Dissimilarity in the evolution of solar EUV and solar radio emission (2800 MHz) during 1999–2002

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[1] For solar UV and EUV the F10 (2800 MHZ solar radio emission), Lyman alpha, and Mg II are used as proxies. During 1999–2002, many solar indices showed two maxima, one near July 2000 and another near January 2002. For F10 and Lyman alpha, the second maximum was higher than the first maximum by ~10%, but for Rz, the second maximum was lower than the first maximum by ~4%. The observed EUV (26–34 nm from SEM-SOHO) had the second maximum higher than the first maximum, but only by ~3.5%. The model values given in SOLAR2000 [*Tobiska et al.*, 2000] show patterns of 26–34 nm qualitatively similar to F10, with second maximum larger than the first maximum, but the magnitude is much larger, ~20%. Thus there is a discrepancy of ~15% between observed EUV and SOLAR2000 model EUV during 2001–2002. The model values are overestimates and do not seem to have taken into account the observed EUV values. *INDEX TERMS:* 7537 Solar Physics, Astrophysics, and Astronomy: Solar and stellar variability; 7507 Solar Physics, Astrophysics, and Astronomy: Chromosphere; 7509 Solar Physics, Astrophysics, and Astronomy: Corona; 7529 Solar Physics, Astrophysics, and Astronomy: Photosphere; 7534 Solar Physics, Astrophysics, and Astronomy: Radio emissions; *KEYWORDS:* solar indices, dissimilarities

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1. Introduction

[2] Solar activity indices show variations in a wide range of time scales, from a few days to several years [*Donnelly et al.*, 1985, 1986; *Hinteregger et al.*, 1981]. Different indices originate in different parts of the solar atmosphere. Each solar region is also a source of radio emissions of certain frequencies, where higher frequencies escape from deeper regions. The magnitudes (percentage changes) differ considerably from one index to another [*Lean*, 1987]. In the work of *Kane* [2002a, 2002b], the behaviors of various indices near sunspot maxima and minima were compared for cycles 18–23. Based on the examination of 12-month moving averages, the general conclusion was that the evolutions of various solar indices around years of sunspot maxima and minima were not always similar to that of sunspots. Sometimes, lags and/or leads of a few months were seen.

[3] Since all solar indices attain maxima near sunspot maximum and minima near sunspot minimum, the long-term correlation between all indices was very high, particularly during rising and declining phases of a solar cycle. However, during the sunspot maximum years, dissimilarities of evolutions of different solar indices were often seen, even in 12-month moving averages. A particularly interesting feature of sunspot numbers was that during years around sunspot maxima, there was generally only one prominent maximum, but in some cycles, there was a broad plateau. If the beginning and end of the plateau are termed as first and second maxima (separated by several months), the first maximum for sunspots was generally the higher one, and the valley in between was very shallow. Solar indices at or near the solar surface generally showed similar structures, with maxima matching with sunspot maxima within a month or two. Indices originating in the chromosphere and above showed two peaks in roughly the same months as sunspots, but for some indices, the second maximum was larger than the first maximum, and the valley between the two maxima was deeper, as compared with sunspot maxima.

[4] For several studies of Sun-Earth relationship, the variations of solar indices need to be established. For ionospheric F region, solar EUV is important. Observations of EUV have been very few (for technical reasons) and in the absence of EUV data, other solar indices are used as proxy. An index consistently used earlier as proxy for EUV is F10, the (observed) solar radio emission at 2800 MHz, 10.7 cm, mainly because the data for F10 are available regularly for a long time (since 1947). Sunspot data are also available, for a much longer time, but correlation studies indicate that in cases where EUV data are not available for comparison, ionospheric parameters are better correlated with F10 than with sunspots. Since 1981, all models, from the reference spectrum (SC#21REFW) of *Hinteregger et al.* [1981] to SOLAR2000 of *Tobiska et al.* [2000], have used F10 copiously. Since 1996, EUV measurements are available in a regular and reliable way [*Judge et al.*, 1998]. In the present communication, the

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variations of F10 and EUV are compared during 1999–2002.

2. Data

[5] Sunspot and F10 data were obtained from the NOAA website (available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/), EUV data were obtained from the University of Southern California website [*Judge et al.*, 1998] (available at http://www.usc.edu/dept/space_science/semdata.htm), Lyman alpha data were obtained from the University of Colorado at Boulder ftp site [*Woods et al.*, 2000a] (available at ftp://laspftp.colorado.edu/pub/solstice/composite_lya.dat), Mg II data were obtained from the NOAA website (available at http://www.sec.noaa.gov/ftpdir/sbuv/NOAAMgII.dat), and SOLAR2000 model data were obtained from Space Environment Technology's Space Weather Division website (available at http://spacewx.com/).

3. Plots of Observed Values

[6] Figure 1a shows the plots of the observed monthly values for F10 (2800 MHz flux), two EUV ranges 26–34 nm and 0.1–50 nm, Lyman alpha, Mg II and sunspot number Rz. There are considerable month-to-month fluctuations (mostly irregular), but one can see a first maximum near July 2000 and a second maximum near February 2002 (both marked by dots). To bring out the maxima more clearly, 12-month running means were calculated and are shown in Figure 1b. The maxima are marked by dots. The numbers in parentheses below the dots are the actual values at the maxima, while the numbers in rectangles above the dots are normalized values at the maxima, with values for the first maximum set as 100. For Rz, the second maximum is lower than the first maximum, by ~4%. For other indices, the second maximum is higher than the first maximum, but there are quantitative differences. For 2800 MHz (10.7 cm) flux (F10), the second maximum is higher than the first maximum by 9.4%, but for the two EUV ranges, the second maximum is higher only by ~3.5%. For Lyman alpha, the second maximum is higher by ~8.9%, almost the same as for F10 (9.4%). For Mg II, the second maximum is higher only by ~1%. (It may be remembered, however, that changes in Mg II are always smaller. For example, from the solar minimum in 1996 to the solar maximum in 2000–2002, F10 and EUV increased by a factor of ~2.80, a change of 180%, Lyman alpha by a factor of ~1.6, a change of ~60%, while Mg II increased by a factor of 1.16 only, a change of 16%; see details in the work of *Kane* [2002c]). Thus the relative heights of the first and second maxima are similar for F10 and Lyman alpha (second maximum larger by ~9%) but much smaller for EUV (second maximum larger only by ~3.5%). For sunspot number Rz, there is a qualitative difference (second maximum smaller, by ~4%). An examination of several other indices (not shown here), indicated that for radio frequencies up to ~1500 MHz escaping from upper corona, the first maximum was higher, while for higher frequencies escaping from middle and lower corona (including 2800 MHz), the second maximum was higher. Indices near the photosphere had mostly the first maximum higher. In the work of *Kane* [2002c], it was shown that amplitudes are generally low near the photosphere, increase in the upper chromosphere, diminish in the transition region (temperature ~100,000 K) and then increase rapidly in the lower corona, diminishing further in the upper corona. This pattern is similar to that of the "emission measure distribution" reported by *Warren et al.* [1998, 2001] and should have an implication for the physical model of EUV flux generation in solar dynamo system.

4. Comparison With the Irradiance Model Estimates of SOLAR2000

[7] As inputs in the terrestrial atmosphere, one needs Irradiance models. These involve (1) reference spectra, i.e., the flux versus wavelength, and (2) formulae for their variations with solar cycle. *Donnelly and Pope* [1973] gave a reference spectrum for moderate solar activity (F 10 = 150). Using the AE-E data, *Hinteregger et al.* [1981] provided a reference spectrum (SC#21REFW) for low solar activity (cycle 21 solar minimum, F 10 = 68). These were followed by the models of *Nusinov* [1984], *Tobiska and Barth* [1990], *Schmidtke et al.* [1992], *Tobiska* [1991], *Richards et al.* [1994], and *Tobiska and Eparvier* [1998]. All these empirical solar EUV models were derived from the AE-E data. However, some accurate EUV measurements from sounding rockets during solar cycle 22 (1992–1994) indicated that the irradiances based on the AE-E data could be underestimates by as much as a factor of 2 at some wavelengths [*Woods et al.*, 2000b; *Bailey et al.*, 2000; *Solomon et al.*, 2001]. Hence a big collaborative project was planned, which started in 1998 and has resulted in SOLAR2000 [*Tobiska et al.*, 2000], which is a new image- and full-disk proxy empirical solar irradiance model, with 1 nm resolution in the spectral range 1–1,000,000 nm for historical modeling and forecasting. For use of research workers who would like to have a quantitative measure of solar input in the terrestrial atmosphere, a new solar proxy (termed E10.7) has been generated as an output product of the SOLAR2000 model. It is the time-dependent solar EUV flux at the top of the Earth's atmosphere, integrated over the range 1–105 nm, and expressed in 2800 MHz 10.7 cm (F10) radio flux units.

[8] From the Space Environment Technology's Space Weather Division website (available at http://SpaceWx.com) (Vers. 1.24 SOLAR2000RG link), we accessed the spectra for 39 wavelength intervals 1.86–2.95 nm, 3.00–4.92 nm,. . .,100.1–105 nm for each day during 1996–2002, obtained the monthly mean spectra, combined these for broader wavelength intervals, and obtained their 12-month moving averages. The plots of the Irradiance model for the two EUV ranges 26–34 nm and 1–50 nm are shown in Figure 1c. Both EUV ranges 26–34 nm and 1–50 nm show the second maximum higher than the first maximum but by a large margin, ~20%, almost 5 times the margin for observed EUV (~3.5%). The third plot is for E10.7, the SOLAR2000 model average over the range 1–105 nm. Here too, the margin is large, ~20%, same as for SOLAR2000 EUV. Thus SOLAR 2000 model values show the second maximum larger than the first maximum by a factor of 2 or more as compared with the observed values, contrary to the assertion that the model values track observed EUV values within ~5% (Kent Tobiska, private communication, 2001). Workers using the SOLAR2000 model values need to keep this difference in mind. The model values can

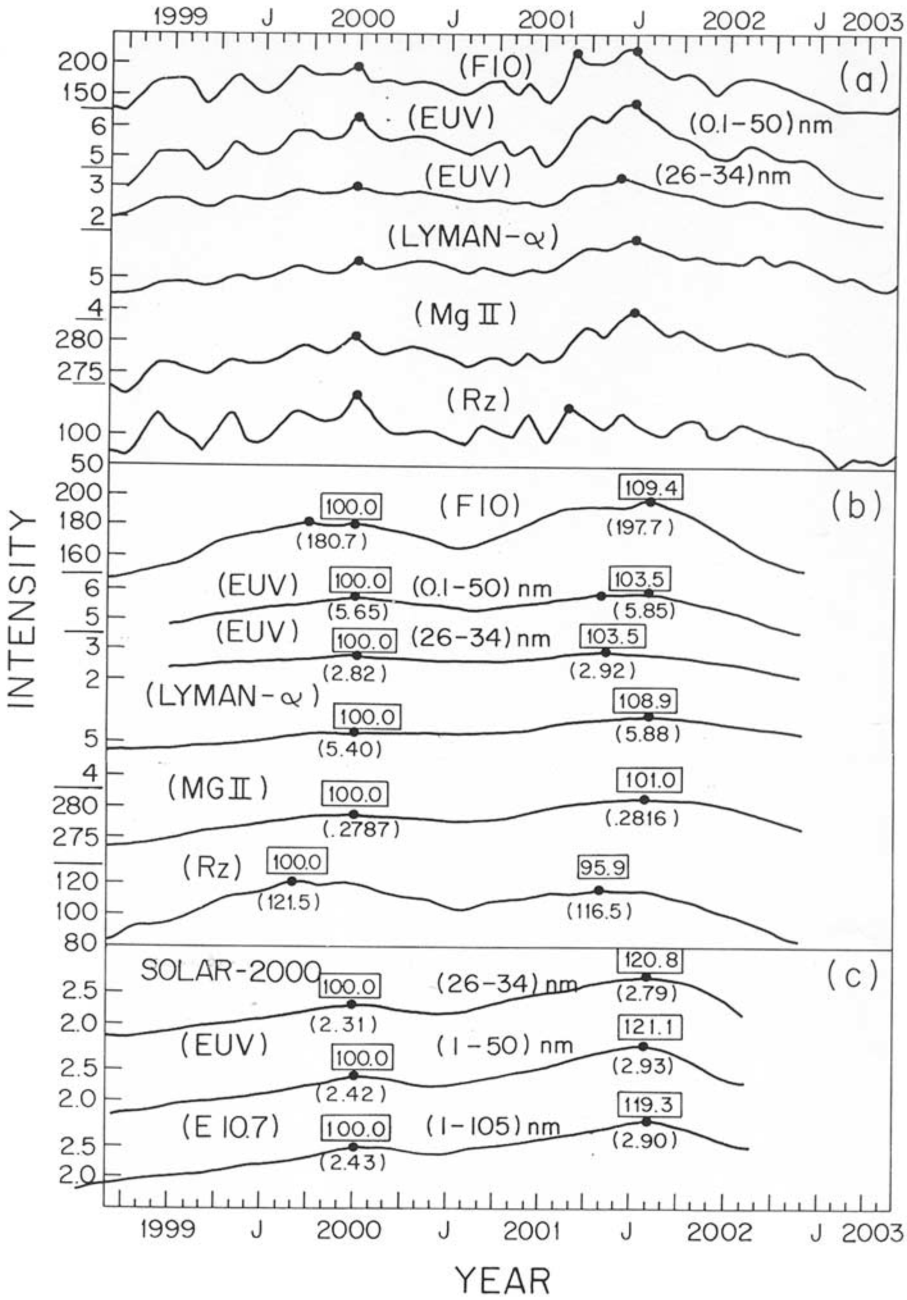

Figure 1. Plots for 1999–2002 of (a) the monthly values of six solar indices, namely F10 (2800 MHz flux), the two observed EUV ranges 26–34 nm and 0.1–50 nm, and observed Lyman alpha and Mg II, (b) 12-month running means of the same six solar indices, and (c) 12-month running means of the SOLAR2000 model values of EUV ranges 26–34 nm and 1–50 nm, and the parameter E10.7 (integrated model solar EUV flux 1–105 nm). The maxima peaks are marked with dots. The numbers in parantheses are values at the peaks (relative to 1.0 at solar minimum of 1996), and the numbers in rectangles are normalized values, with values at the first peak set as 100.

be different from the observed values (in the present case, overestimates), by as much as 15–20%. This is not a random statistical uncertainty but a systematic difference.

5. Conclusions

[9] For solar EUV, the observed F10 (2800 MHz, 10.7 cm solar radio emission) has been used copiously as a proxy. Even in the latest Solar Irradiance model SOLAR2000, F10 seems to be an important factor. In this communication, it is shown that during 1999–2002, F10 and sunspot number Rz showed two maxima, one near July 2000 and another near January 2002, with a minimum in between near February 2001. The second maximum was higher than the first maximum by ∼10% for F10 and Lyman alpha, but for sunspot number Rz, the second maximum was lower than

the first maximum by ~4%. The observed EUV (26–24 nm from SEM-SOHO) had the second maximum higher than the first maximum but only by ~3.5%. The model values given in SOLAR2000 [*Tobiska et al.*, 2000] show patterns of 26–34 nm with the second maximum higher than the first maximum by as much as ~20%. Thus there is a discrepancy of ~15% between observed EUV and SOLAR2000 model EUV during 2001–2002. The model values show ratios of second to first maximum (20%) much larger than even those of observed F10 and Lyman alpha (~9%). The model values are overestimates by ~15%, at least in the present case. Workers using the model values as inputs for any investigation need to keep this possibility in mind.

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