Don McMullin[3]

[1]Interferometrics, 14120 Parke Long Court, Suite 103, Chantilly, VA 20151, USA
[3]Code 7660, E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375 USA
[3]Praxis, Inc., Praxis Inc., 2200 Mill Rd., Alexandria, VA 22314 USA

Abstract

Studies of the solar UV (120–290 nm) spectral irradiance have shown that its variation correlates well with that of the core-to-wing ratio of the Mg II compound absorption feature near 280 nm. The two chromospheric emission lines in the feature's core cause nearly all of the Mg II index variation. The Mg II index has also been shown to correlate with solar He II emerging from the transition region. Although earlier studies appeared to show that an accurate representation of the solar Ly-α irradiance required the separation of the long- and short-term components of the Mg II index, recently recalibrated measurements show that Ly-α also has a linear relationship with Mg II. We analyze the solar spectral irradiance derived from SOHO EIT images roughly corresponding to coronal line emission of Fe IX/X, Fe XII, and Fe XV and find that the Mg II index represents their variation more effectively than the more commonly used $F_{10.7cm}$ flux. The long-term behavior of $F_{10.7cm}$, Mg II, and sunspot number are compared showing a strong divergence of the latter during the latter stages of the solar cycle 23 maximum.

Overview and Outline

Variations in the solar EUV (10–120 nm) and UV (120–400 nm) spectral irradiance is known to affect Earth's atmosphere, especially its upper layers. Longer-term, they also may influence terrestrial climate. Direct measurements of the EUV/UV irradiance are difficult and expensive. They must be performed above the absorbing atmosphere and the instruments must carry on untended for long periods of time. Accordingly, easily measured (relatively) solar indices provide an alternative to direct irradiance measurements. Solar indices are useful if direct measurements are:

- unavailable, or
- of insufficient quality.

Direct measurements can suffer from excessive noise or large instrumental trends, thereby degrading their quality.

Here, we evaluate solar indices for their ability to describe EUV/UV measurements. Solar indices considered are the international sunspot number (SSN), the 10.7 cm solar radio flux, the He I 1083 nm Equivalent Width (He I), and the Mg II core-to-wing ratio (Mg II). Each of these solar indices is considered to be a proxy for solar bright features (e.g. faculae, plage, and active network regions) which are understood to cause variations in the solar EUV and UV flux.

The UV and EUV irradiance analysis are presented separately since the available experiments usually measure only one or another. We display and validate UV and EUV irradiances through experimental intercomparisons. The Mg II index and its composite versions are introduced. Four solar facular/plage index proxies are intercompared on short and long time frames. The UV and EUV irradiance time series are then compared with Mg II and $F_{10.7cm}$.

Solar UV Irradiances and Validation

The solar UV irradiance has been measured by several experiments since 1978. We consider two UV spectral irradiance experiments aboard the Upper Atmosphere Research Satellite (UARS):

- Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)
- Solar Stellar Irradiance Comparison Experiment (SOLSTICE)

These experiments have the following advantages:

- Time series extending 12+ years
- Self-calibrating
- Nearly 100% data overlap

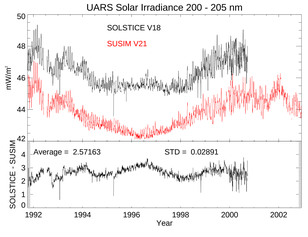
Solar UV irradiance has two dominant and persistent periodicities:

- Solar Cycle (∼11 year)
- Solar Rotation (∼27 day)

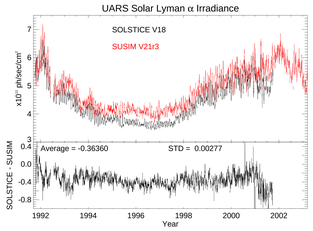
Solar UV irradiance variation is stronger for:

- shorter wavelengths
- emission lines
- absorption line cores

Displayed below are the SUSIM and SOLSTICE time series of the 200–205 nm integrated irradiance (Brueckner et al., 1993; Woods et al., 1993).



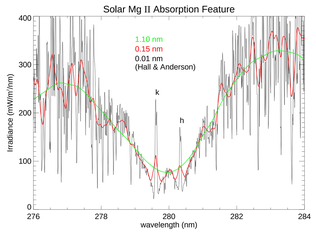
In both time series, the decline of solar cycle 22, the ensuing solar minimum, the rise of solar cycle 23 are apparent. The effects of solar rotation (∼27 day periodicity) are also observed to be similar as is evident through examination of the differences plotted below. The level of correspondence between the two data sets shown here is typical of wavelengths below 263 nm. Although the time series show very similar relative behavior, the irradiance level is significantly different. This is attributed to uncertainties in the ground calibration and its transfer to the space venue.



The Ly-α irradiance provides a second example of the level of correspondence between SUSIM and SOLSTICE whose Ly-α time series are displayed below. The solar cycle and rotation effects are again evident, but the magnitude of the variation is much higher. As before, the two time series are offset. Although the offset is larger relative to the level of irradiance, it is smaller relative to the solar variation. Earlier studies (e.g., Floyd et al., 1997) had shown that the solar Ly-α irradiance might be best fit with a linear combination of long- and short-term components of the Mg II index, but more recently calibrated data no longer support this.

The Mg II Core-to-Wing Ratio

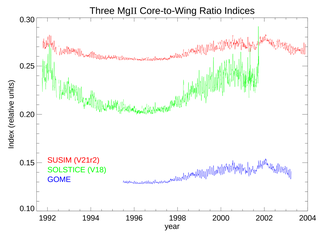
The Mg II core-to-wing ratio index (Mg II) has been measured by more than 8 long-term solar UV irradiance experiments since 1978.



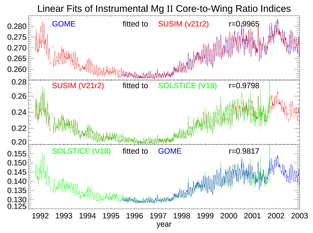
The Mg II core-to-wing ratio index (Mg II):

- is based on the Mg II absorption feature near 280 nm (see figure above)
- is defined to be the irradiance ratio of the chromospheric core to the photospheric wings
- is measured by more than eight solar UV irradiance experiments
- is not normally an absolute measurement – actual values dependent on the resolution of each measuring instrument
- from different instruments are linearly related (see figure below)
- composite index is formed using measurements from several instruments

Below are displayed Mg II indices gathered during the last decade from three instruments, SOLSTICE, SUSIM, and GOME having underlying instrumental resolutions of 0.20 nm, 1.1 nm, and 0.17 nm, respectively (deToma et al., 1999; Floyd et al., 1998; Weber et al., 1998).

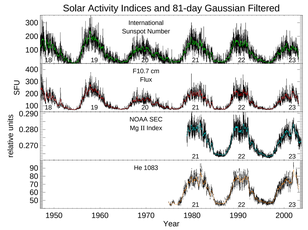


The plots below show these same indices when linearly least squares fitted to one another; the high correlations (>0.98) demonstrate their linear dependence.

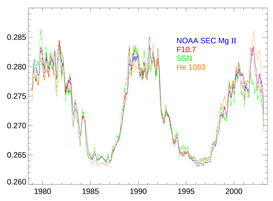


Solar Activity Indices

Solar total and spectral irradiance are known to vary with solar activity. We consider four solar activity indices, the international sunspot number (SSN), the $F_{10.7cm}$ radio flux, the He 1083 nm Equivalent Width (He), and Mg II (Tapping, 1987; Donnelly et al., 1986; Viereck & Puga, 1999). The $F_{10.7cm}$ index is the 10.7 cm radio flux measured the ground daily since 1947. The He 1083 nm Equivalent Width (He) is the width of the solar 1083 nm infared absorption line assembled from ground based solar images obtained since 1974. These time series are displayed below. Also plotted is long-term (filtered) version of each time series which was produced by convolving the original time series with an 81-day FWHM Gaussian function. This convolution effectively removes (i.e. smooths over) the effects which occur on solar rotation time scales.



We compare these smoothed time series by finding the linear relationship with each of the others while including only those data common to all. This allows comparision of the quality of the data themselves while removing the dependence on the number of data points. Plotted below is the case where Mg II is fitted by the other three. Below the figure are two tables showing the correlations of the long and short-term components of each index to one another. (The short-term component is equal to the difference between the index and its 81-day filtered version.)



Long-Term	SSN	F10.7	Mg II	He 1083
SSN	1.000	0.981	0.975	0.951
F10.7	0.981	1.000	0.991	0.973
Mg II	0.975	0.991	1.000	0.984
He 1083	0.951	0.973	0.984	1.000

Short-Term	SSN	F10.7	Mg II	He 1083
SSN	1.000	0.803	0.698	0.627
F10.7	0.803	1.000	0.762	0.666
Mg II	0.698	0.762	1.000	0.853
He 1083	0.627	0.666	0.853	1.000

Through these comparisons of SSN, $F_{10.7cm}$, He, and Mg II, we observe:

- their long-term behavior is quite similar, especially Mg II and $F_{10.7cm}$,
- during the secondary peak of the Solar Cycle 22 maximum:
  - SSN did not experience the 2nd peak near the end of 2001
  - He 1083 was significantly higher than the others
- not secular trend in level of the minima are observed.

Irradiances from SOHO EIT

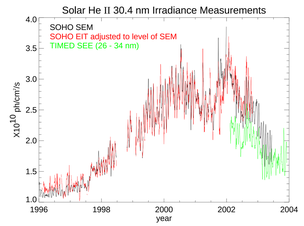
The EUV Imaging Telescope (EIT) has obtained images of four solar emission lines. The table below summarizes the four EIT channels:

Emission line	λ	Temp. (K)
He II	30.4 nm	80K
Fe IX/X	17.1 nm	1M
Fe XII	19.5 nm	1.5M
Fe XV	28.4 nm	2M

Although not originally intended to produce solar spectral irradiances, the EIT images were flat-fielded, calibrated for degradation, and summed to produce a daily irradiance time series. Nearly all of the degradation was accounted for through comparison with measurements of the onboard calibration lamps. However, some effects of the periodic CCD detector bakeouts remained in the images through time. To successfully carry the EIT responsivity through bakeouts, a solar activity index, $F_{10.7cm}$ or Mg II, was required. EIT irradiances are given in relative units (DN) because EIT was not absolutely calibrated on the ground before flight.

Solar EUV Irradiances and Validation

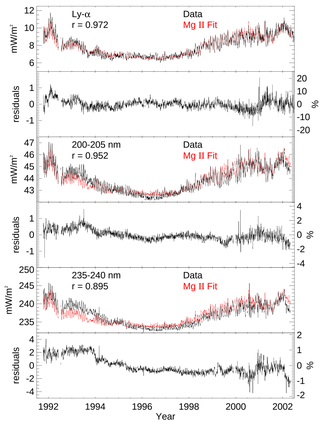
Although this is now changing, there have been fewer long-term EUV irradiance experiments than for the UV. Currently, there are three experiments having available long-term irradiance measurements of the important He II 30.4 nm emission line, the Solar EUV Experiment (SEE) aboard the TIMED satellite, and the Solar EUV Monitor (SEM), and EIT.

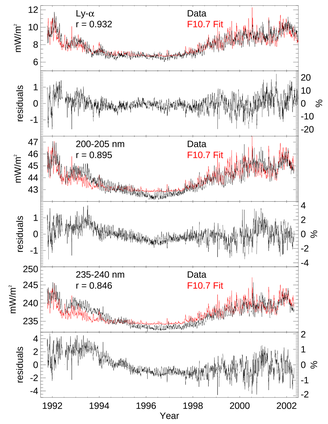


The EIT irradiance time series has been adjusted for a best fit of that of the SEM. As before, the relative correspondence among the time series is quite good, although there is a constant but small offset between the SEE and SEM.

Solar UV Correspondence with Indices

Integrated SUSIM solar UV irradiances for the 200–205 nm and 235–240 nm wavelength bins and also the Lyα irradiance are separately fitted with Mg II and $F_{10.7cm}$ as displayed below.

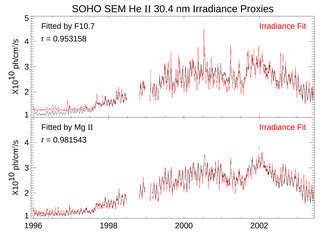


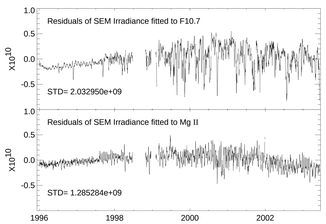


Generally, the correspondence with Mg II and $F_{10.7cm}$ is stronger for shorter wavelength where the solar variation is larger. Long-term differences between the fits and measurements are likely caused by unresolved instrumental trends. In every case, the solar UV irradiances correspond more closely to using Mg II.

Solar EUV Correspondence with Indices

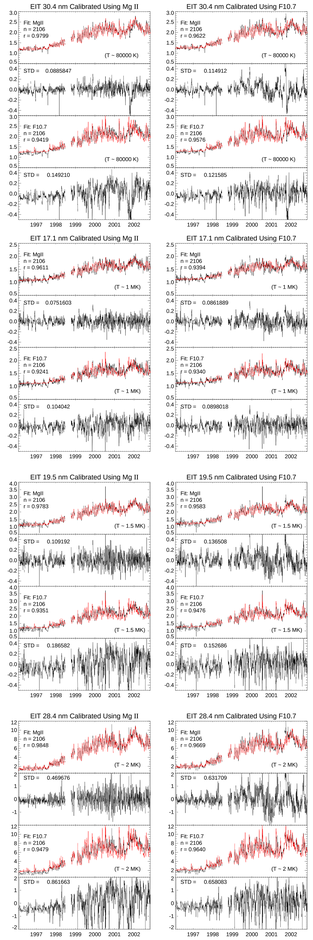
The SEM 30.4 nm flux is separately fit with $F_{10.7cm}$ and Mg II as displayed below.





The SEM time series of He II suggests that Mg II better explains transition region emissions. A comparison of the residuals of each fit show clearly that Mg II captures the short-term behavior more effectively than does $F_{10.7cm}$. That Mg II explains the SEM He II 30.4 nm data was shown earlier by Viereck et al. (2001) and Floyd & Herring (2000).

As the SEE has been collecting data for less than two years, we do not yet consider its behavior relative to solar indices. By contrast, EIT has gathered solar images since solar minimum in 1996. The problem, of course, is that a solar index is required to process the raw EIT images into solar spectral irradiances. Any results favoring one index over another therefore could be questioned on the basis of circular reasoning. To overcome this objection, we process the EIT images using each of $F_{10.7cm}$ and Mg II and compare the results. In each of the four sets of figures below, we calibrate each EIT time series (Fe IX/X, Fe XII, Fe XV, and He II) using $F_{10.7cm}$ and Mg II. Each time series was then fit with each of those two indices.



For calibration by Mg II, we find that Mg II fit the EIT data better in every case. For calibration by $F_{10.7cm}$, the fits with Mg II were at least as good as fits with $F_{10.7cm}$. Thus, we conclude that the Mg II core-to-wing ratio index describes EUV spectral irradiance time series for coronal temperatures up to 2MK better than does $F_{10.7cm}$.

Summary and Conclusion

Based on data from long-term solar EUV and UV spectral irradiance experiments, we find that the Mg II core-to-wing ratio index better describes the time series behavior of UV and EUV irradiances studied than does $F_{10.7cm}$. This corresponds to emissions from the solar atmosphere having a range of temperatures of ∼4K–2MK. This common time series behavior indicates an important connection exists between the corresponding solar atmospheric layers from where these radiations originate. Heretofore, models of the solar EUV have been often based on $F_{10.7cm}$ (Lean, 1990). Originally, $F_{10.7cm}$ was used because Mg II was, at that time, unavailable. studies have shown that $F_{10.7cm}$ flux is made up of not only "thermal" radiation, but also from free electrons in gyroresonance which occurs where strong magnetic fields are present, mainly sunspots (Tapping, 1987).

We have also shown that the differences between the Mg II and $F_{10.7cm}$ time series occur over mainly short-term (solar rotation) time scales. Short-term differences among indices and irradiances can be caused by for by strong but occasional transient effects (e.g. flares) or its center-to-limb variation (Donnelly & Puga, 1990; Crane et al., 2003). These facular/plage solar indices also show no identifiable long-term trends. However, the recent secondary peak in $F_{10.7cm}$, Mg II, and He 1083 at the start of 2002 is not reflected in international sunspot number. This divergence between sunspot number and more direct radiative measures of solar activity should be carefully noted when considering historic solar behavior.

Bibliography

Brueckner, G. E., Edlow, K. L., Floyd, L. E., Lean, J. L., and Vanhoosier, M. E. (1993). The solar ultraviolet spectral irradiance monitor (SUSIM) experiment on board the Upper Atmosphere Research Satellite (UARS). *J. Geophys. Res.*, 98:10695–+.

Crane, P., L. P., Cook, J., Herring, L., and Avrett, E. (2003). The Center-to-Limb Behavior of Solar Active Regions at Ultraviolet Wavelengths. *A&A*, page in review.

de Toma, G., White, O. R., Knapp, B. G., Rottman, G. J., and Woods, T. N. (1997). Mg II core-to-wing index: Comparison of SBUV2 and SOLSTICE time series. *J. Geophys. Res.*, 102:2597–2610.

Donnelly, R. F., Heath, D. F., and Lean, J. L. (1982). Active-region evolution and solar rotation variations in solar UV irradiance, total solar irradiance, and soft X rays. *J. Geophys. Res.*, 87:10318–10324.

Donnelly, R. F., Hinteregger, H. E., and Heath, D. F. (1986). Temporal variations of solar EUV, UV, and 10.830-A radiations. *J. Geophys. Res.*, 91:5567–5578.

Donnelly, R. F. and Puga, L. C. (1990). Thirteen-day periodicity and the center-to-limb dependence of UV, EUV, and X-ray emission of solar activity. *Sol. Phys.*, 130:369–390.

Floyd, L., Brueckner, G., Crane, P., Prinz, D., and Herring, L. (1997). Correlations of Solar Cycle 22 UV Irradiance. In *ESA SP-415: Correlated Phenomena at the Sun, in the Heliosphere and in Geospace*, pages 235–+.

Floyd, L. E. and Herring, L. C. (2000). An Analysis of the EUV Time Series from the First Order Channel of the SOHO CELIAS SEM Experiment. *Physics and Chemistry of the Earth C*, 25:421–424.

Floyd, L. E., Reiser, P. A., Crane, P. C., Herring, L. C., Prinz, D. K., and Brueckner, G. E. (1998). Solar Cycle 22 UV Spectral Irradiance Variability: Current Measurements by SUSIM UARS. *Sol. Phys.*, 177:79–87.

Hall, L. A. and Anderson, G. P. (1991). High-resolution solar spectrum between 2000 and 3100 A. *J. Geophys. Res.*, 96:12927–+.

Lean, J. (1990). A comparison of models of the sun's extreme ultraviolet irradiance variations. *J. Geophys. Res.*, 95:11933–11944.

Tapping, K. F. (1987). Recent solar radio astronomy at centimeter wavelengths - The temporal variability of the 10.7-cm flux. *J. Geophys. Res.*, 92:829–838.

Viereck, R., Puga, L., McMullin, D., Judge, D., Weber, M., and Tobiska, W. K. (2001). The Mg II Index: A Proxy for Solar EUV. *Geophys. Res. Lett.*, 28:1343–+.

Viereck, R. A. and Puga, L. C. (1999). The NOAA Mg II core-to-wing solar index: Construction of a 20-year time series of chromospheric variability from multiple satellites. *J. Geophys. Res.*, 104:9995–10006.

Weber, M., Burrows, J. P., and Cebula, R. P. (1998). Gome Solar UV/VIS Irradiance Measurements between 1995 and 1997 - First Results on Proxy Solar Activity Studies. *Sol. Phys.*, 177:63–77.

Woods, T. N., Prinz, D. K., Rottman, G. J., London, J., Crane, P. C., Cebula, R. P., Hilsenrath, E., Brueckner, G. E., Andrews, M. D., White, O. R., Vanhoosier, M. E., Floyd, L. E., Herring, L. C., Knapp, B. G., Pankratz, C. K., and et al. (1996). Validation of the UARS solar ultraviolet irradiances: Comparison with the ATLAS 1 and 2 measurements. *J. Geophys. Res.*, 101:9541–9570.

Woods, T. N., Rottman, G. J., and Ucker, G. J. (1993). Solar-Stellar Irradiance Comparison Experiment I. II - Instrument calibrations. *J. Geophys. Res.*, 98:10679–+.

Acknowledgements

We thank the many institutions and individuals who provided data used in this study. Rodney Viereck of NOAA SEC provided the most recent Mg II composite index. The He 1083 data are derived from NSO/Kitt Peak data which are produced cooperatively by NSF/NOAO, NASA/GSFC, and NOAA/SEL. Data from U. Colorado experiments TIMED/SEE (PI: Tom Woods) and SOLSTICE (PI: Gary Rottman) were retrieved from their respective WWW sites. The International sunspot number and $F_{10.7cm}$ flux were obtained from the National Geophysical Data Center. SOHO is a mission of international cooperation between ESA and NASA.