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Solar hydrogen Lyman-α variation during solar cycles 21 and 22

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Abstract. A full-disk, line-integrated solar Lyman-α dataset is presented that spans two solar cycles. The dataset is created partially from AE-E and SME data that is scaled to the Pioneer Venus Orbiter Ultraviolet Spectrometer (PVOUVS) upwind Lyman-α sky background data which is converted to a solar surrogate. PVOUVS measurements overlap AE-E, SME, and UARS observing periods and are calibrated to UARS/SOLSTICE irradiance units at 1 AU. The scaled AE-E/SME, the SOLSTICE, and the PVOUVS surrogate data in the interim between the satellites collectively form a composite dataset with a quiet sun value of $3.0\pm0.1\times10^{11}$ photons cm^{-2} s^{-1} common for three solar minima and a solar maximum value of $6.75\pm0.25\times10^{11}$ photons cm^{-2} s^{-1} common to cycles 21 and 22.

Introduction

Far ultraviolet solar irradiances between 115 and 200 nm are primary energy inputs to the terrestrial atmosphere. These emissions are responsible for major photochemical processes and are absorbed by constituents from the stratosphere, the mesosphere, and the lower thermosphere. H Lyman-α photons, in particular, pass through an O_2 aborption window at 121.6 nm, penetrate to the mesosphere to photoionize NO and form the ionospheric *D*-region, and activate ozone photochemistry. Studies of the temperature, composition, and dynamics in the Earth's upper atmosphere rely upon accurate knowledge of the absolute solar irradiance and its relative temporal variation from short to long timescales.

Line-integrated solar Lyman-α irradiance variations have been measured by several satellites beginning in the 1960's [OSO 4 (1967-1969), OSO 5 (1970-1975), OSO 6 (1969), AE-E (1977-1980), SME (1981-1989), San Marco (1988), and UARS (1991-1997)]. Coincident with these datasets were rocket and shuttle calibration underflights. Lean [1987] summarized general characteristics of the pre-UARS measurements. These observations show that Lyman-α varies on timescales related to activity in the magnetic field or to geometry. One timescale is the dipolar magnetic field's 22-year reversal cycle that manifests an 11-year solar cycle. A second timescale is the evolution and decay of active regions in complexes and/or groups. Convective zone magnetic flux erupts into the solar atmosphere, creates these regions, and changes in a complicated manner over several months. The 27-day solar rotational modulation is another timescale of active region variability though the phasing will change depending upon whether the observer is at Venus or at Earth.

Toward the end of the SME mission, the estimated Lyman-α absolute irradiance 1σ uncertainty was 15% [*Rottman,* 1987]. The range of SME-observed solar cycle variability was a factor of 2, differing from the AE-E/rocket measured factor of 3 [NSSDC/SC#21REFW, *Hinteregger,* 1981]. This discrepancy created confusion since both solar minimum and near solar maximum values were in disagreement. The SC#21REFW solar minimum flux of 3×10^{11} photons cm^{-2} s^{-1} differed significantly from SME's 2.3×10^{11} value. Further complicating matters, rocket measurements during solar minimum (1972-1977) gave fluxes from 2 to 3×10^{11} [*Rottman,* 1981] and SUSIM (Spacelab 2) measured 3×10^{11} [*Van Hoosier and Brueckner,* 1987] in August 1985 near solar minimum.

The comparison of Lyman-α with proxies did not resolve the discrepancies. For example, Lyman-α varied differently from 10.7 cm radio flux on these timescales [*Barth et al.,* 1990; *Tobiska,* 1991]. Hence, it could not be determined whether the solar maximum and minimum discrepancies were a result of inter-instrumental differences or of actual solar irradiance variations.

Another issue clouded the literature. During the end of the rising phase of solar cycle 21, AE-E Lyman-α dramatically changed in absolute value before and after a two week non-observed interval. This jump was not as evident in other emissions measured by AE-E and also did not occur at any time during the SME observations. Similarly, ground-based proxies for Lyman-α such as He I 10,830 Å EW did not show the same change during the same period.

Data are now available that resolve much of this confusion. We believe the evidence points to calibration differences in both AE-E and SME.

Composite Lyman-α dataset

Using the UARS/SOLSTICE solar Lyman-α and the PVOUVS (1979-1992) upwind sky background interplanetary Lyman-α [*Ajello et al.,* 1987; *Pryor et al.,* 1992; *Ajello et al.,* 1994], we have produced a composite Lyman-α dataset spanning two full solar cycles. SOLSTICE Lyman-α measurements began on October 3, 1991 and continue to the present with an absolute accuracy at Lyman-α of 5% (1σ) [*Rottman et al.,* 1993; *Woods et al.,* 1993]. Sky background hydrogen brightness is sensitive to solar line-center emission, solar wind density, and interplanetary hydrogen density. Its upwind time series has been modeled empirically, I_{Model}, using He I 10,830 Å EW as a Lyman-α proxy to provide line-center emission with solar phasing as if it were seen from Venus [*Pryor et al.,* 1992, 1996, 1997; *Ajello et al.,* 1994]. The model removes geometrical variations seen in the data due to upwind viewing at different positions in Venus' orbit around the Sun.

The upwind PVOUVS data, I_{PVOUVS}, can be converted to a *solar* Lyman-α surrogate for comparison to AE-E, SME, and UARS if we assume a constant relationship between Lyman-α

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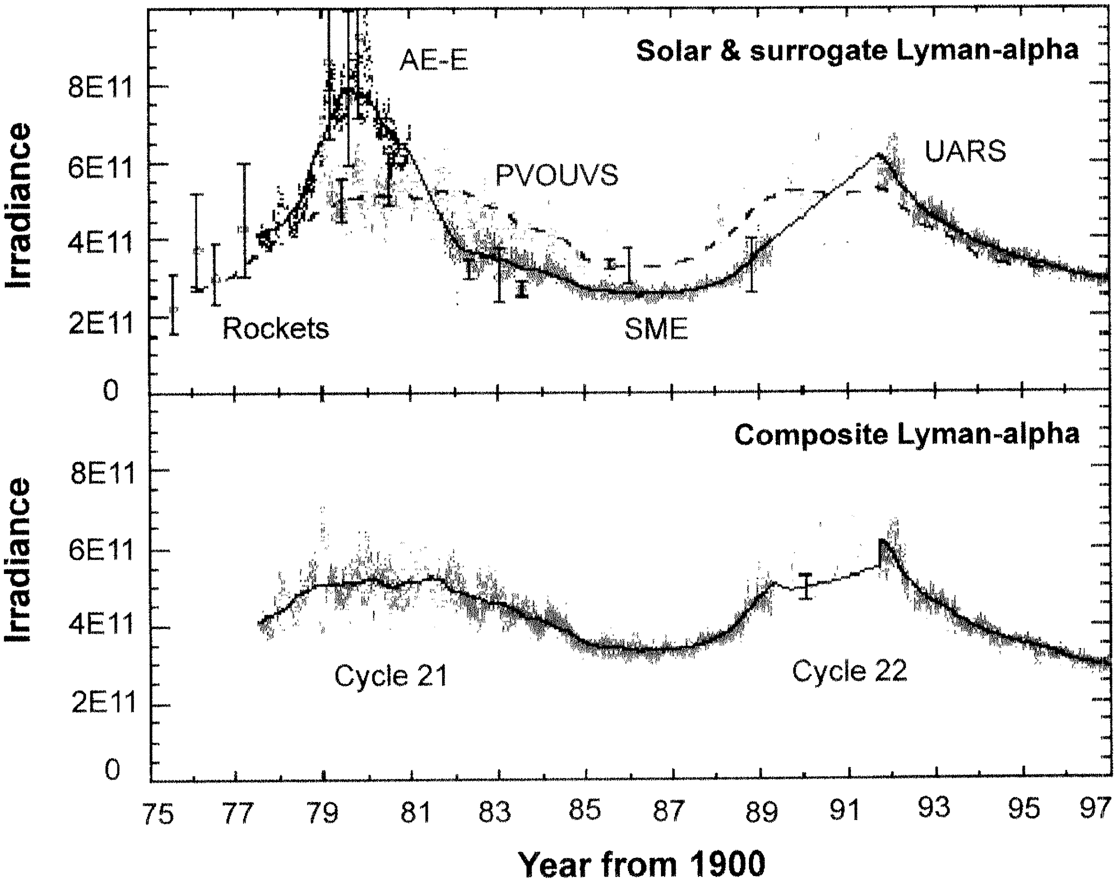

Figure 1. (a) Intercomparison of the $F_{PVOUVS\_Ly-\alpha}$ surrogate (orange), rocket (error bars), and satellite (AE-E blue, SME green, UARS red) Lyman-α irradiances. A dashed line fits the He I 10,830 Å EW to the PVOUVS surrogate. Error bars on rocket measurements are 1σ [*Tobiska*, 1991]. (b) Two-solar cycle composite Lyman-α using scaled AE-E and SME data, unscaled UARS/SOLSTICE, and PVOUVS surrogate data. The 1σ error bar (scatter indicator) is derived from the He I fit (solid line) to the composite Lyman-α. Solar minimum is $3.0\pm0.1\times10^{11}$ and maximum is $6.75\pm0.25\times10^{11}$ photons $cm^{-2}\,s^{-1}$.

sky background line-center and solar full-disk line integrated intensity variations over solar cycle timescales [*Ajello et al.*, 1987]. The Lyman-α proxy used in creating I_{Model} is formed from the relationship between He I 10,830 Å EW and SME Lyman-α [*Tobiska*, 1991] and is then multiplied by the ratio of PVOUVS upwind data to the model. This removes the long-term He I variability differences, incorporates a correction for orbital geometry, and creates a PVOUVS Lyman-α surrogate time series given by equation 1

$$F_{PVOUVS\_Ly-\alpha} = C \times \{ I_{PVOUVS} / I_{Model} \} \times$$
$$\{(\text{He I } 10830 \text{ Å EW}) \times 3.778E9 + 8.403E10\}. \quad (1)$$

This surrogate is converted to irradiance units by C=1.37 which allows the surrogate to match SOLSTICE Lyman-α for commonly measured days. Figure 1a compares AE-E, SME, UARS, and rocket datasets with a plot of this equation. For visual comparison to the solar data, a 365-day smooth of the He I fit to the surrogate $F_{PVOUVS\_Ly-\alpha}$ is shown (dashed line).

It should be noted that I_{Model} has been transformed to Venus-based solar phasing and I_{PVOUVS} is measured at Venus. However, the $F_{PVOUVS\_Ly-\alpha}$ surrogate mixes Earth-based solar phasing (He I) with a Venus-based solar phasing ratio, i.e., the PVOUVS data divided by the model. Although this mixed solar phasing is inappropriate for studying 27-day and, probably, intermediate-term activity, it is not a significant complication for understanding long-term solar cycle variations.

Using the PVOUVS Lyman-α surrogate as the baseline, AE-E and SME data are scaled to a best fit of the surrogate absolute values. Table 1 shows the mean of the scaling ratios, i.e., the factors by which AE-E and SME data in the date intervals are multiplied to obtain the composite Lyman-α dataset. Figure 1b graphically depicts the new composite Lyman-α flux for two solar cycles. It is comprised of scaled AE-E and SME data, the unscaled UARS/SOLSTICE data, and the PVOUVS surrogate for dates on which other measurements are not available.

TABLE 1. Scaling ratios for AE-E and SME

Satellite	Time interval	scale factor
AE-E	(77182-78323)	1.000
AE-E	(78336-80047)	0.650
AE-E	(80075-80365)	0.762
SME	(81281-89103)	1.295

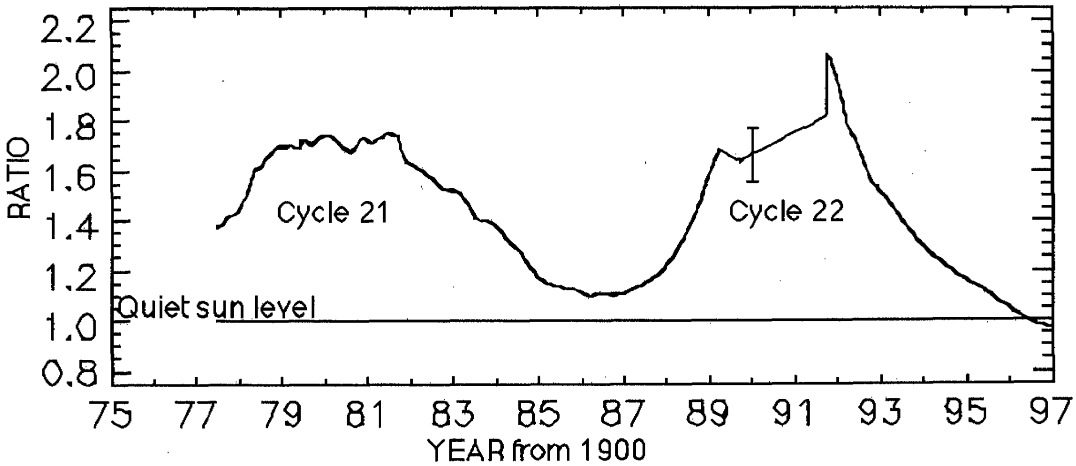

Figure 2. Composite Lyman-α solar cycle variability (365-day smoothed) as a ratio relative to the quiet sun level ($3.0 \pm 0.1 \times 10^{11}$ photons $cm^{-2} s^{-1}$). The 1σ error bar (scatter indicator) is derived from the He I 10,830 Å EW fit (solid line) to the composite Lyman-α.

Discussion

When the scaled AE-E/SME datasets and the PVOUVS surrogate are compared, the earlier discrepancies can be explained. We first make the assumption that the surrogate is well calibrated in a relative sense across the peaks of cycles 21 and 22. The PVOUVS long-term calibration is well-known [*Pryor et al.,* 1992, 1996, 1997]. If the AE-E Lyman-α are to fit the surrogate then AE-E must have had uncalibrated changes twice during its mission. If this is the case, then the solar cycle 21 maximum irradiance level is known. Similarly, if the SME data is used at its $+2\sigma$ level then we find agreement with the surrogate Lyman-α and this leads to a solar cycle 21-22 minimum irradiance level. A concurrent, independent study of long-term Lyman-α by Woods and Rottman [1997] draws similar conclusions with both the AE-E and SME datasets.

The composite Lyman-α in Figure 1b supports a quiet sun value of $3.0 \pm 0.1 \times 10^{11}$ photons $cm^{-2} s^{-1}$. This flux level is common to three cycles and was seen in solar cycle 20 [NSSDC/SC#21REFW spectrum, *Hinteregger,* 1981], solar cycle 21 [*Van Hoosier and Brueckner,* 1987], and solar cycle 22 [SOLSTICE measurements near solar minimum].

Figure 1b also suggests a 3-day smoothed daily maxima irradiance of $6.75 \pm 0.25 \times 10^{11}$ for both solar cycles although the 365-day smoothed data indicates possible differences between the solar cycles. Differences in the areal extent and the number of active region complexes on the solar disk during high solar activity might explain some inter-cycle differences. In addition, the few surrogate data points in the period between SME and UARS have wide scatter. It is likely that the surrogate's calibration with UARS will change by a small amount once the Galileo (1989-1995) Lyman-α sky background data are evaluated. These data are similar to the PVOUVS radiances, they overlap PVOUVS and UARS data, and they are currently being analyzed by the authors of this paper in separate, related research.

We can estimate the solar cycle 21 and 22 variability ratios above quiet sun levels. This variability is graphically shown in Figure 2 using a 365-day smooth where solar cycle 21 maximum/minimum is 1.6 and solar cycle 22 maximum/minimum is 2.0. The ratios are larger if 3-day smoothed data are used.

Conclusions

A composite Lyman-α dataset spanning two full solar cycles has been developed from AE-E, SME, and UARS solar full-disk, line-integrated Lyman-α and PVOUVS Lyman-α sky background data. A geometrically corrected solar Lyman-α surrogate has been created from the PVOUVS upwind sky background data and is calibrated to the UARS/SOLSTICE Lyman-α absolute values. The AE-E and SME data are scaled to the PVOUVS surrogate levels to create the composite Lyman-α dataset.

The comparison between the scaled AE-E/SME and PVOUVS surrogate data suggests that the AE-E Lyman-α monochromator experienced sensitivity changes and thatthe AE-E absolute calibrations should be revised. It also implies that the SME data should be used at its $+2\sigma$ level. The composite Lyman-α dataset produces a quiet sun value of $3.0 \pm 0.1 \times 10^{11}$ photons $cm^{-2} s^{-1}$ which is common for three solar minima and a solar maximum value of $6.75 \pm 0.25 \times 10^{11}$ photons $cm^{-2} s^{-1}$ which is common for cycles 21 and 22. The composite Lyman-α dataset is available electronically in ASCII format from the authors at the internet email address of:

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