

Improved solar Lyman α irradiance modeling from 1947 through 1999 based on UARS observations

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Abstract. The solar Lyman α radiation is the brightest solar vacuum ultraviolet (VUV; $\lambda < 200$ nm) emission, and this radiation is deposited in Earth's atmosphere above 70 km. The Lyman α irradiance and its variability are therefore important for many studies of the Earth's upper atmosphere. A long-term data set of the solar Lyman α irradiance from 1947 through 1999 is constructed using the measurements from the Atmospheric Explorer E (AE-E), the Solar Mesospheric Explorer (SME), and the Upper Atmosphere Research Satellite (UARS) along with predictions from proxy models to fill in data gaps and to extrapolate back to 1947. The UARS measurement is used as the reference, and the AE-E and SME measurements and the proxy models are adjusted to agree with the UARS values. The estimated 1- σ uncertainty for this long-term Lyman α time series is 10%. The average solar rotation (27-day) variability in Lyman α is 9% from this composite times series, and the solar rotation variability averaged over 2 years at solar minimum and maximum conditions is 5 and 11%, respectively. The average solar cycle (11-year) variability is a factor of 1.5 when the data are smoothed over 2 years, and the extreme Lyman α variability is a factor of 2.1. The Lyman α irradiances averaged over 2 years during solar minimum and maximum conditions are 3.7 and 5.6×10^{11} photons $s^{-1} cm^{-2}$, respectively. The proxy models include three components to better fit the UARS measurements; nonetheless, there remain differences between the proxy models and the observed Lyman α irradiance, which are related to the source of the Lyman α radiation being different than that for the proxies. The available proxies are primarily chromospheric and coronal emissions, whereas the Lyman α variability is manifested more in the transition region. It is shown that emissions throughout the chromosphere, transition region, and corona vary differently mainly because their contrasts for active network and plage components are different. A transition region proxy is needed to improve the empirical proxy models of solar irradiance, and this composite Lyman α time series could serve as a proxy for other transition region emissions.

1. Introduction

The bright solar Lyman α radiation of the hydrogen emission at 121.6 nm is an important ultraviolet (UV) source of energy throughout the solar system. For the Earth the solar Lyman α photons penetrate into the mesosphere and deposit their energy mainly by molecular oxygen dissociation in the 70–100 km region. In addition, the solar Lyman α radiation dissociates water in the mesosphere and ionizes nitric oxide to form the ionospheric *D* layer between 80 and 110 km. Because the solar Lyman α radiation is the dominant component in the solar spectrum to drive atmospheric changes in the 70–110 km region, it plays an important role in the chemistry of the minor species such as water vapor, ozone, and nitric oxide [Frederick, 1977; Brasseur and Simon, 1981]. Therefore accurate measurements of the solar Lyman α irradiance are important for studies of the ionosphere and mesospheric chemistry.

The determination of the hydrogen density in the heliosphere, comets, and planetary atmospheres is largely based on measuring the brightness at Lyman α caused by the resonant scattering of the solar Lyman α emission. In particular, the column density of hydrogen is derived by dividing the measured brightness of the H I Lyman α emission by the *g* factor, or fluorescence efficiency, and the *g* factor is based on well-known atomic parameters, such as the emission's oscillator strength, and the solar irradiance [Meier, 1995]. Consequently, the accuracy of the hydrogen abundance is directly dependent on the accuracy of the Lyman α brightness measurement and on the accuracy of the solar Lyman α irradiance, both intensity and line profile. Often there are not correlative measurements of the solar Lyman α irradiance, so estimates or measurements at different times are instead used to analyze the hydrogen abundance in these solar system studies. The long-term, continuous time series of Lyman α irradiance presented here will address this issue by providing accurate solar Lyman α irradiances since 1947, at about the time when space-based measurements of the H I Lyman α emissions within the solar system began.

In order to make a long-term time series of the solar Lyman α irradiance, models of the Lyman α irradiance are needed for time periods when measurements are not available. Understanding the sources of the Lyman α radiation is important for developing accurate models of the Lyman α irradiance. The Lyman α irradiance has both chromospheric and transition region sources [Vernazza *et al.*, 1981], and the

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radiative process of this emission complicates the emergence of the Lyman α radiation. The main component of Lyman α irradiance is the central 0.1 nm line core, which is formed at a temperature of $\sim 40,000$ K in the transition region [Fontenla *et al.*, 1991]. The Lyman α line width of 0.1 nm is due to radiative damping, the Stark effect (electric field broadening), and resonance broadening [Roussel-Dupré, 1983; Vernazza *et al.*, 1981]. The transition region Lyman α core emission, besides contributing to the irradiance output, radiates down into the chromosphere where coherent scattering leads to partial redistribution of the Lyman α radiation into broad wings [Roussel-Dupré, 1983; Vernazza *et al.*, 1981]. The source of the Lyman α wing goes deeper into the chromosphere as one observes farther from the line center. The source function for the Lyman α emission as calculated by Fontenla *et al.*'s [1991] model is presented by Woods *et al.* [1995]. The source function for the quiet Sun model (model C-average cell interior) has the peak Lyman α emission near 40,000 K in the lower transition region. For the plage model (model P), the Lyman α source function has its peak higher in the transition region at a temperature of $\sim 70,000$ K and accompanied by an increase in the radiance by a factor of ~ 6 . This shift of the source function to higher in the transition region for plages is probably the main reason why the Lyman α irradiance varies more like a transition region emission than like a chromospheric emission.

Recent progress to consolidate the past solar Lyman α irradiance measurements into a long-term composite time series includes the effort of Woods and Rottman [1997] and Tobiska *et al.* [1997]. These previous results only included UARS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) data through 1994, which is almost 2 years before the recent solar minimum. The new results presented here include both solar cycle minimum and maximum measurements by the UARS SOLSTICE, significant improvements to the UARS SOLSTICE data processing, and a composite time series of Lyman α irradiance that fills the measurement gaps and extends the time series back almost 30 years further than the previous estimates. The improvements to the UARS SOLSTICE Lyman α irradiances are presented first, followed by the proxy models of the Lyman α irradiance that are calibrated to the UARS solar data. Then the composite of the revised measurements and proxy model predictions is presented as a single, consistent time series of the Lyman α irradiance from 1947 through 1999 with no data gaps. Finally, the sources of the Lyman α emission and of the proxies are examined in order to interpret the differences seen between the Lyman α and proxies variability.

2. Lyman α Measurements

Because of the atmospheric absorption, the solar Lyman α radiation must be measured from space. Several satellites have measured the solar Lyman α irradiance: Solrad 8 (1966), Orbiting Solar Observatory 3 (OSO 3: 1967), OSO 4 (1967-1968), OSO 5 (1969-1975), OSO 6 (1969-1970), Nimbus 3 and 4 (1969-1973), Atmospheric Explorer E (AE-E: 1977-1980), Solar Mesospheric Explorer (SME: 1981-1989), San Marco (1988), and Upper Atmosphere Research Satellite (UARS: 1991-2000). There have also been over 60 sounding rocket measurements of solar Lyman α since 1949; many of these rocket experiments were from the Air Force Geophysical Laboratory (now Phillips Laboratory), the Naval Research

Laboratory, and the University of Colorado to provide an underflight calibration for the satellite measurements. Despite the underflight calibration effort, the satellite measurements of the solar Lyman α irradiance do have significant differences. These differences are partly due to using different photometric standards and to having limited on-board calibration for the pre-UARS solar instruments. Resolving these differences is important in order to combine the different data sets into a single reference and thereby to estimate long-term solar variability.

The satellite measurements used here are from the AE-E, SME, and UARS. The uncertainties for the SME Lyman α irradiances are $\sim 40\%$ [Rottman, 1981; Mount and Rottman, 1983], and the uncertainties for the AE-E Lyman α irradiances are $\sim 30\%$ [Hinteregger *et al.*, 1981]. Whereas, the uncertainty for the UARS Lyman α irradiance is 5% [Woods *et al.*, 1996]. The SME and AE-E measurements could therefore be adjusted within their respective uncertainty levels to agree with the UARS values. These uncertainties and others used elsewhere in this report are 1- σ values.

Because these three satellite missions do not overlap in time, the adjustments for the AE-E and SME data must be determined using proxy models of the Lyman α irradiance that are scaled to the UARS solar measurements. Woods and Rottman [1997] used proxy models involving the Penticton (Ottawa) 10.7-cm radio flux ($F_{10.7}$) [Tapping, 1987], the National Oceanic and Atmospheric Administration (NOAA) Mg II core-to-wing ratio (Mg C/W) [Heath and Schlesinger, 1986; Donnelly *et al.*, 1994], the National Solar Observatory (NSO) He 1083-nm equivalent width (He EW) [Harvey and Livingston, 1992], and the Pioneer Venus (PV) Langmuir probe solar measurements (Ipe) [Hoegy *et al.*, 1993]. Tobiska *et al.* [1997] used a proxy model derived from the Lyman α sky background measurements made over two solar cycles by the PV Orbiter Ultraviolet Spectrometer (PVOUVS). The AE-E and SME adjustments from Woods and Rottman [1997] and from Tobiska *et al.* [1997] are very similar. Their differences arise primarily in the data chosen as the UARS Lyman α irradiance reference value. Tobiska *et al.* [1997] chose to use the measurements solely from the UARS SOLSTICE [Rottman *et al.*, 1993]. Woods and Rottman [1997] also used the SOLSTICE Lyman α values but modified by a factor of 0.95 to represent an average of the measurements from the two UARS instruments, SOLSTICE and Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) [Brueckner *et al.*, 1993]. The 10% difference between the UARS SOLSTICE and UARS SUSIM Lyman α irradiances is within their 2- σ absolute uncertainty of 10% [Woods *et al.*, 1996].

The previous studies by Woods and Rottman [1997] and Tobiska *et al.* [1997] considered data only during the declining phase of solar cycle 22. This new analysis extends from solar cycle 22 maximum through solar minimum and into the rising phase of solar cycle 23. Consequently, the longer time period, coupled with improvements to the UARS SOLSTICE data processing algorithms and calibration parameters, prescribes different scaling factors for the AE-E and SME Lyman α irradiances.

For the long-term composite Lyman α time series presented here, the UARS SOLSTICE version 13 Lyman α irradiances are chosen as the reference. The differences between the UARS SUSIM (version 19) and SOLSTICE Lyman α irradiances are now only a few percent as shown in Figure 1. Prior to 1993 the SOLSTICE values are, on average, 2% lower than the

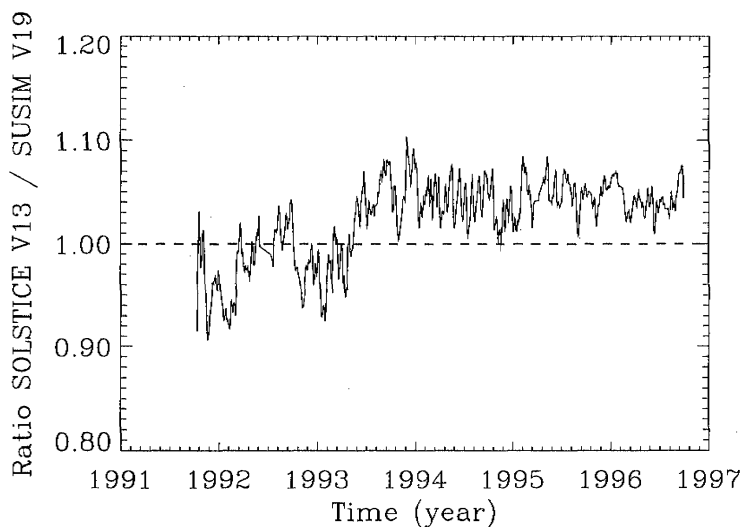


Figure 1. Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) – SOLAR STellar Irradiance Comparison Experiment (SOLSTICE) Lyman α comparison. The average ratio changes from 0.98 to 1.04 during 1993.

SUSIM values. After 1993 the SOLSTICE values are, on average, 4% higher than the SUSIM values. These differences are instrument and calibration artifacts. We considered using the average of SUSIM and SOLSTICE data as the reference but decided that the reference time series would be more consistent using data from a single instrument. As compared to a factor of 2 for solar cycle variability, the differences of a few percent between SOLSTICE and SUSIM would not significantly alter the results presented here.

An important difference between this new composite Lyman α time series and *Woods and Rottman's* [1997] and *Tobiska et al.'s* [1997] time series is that the SOLSTICE version 13 data products are now used. The two previous

results used the SOLSTICE version 9 data products. The SOLSTICE version 13 data processing software has several algorithm enhancements. The four algorithm changes that affect the Lyman α irradiance the most are (1) a new, time-dependent, wavelength-scale correction, (2) a new, time-dependent, field of view (FOV) correction, (3) an improved, overflow counter correction, and (4) an improved algorithm to calculate the line integral. The ratio of the SOLSTICE Lyman α version 9 to version 13 is shown in Figure 2. The primary difference is from the new wavelength-scale correction. The second most important improvement is from the new FOV correction. The improved overflow counter correction reduces day-to-day noise but does not contribute to the long-term

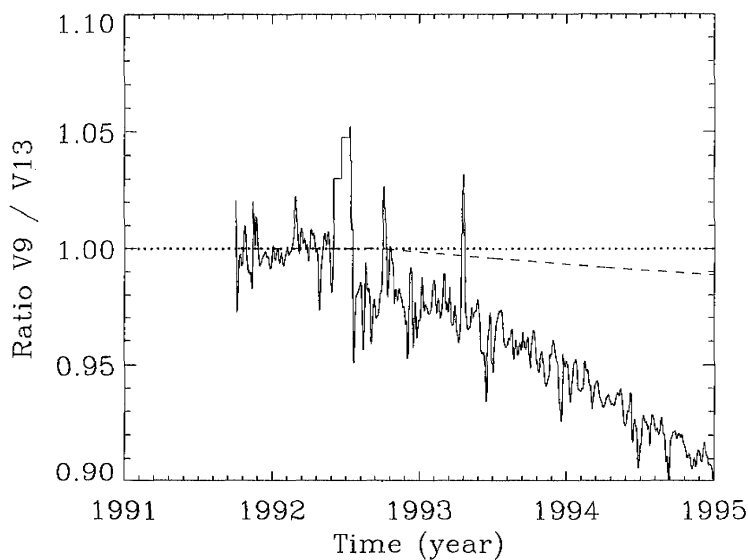


Figure 2. Comparison of SOLSTICE Lyman α version 9 to version 13. The dashed line is the new field of view correction. The remaining difference is primary from the new wavelength-scale correction.

trend. The new line integral algorithm improves the accuracy of deriving the irradiance into 1-nm intervals, but it does not contribute to the long-term trend.

The new wavelength-scale correction is needed to account for a slow drift of the SOLSTICE grating drive encoder electronics. This encoder degradation was first discovered from examination of changes in solar line widths; some were slowly growing wider, and some were slowly growing narrower. Through the comparisons of daily spectra to a reference solar spectrum early in the UARS mission, the grating drive encoder signal was found to be slowly drifting, and a simple correction for the encoder degradation is now applied. The new wavelength-scale correction algorithm has yielded line widths that remain constant over the mission. This wavelength-scale correction is the most significant improvement over the previous work as it affected the long-term trend by several percent.

The FOV correction is a new calibration for the "hole" seen in the SOLSTICE G channel (119-180 nm) FOV maps [Woods *et al.*, 1999]. This FOV correction is largest for the longer wavelengths of the G channel; nevertheless, this correction is also important for the SOLSTICE Lyman α time series. The FOV correction for Lyman α is about a 1-2% correction and is shown in Figure 2 as the dashed line.

The improvements in the overflow counter correction algorithm, which is used when detector counts exceed the 16-bit hardware counter, has yielded lower day-to-day noise in the SOLSTICE Lyman α time series.

The fourth algorithm improvement is the change from a numerical integration to an analytical integration using basis spline functions fitted to the data [Lawson and Hanson, 1974; de Boor, 1978]. The basis spline integrations are done for both the line integrations, such as for the Lyman α emission, and the 1-nm intervals used in the UARS Level 3BS data products. The use of analytical integrations has improved the accuracy of creating 1-nm intervals for the SOLSTICE Level 3BS data product. With the old numerical integration algorithm, there were differences of a few percent between the Lyman α irradiance represented by the 121-122 nm interval irradiance and the irradiance from a Gaussian fit to the Lyman α line. Now the Lyman α irradiances extracted the two different ways are in agreement using the new analytical integration algorithm.

3. Lyman α Proxy Models

Models of solar irradiance are used primarily for atmospheric studies for time periods when measurements are not available. A commonly used solar irradiance model for upper atmospheric studies is Hinteregger *et al.*'s [1981] proxy model. This model and other proxy models employ empirically derived relationships of solar irradiance at one wavelength relative to an index of solar variability that is available on an almost daily basis over many years. Improvements in modeling the solar Lyman α irradiance variability can be obtained by specifying the irradiance as a function of the distribution of quiet and magnetic solar surface features, such as was done by Lean and Skumanich [1983] and Worden [1996]. Both of their models parameterize the solar irradiance as three components: quiet Sun, active network, and plage areas whereby the areas of each component are derived from Ca II K solar images. A more detailed description of these three components and the relationship of

these components to the empirical proxy models is given in section 6. A more physical model of the Lyman α irradiance is the radiative transfer calculations using semiempirical models of the solar atmospheric structure (density and temperature), such as those by Vernazza *et al.* [1981] and Fontenla *et al.* [1999]. In Fontenla *et al.*'s [1999] model, solar images are used to identify seven components of the solar atmosphere (e.g., cell interior, network, and plage), and then an emission's source function is calculated using seven static models of the solar atmosphere. However, the image analyses have only been done over a limited time period and thus are difficult to extend back to the time of the AE-E mission and before. Therefore the simpler proxy model approach is applied here but with some improvements over previous proxy models.

The validity of a proxy model is strongly dependent on the validity of the proxy over its entire time range and on the physical processes connecting the proxy emission and the Lyman α emission within the solar atmosphere. The Lyman α radiation is formed in the chromosphere and transition region of the solar atmosphere, so the most appropriate solar proxies should likewise have a dominant contribution from these regions. In addition, the time series of the proxies need to be long enough to overlap AE-E, SME, and UARS. The three indices used here for Lyman α proxy modeling are the $F10.7$, Mg C/W, and He EW. The solar $F10.7$ measurement has the longest duration dating back to 1947. The two primary sources in the solar atmosphere for the 10.7-cm radio flux are the free-free electron emission (bremsstrahlung) throughout the chromosphere, transition region, and lower corona and gyroresonant absorption in strong magnetic fields in the transition region and corona [Tapping, 1987]. While the daily $F10.7$ is better correlated with coronal emissions than with the Lyman α emission, both the 81-day average $F10.7$ and the square root of $F10.7$ have a good correlation with the Lyman α emission, better than 0.95. Because the correlation with the square root of $F10.7$ is better than the correlation with $F10.7$, the square root of $F10.7$ is used here solely as an empirical improvement. The He EW measurement is representative of the chromosphere and transition region but is also sensitive to coronal holes. The Mg C/W is representative of the chromosphere.

The empirical fits of the UARS Lyman α irradiance measurements to the three solar indices yield the following models for the solar Lyman α irradiance:

$$E = A + C_L R_{81} + C_S (P - R_{81}), \quad (1a)$$

$$E_{He} = 1.1764 + 0.05668 He_{81} + 0.04032 (He - He_{81}), \quad (1b)$$

$$E_{Mg} = -31.68 + 133.7 Mg_{81} + 79.52 (Mg - Mg_{81}), \quad (1c)$$

$$E_{F10} = 0.5839 + 0.3554 \sqrt{F10_{81}} + 0.1730 (\sqrt{F10} - \sqrt{F10_{81}}). \quad (1d)$$

The proxy variables P are labeled He for the NSO He-1083 nm EW, Mg for the NOAA Mg II core-to-wing ratio, and $\sqrt{F10}$ for the square root of $F10.7$. The irradiance E is given in units of 10^{11} photons $s^{-1} cm^{-2}$. The variables, or indices, with the "81" subscript are the daily proxy values smoothed over a period of 81 days. Data gaps in the proxies, which pose a problem for the 81-day smoothing function, are filled by interpolation if the gap is smaller than 6 days or by fast Fourier transform analysis if the gap is larger [Worden, 1996]. These proxy models are derived empirically using the common method of multiple linear regression. The SOLSTICE Mg II core-to-wing ratio is also used for analysis later, and the SOLSTICE Mg