

## Hysteresis and non-linearity between solar EUV and 10.7 cm fluxes

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It has been reported in literature that for values of the solar 2800 MHz radio flux (10.7 cm, F10) exceeding 200, solar EUV values show saturation effects. This aspect was examined using EUV data obtained by the AE-E satellites during 1977-1981 and the SEM/SOHO satellite data from 1996 onwards up to date. It was noticed that the saturation effects were not always seen in sequences of days when F10 exceeded 200. In both of these data sets, near solar maximum, there were slight differences in the evolution of the EUV and F10. Either their peaks were slightly displaced and/or their evolution profiles were different, the F10 remaining steady for several months after peaking (flat peak), while the EUV started decreasing soon after peaking, indicating probable 'hysteresis' loops.

**Key words:** Solar EUV, Solar 10.7 cm flux

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### 1 Introduction

Solar UV (mainly Lyman alpha, 1216Å) and EUV radiations are the primary energy sources of the terrestrial atmosphere. These radiations ionize the primary atmospheric constituents O, O<sub>2</sub>, N<sub>2</sub>, NO, He and H, creating the various ionospheric layers. Hence, accurate measurements of EUV and UV are important for studies of ionospheric variability. However, reliable data for these are not readily available and other solar indices, notably the 10.7 cm solar radio emission flux index (henceforth termed as F10), are often used as proxy. Relationship between solar EUV and F10 has been investigated by many workers (see review by Lean<sup>1</sup> and references therein) and it is reported that on a long-term (solar cycle) basis, EUV and F10 are linearly related, though some deviations from linearity are observed during solar maximum and solar minimum. On short-term (solar rotation) basis, the relationship is irregular and unpredictable<sup>2</sup>. A curious aspect is the phase relationship between ionospheric F2 region daytime maxima and solar indices.

In earlier studies, sunspots and F10 were considered as similar, so much so that Joachim<sup>3</sup> established a formula relating the two to each other. However, there are often considerable phase differences. From his study of correlations between thermospheric density and temperature, Hedin<sup>4</sup> reported that correlations were better with EUV than with F10. When  $f_o F_2$  is compared with sunspots, the relationship is linear for low sunspot numbers, but for

high sunspot numbers,  $f_o F_2$  seems to show 'saturation' effects. Lakshmi *et al.*<sup>5</sup> showed that the saturation effects almost disappeared when solar EUV (170-190Å) was used instead of sunspots.

Kane<sup>6</sup> showed that use of F10 resulted in lesser saturation effects than those using sunspots, though greater than those using EUV. Balan *et al.*<sup>2</sup> analyzed the ionospheric total electron content (TEC) data at several locations in the Northern Hemisphere during 1980-1985 and showed that for values of F10 less than 200, the relationship with TEC(max) was linear, but for higher values of F10, saturation effects were observed at all locations. Richards<sup>7</sup> and Richards *et al.*<sup>8</sup> made some model studies and found that their model values of EUV tallied well with the measured values of EUV and both had similar relationship with F10, namely, saturation of EUV for large F10 values.

In the present communication, the phase relationship between F10 and EUV is studied for two periods when EUV data were available continuously for several years, namely, the AE-E data<sup>9</sup> during 1977-1981 and the SOHO-SEM data<sup>10</sup> from 1996 onwards.

### 2 AE-E and SEM/SOHO data

The AE-E data (1977-1981) are in 15 wavelength groups of flux ratios  $F/F_{ref}$ , where  $F$  is the measured flux for a particular day and wavelength group, while  $F_{ref}$  refers to the sunspot minimum reference period 13-28 July 1976 (Hinteregger *et al.*<sup>9</sup>). The wavelength groups are: 168-190, 190-206, 206-255, 255-300, 304,

510-580, 584, 590-660, 1026, 335, 284, 200-204, 178-183, 169-173 and 1216 Å. The Lyman alpha data (1216 Å) were from a fixed wavelength monochromator, and the rest were from four other wavelength-scanning monochromators with completely independent and physically different diffraction gratings (Hinteregger *et al.*<sup>11</sup>). These data have accuracy and reliability problems as discussed later.

The Solar EUV Monitor (SEM) solar extreme ultraviolet (EUV) spectrometer aboard the Solar and Heliospheric Observatory (SOHO) has been providing the first long-term solar EUV data using a spectrometer specifically designed to be highly stable throughout an extended mission<sup>10</sup>. Data are available from 16 Dec. 1995 in two wavelength ranges, 260-340 Å and 1-500 Å.

### 3 Results for AE-E data

#### 3.1 Daily values

For EUV, Balan *et al.*<sup>2,12</sup> computed and used the solar EUV daily values from the solar EUV flux model SERF2 of Tobiska and Barth<sup>13</sup> and Tobiska<sup>14</sup>, for the period 1981-1985. The actual experimental AE-E data are available only for 1977-1981. Figure 1 shows a plot of the daily values of the fluxes for the AE-E wavelength ranges 168-190, 206-255, 255-300, 510-580, 590-600 Å, and wavelengths 1026 Å (Lyman beta) and 1216 Å (Lyman alpha), versus the F10 values during 1977-1981, to cover a large range (~70 to 370) of F10 values.

There are plenty of points up to F10~200, and these are joined by continuous full lines, and/or a rough average full line drawn through them (visual eye-ball estimation). For F10 exceeding 200, there are fewer points, and the full lines are extended arbitrarily to the one last point at F10 = 350. Some of these (notably the first three plots) show lesser slopes during F10 200-350 as compared to F10 70-200, indicating possible saturation effects. The observed points show a considerable scatter for F10 values above ~200, but the points seem to lie on two separate distinct (dashed) lines, one above the full line and other below it, indicating possible anti-clockwise 'hysteresis' loops, which implies that even at moderate F10 values, the EUV could have two sets of levels, different for the upswing and downswing of a solar cycle. However, the F10 values change considerably from day-to-day and it is not certain that their relationship with EUV is fixed. Figure 2 shows a plot of the daily values of sunspot number Rz, F10, and

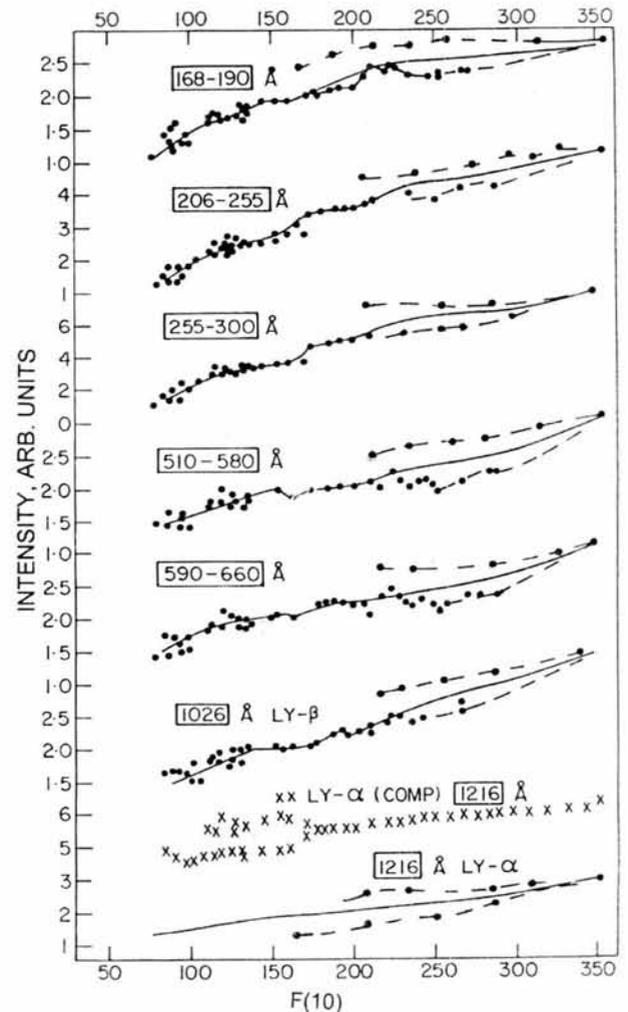


Fig. 1—Plots of the daily values of AE-E EUV-UV versus the 2800 MHz, 10.7 cm radio flux (F10), during 1977-1981. Up to ~200 F10, the full lines join the observed points and/or roughly pass through them. After ~200 F10, the full lines are extended arbitrarily to the last observed point at 350 F10, but the observed points seem to lie on two distinct (dashed) lines, one above and one below the full line, indicating a possible loop structure (hysteresis) at large F10 values

the various EUV and UV lines for the month of November 1979, during which F10 reached its highest value of 367 on 10 November and was above 200 during 4-20 November (portion shown black).

In spite of several values missing in the EUV data (marked by dashed lines), most of the indices had a maximum on 10 Nov. 1979 (marked by dots). Also the various plots compare well, except that for the 510-580 Å and 590-660 Å wavelength ranges, there is an additional peak on 18-19 Nov. 1979. Thus, no saturation effects in EUV are seen during 4-20 Nov. 1979 when F10 exceeded 200. For November-December 1979, Rishbeth<sup>15</sup> mentioned that all the

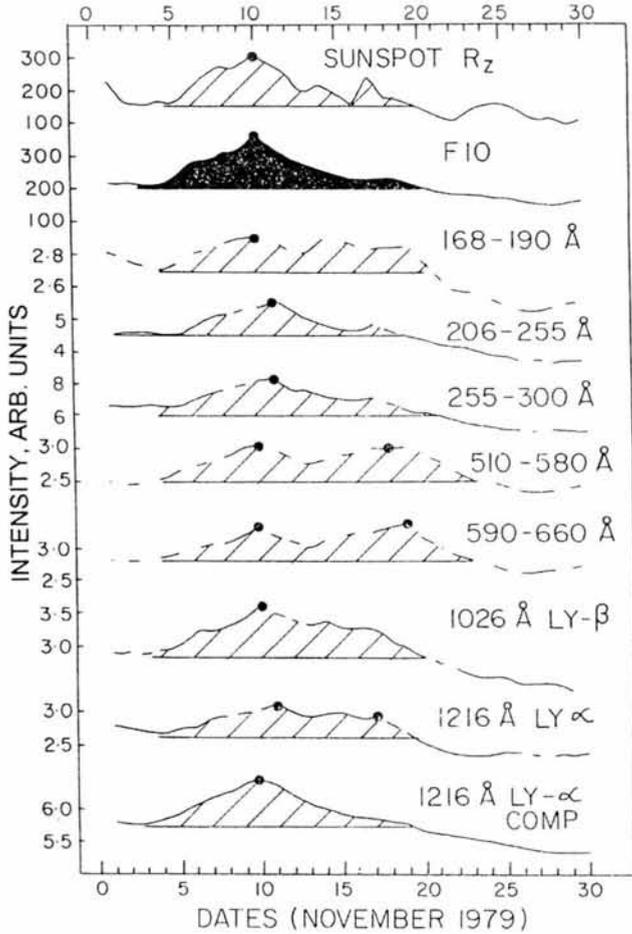


Fig. 2—Plots of the daily values of sunspot number, F10, and AE-E EUV-UV during the month of November, 1979. The portion when F10 exceeded 200 is shown black.

solar indices were highly inter-correlated (values of correlation  $+0.90$  or more), indicating that the saturation effects of other indices with respect to F10 must be negligible for this interval. However, Fig. 3 shows another example, where daily values are plotted for the month of April 1981.

Here, the situation was quite different. The F10 values exceeded 200 during 2-20 Apr. 1981 with a maximum on 9 April (marked by a dot), but only Lyman beta showed a similar increase. All other indices showed a rather flat level, suggesting saturation effects. Thus, saturation does not seem to be an invariable feature. It may occur in some months where F10 exceeded 200, but not in all such months. For the 30 daily values of April 1981, values of inter-correlation are shown as a correlation matrix in Table 1.

As can be seen, not all values of correlation are high (above  $0.70$ ), indicating that different indices had different types of day-to-day variations. Correlation

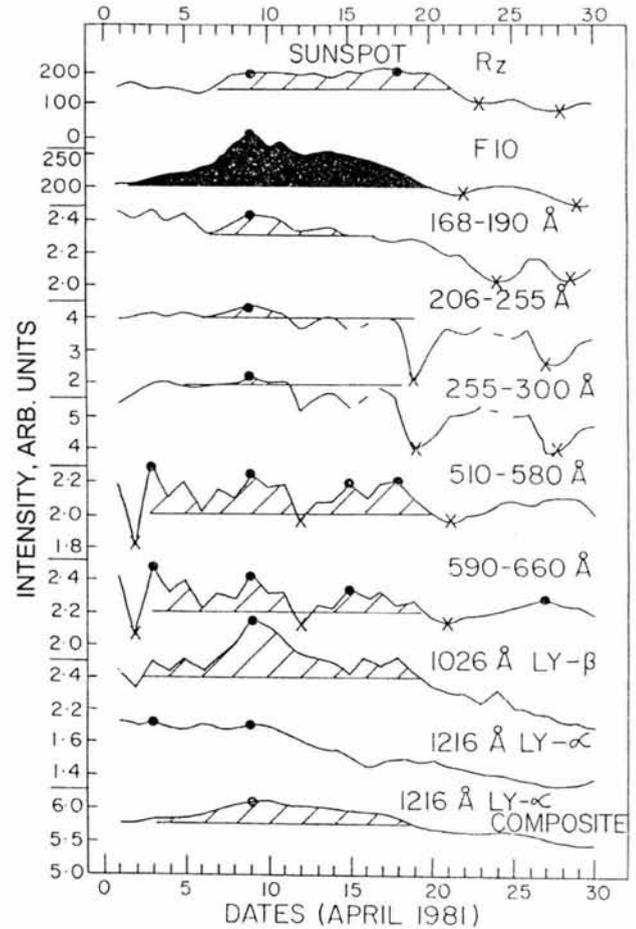


Fig. 3—Plots of the daily values of sunspot number, F10, and AE-E EUV-UV during the month of April, 1981. The portion when F10 exceeded 200 is shown black and the same interval in other indices is shown hatched.

with F10 is better than that with sunspots. During November 1979 (Fig. 2), the values of inter-correlation were much better, exceeding  $+0.8$  except for the  $510\text{-}660\text{ \AA}$  wavelength range.

It should be remembered that there are two major components of the  $2800\text{ MHz}$  (F10) emission, rotationally modulated, and unmodulated. The unmodulated emission comes from outside active regions, is mostly thermal Bremsstrahlung, and dominates the Sun during solar minimum. The rotationally modulated emission is mostly a thermal gyro-resonance emission from the strong magnetic fields above sunspots (though some non-thermal emission is also indicated), and may come from a wide range of altitudes, say  $10,000\text{-}40,000\text{ km}$  above solar surface<sup>16,17</sup>. Thus, there can be occasions when the evolution of the  $2800\text{ MHz}$  (F10) flux might be from very localized regions and other indices (notably EUV) originating from other and/or wider regions

Table 1—Values of inter-correlation of daily values during April, 1981

|         | 168-190 | 206-255 | 255-300 | 510-580 | 590-660 | 1026 | 1216 | 1216Com | F10  | Sunspot |
|---------|---------|---------|---------|---------|---------|------|------|---------|------|---------|
| 168-190 | 1.00    |         |         |         |         |      |      |         |      |         |
| 206-255 | 0.60    | 1.00    |         |         |         |      |      |         |      |         |
| 255-300 | 0.68    | 0.97    | 1.00    |         |         |      |      |         |      |         |
| 510-580 | 0.34    | 0.26    | 0.34    | 1.00    |         |      |      |         |      |         |
| 590-660 | 0.45    | 0.29    | 0.36    | 0.97    | 1.00    |      |      |         |      |         |
| 1026    | 0.83    | 0.64    | 0.74    | 0.45    | 0.44    | 1.00 |      |         |      |         |
| 1216    | 0.90    | 0.70    | 0.76    | 0.28    | 0.39    | 0.78 | 1.00 |         |      |         |
| 1216Com | 0.79    | 0.68    | 0.76    | 0.37    | 0.34    | 0.95 | 0.73 | 1.00    |      |         |
| F10     | 0.71    | 0.64    | 0.72    | 0.43    | 0.37    | 0.92 | 0.63 | 0.98    | 1.00 |         |
| Sunspot | 0.68    | 0.38    | 0.47    | 0.21    | 0.17    | 0.78 | 0.50 | 0.78    | 0.76 | 1.00    |

may not follow the F10 evolution. In such a case, saturation effects of EUV would occur.

Soon after the AE-E data were published<sup>9</sup>, Bossy and Nicolet<sup>18</sup>, Bossy<sup>19</sup> and Oster<sup>20</sup> claimed that the AE-E data suffered from shifts in instrument sensitivities, particularly Lyman alpha, and suggested revisions based on F10. Donnelly *et al.*<sup>21</sup> questioned such a revision and reported that chromospheric EUV agreed well with ground-based measurements of He 10830 Å and differed from those of coronal EUV and F10. Recently, 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<sup>22-24</sup>.

Rishbeth<sup>15</sup> was aware of these problems, but since his study was limited to a period of two months and dealt only with day-to-day variations, the long-term calibration was not of great concern. In Figs 2 and 3, two series for Lyman alpha are used. One is as measured in the AE-E data. The other is a Composite Lyman alpha series prepared by Woods *et al.*<sup>25</sup> taking into consideration the inaccuracies of the AE-E data, comparing with F10 and Mg II (2800 Å), etc. There are considerable differences between the two series as seen in Figs 2 and 3. Thus, one of them (or both?) might have errors. In Fig. 1, the Composite Lyman alpha does not show the hysteresis.

### 3.2 Monthly values

Since daily values are not always well inter-correlated, the monthly values were examined. Figure 4 shows the plot of solar indices versus F10. The F10 range is, of course, smaller now, only ~70-230. Here, the points on the upswing are mostly on a rising average full line, but on the downswing (during 1980-1981), there are a few observed points (marked by crosses) mostly well below the upswing full line.

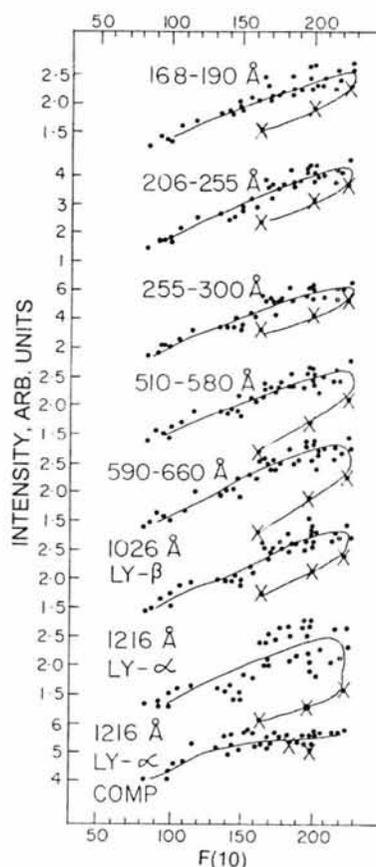


Fig. 4—Plots of the monthly values of AE-E EUV-UV versus F10, during 1977-1981

These data are scarce, but compatible with a hysteresis effect (a loop) at large F10 values.

### 3.3 Moving averages over 12 consecutive monthly values

For AE-E, the basic data were available for the wavelength ranges 168-190, 190-206, 206-255, 255-300, 304, 510-580, 584, 590-660, 1026, 335, 284, 200-204, 178-183, 169-173 Å. Some of these were combined to form wider ranges as 168-204, 206-335

and 510-660 Å. Figure 5(a) (full lines) shows the plots of the 12-month moving averages of the monthly values of these three EUV ranges versus the F10 values (also moving averages). All values are percentage deviations from their mean values.

As can be seen, there are no saturation effects, probably because the F10 range is only from -30% to +20% of the mean value 166 i.e., ~115-200, and there are no values exceeding 200. However, there are clear, large hysteresis effects. To check whether the hysteresis was only for EUV versus F10, the EUV values were plotted versus Lyman beta (1016 Å). These are shown with crosses. The hysteresis effect is now smaller, indicating that EUV and UV have almost parallel variations while the hysteresis is mainly with respect to the F10 index. In Fig. 5(b), the EUV values (moving averages) are plotted versus AE-E Lyman alpha (full lines) and versus Composite Lyman alpha<sup>22</sup> (crosses). The full lines show very

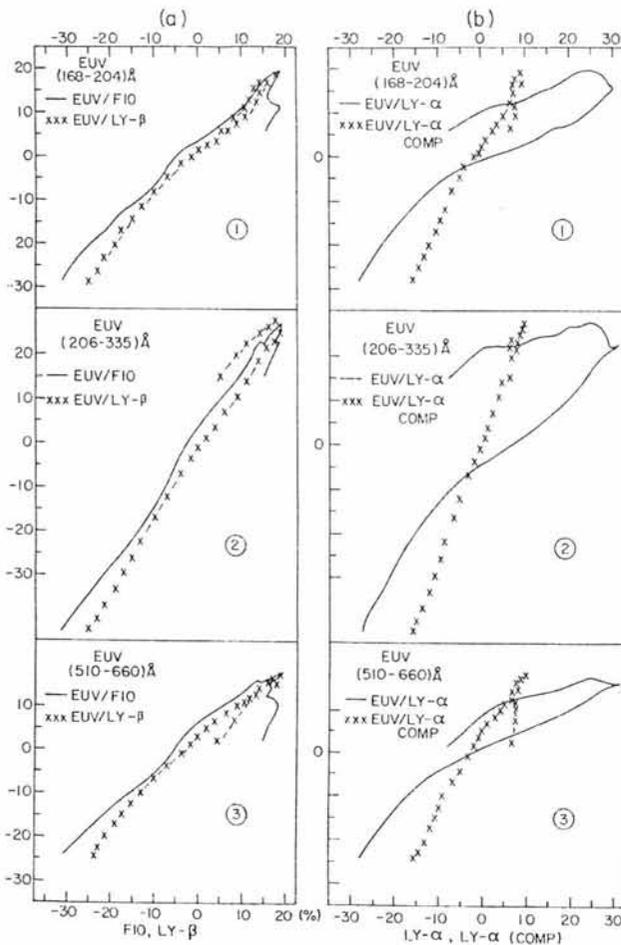


Fig. 5—Plots of the 12-month moving averages during 1977-1981 of (a) AE-E EUV-UV versus F10 (full lines) and AE-E Lyman beta (crosses) and (b) AE-E EUV-UV versus AE-E Lyman alpha (full lines) and Composite Lyman alpha (crosses)

large hysteresis loops, indicating that the AE-E Lyman alpha has variations very different from those of EUV. Thus, doubts about the accuracy and stability of these Lyman alpha measurements are confirmed.

If the Composite Lyman alpha is used (crosses), the hysteresis is much smaller (but not absent), indicating that EUV and Composite Lyman alpha data are fairly reliable. Incidentally, the overall range was large (-30 to +30%) for the AE-E Lyman alpha but small (-15 to +10%) for the Composite Lyman alpha. This could happen if the AE-E data had large instrumental drifts. The absolute level of AE-E measurements has been proved to be in gross error<sup>22-24</sup>, by almost factors of 2. It seems, however, that the relative values (ratios with respect to the July 1976 level) are fairly reliable for the EUV and Lyman beta, but unreliable for Lyman alpha, for which the Composite Lyman alpha values are much more reliable.

A hysteresis effect can occur if the solar cycle evolutions of EUV and F10 are not alike and the maxima might have occurred at different times. Figure 6(a) shows the plots of the monthly values and Fig. 6(b) their 12-month moving averages for the period 1977-1981. The following may be noted:

(a) In Fig. 6(a), during 1979-1981, all the indices have reached near their maximum levels, but

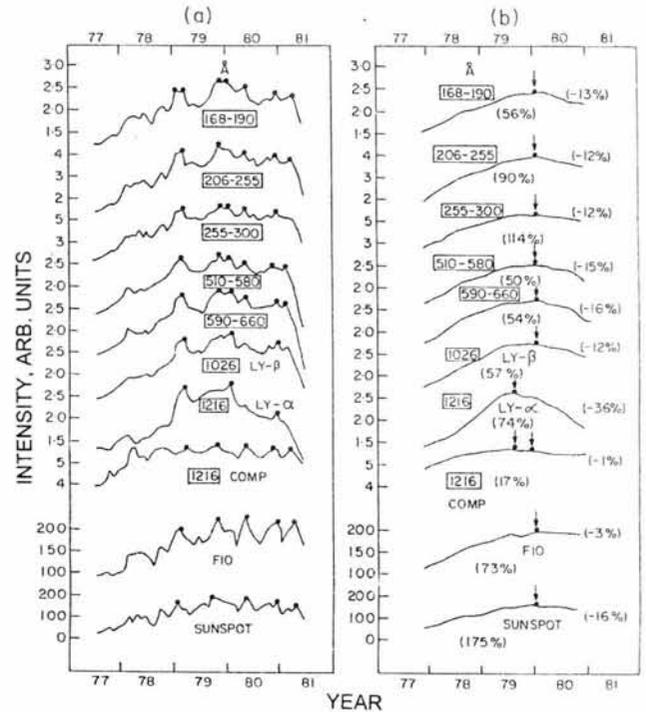


Fig. 6—Plots during 1977-1981 of (a) the monthly values and (b) the 12-month moving averages, of the AE-E EUV-UV and F10 and sunspot number. Peaks are marked with dots

there are fluctuations with several peaks as marked by dots. Most of these peaks tally for all the indices, indicating changes in solar flux as a whole. However, the relative magnitudes of successive peaks are not the same for all indices. For example, the November 1979 peak is larger than the February 1979 peak for the F10 index, but for 255-300 Å EUV, the two peaks are comparable. After Apr. 1981, EUV decreased rapidly, but F10 and sunspots did not decrease much. Table 2 shows the inter-correlation between the monthly values for 1979-1981.

As can be seen, almost all correlations are high (above + 0.8). Surprisingly, those of Composite Lyman alpha (1216Com) are lower, throwing some doubt about the accuracy of this parameter, though Woods *et al.*<sup>25</sup> claim it to be much more accurate than AE-E Lyman alpha (1216).

- (b) Figure 6(b) brings out these differences very strikingly. These plots are very smooth, and there is only one prominent peak in January 1980 in all the indices except in AE-E Lyman alpha, for which the peak was earlier in August 1979 (data errors suspected). However, the evolution is different for F10 and the EUV. After January 1980, F10 was steady but the EUV decreased rapidly. Thus, if F10 is considered as proxy for EUV, the EUV values would be overestimated for intervals soon after the peak.
- (c) The percentage rise from December 1977 to January 1980 in Fig. 6(b) (shown in parentheses) is different for the different indices, being highest (175%) for sunspots, followed by 255-300 Å EUV (114%), 206-255 Å EUV (90%) and 50-75% for all other indices. The succeeding decrease from January 1980 to December 1980 is as large as -(12 to 15)% for the EUV, but only -3% for F10 (the value -36% for AE-E Lyman

alpha is probably erroneous). The percentage for Composite Lyman alpha is low (-1%) and matches that of F10 (-3%), probably because Woods *et al.*<sup>25</sup> have used F10 copiously to estimate the Lyman alpha behaviour.

#### 4 Pioneer Venus measurements: EUV or UV?

The period from 1980 onwards was termed by Donnelly<sup>26</sup> as the 'EUV hole', as full spectrum measurements were not expected to occur till the late 1990s (Tobiska<sup>27</sup>). However, from January 1979 to December 1991, the Pioneer Venus Orbiter (PVO) carried a Langmuir probe to measure the temperature and concentration of electrons in the ionosphere of Venus. When the probe was outside the Venus ionosphere and was in the solar wind, it measured integrated flux, with 55% contribution from Lyman alpha (1216 Å), 30% from the 300-1100 Å band, and the rest from strong lines such as He II, He I, C III, etc. (Hoegy and Mahajan<sup>28</sup>, Hoegy *et al.*<sup>29</sup>, Mahajan *et al.*<sup>30</sup>). Also, more than 85% contribution was from wavelengths exceeding 500 Å (Hoegy *et al.*<sup>29</sup>). An examination of these data showed that the variation was very similar to the Composite Lyman alpha<sup>25</sup>, with solar cycle variation of ~50%. These measurements would, therefore, be more representative of UV rather than EUV, and hence, are not considered in the present communication.

#### 5 SEM/SOHO EUV

The Solar EUV Monitor (SEM) aboard the Solar and Heliospheric Observatory (SOHO) is providing daily values of EUV fluxes<sup>10</sup> in the wavelength ranges 260-340 Å and 1-500 Å, since January 1996.

##### 5.1 Daily values

Figure 7 shows a plot of the daily values of the SEM/SOHO EUV versus F10 for 1996-2002. The scatter is large and, if EUV values for the same F10

Table 2—Inter-correlation of monthly values during 1979-1981

|         | 168-190 | 206-255 | 255-300 | 510-580 | 590-660 | 1026 | 1216 | 1216Com | F10  | Sunspot |
|---------|---------|---------|---------|---------|---------|------|------|---------|------|---------|
| 168-190 | 1.00    |         |         |         |         |      |      |         |      |         |
| 206-255 | 0.99    | 1.00    |         |         |         |      |      |         |      |         |
| 255-300 | 0.98    | 1.00    | 1.00    |         |         |      |      |         |      |         |
| 510-580 | 0.94    | 0.94    | 0.94    | 1.00    |         |      |      |         |      |         |
| 590-660 | 0.96    | 0.95    | 0.95    | 1.00    | 1.00    |      |      |         |      |         |
| 1026    | 0.97    | 0.98    | 0.98    | 0.97    | 0.97    | 1.00 |      |         |      |         |
| 1216    | 0.85    | 0.84    | 0.84    | 0.91    | 0.91    | 0.91 | 1.00 |         |      |         |
| 1216Com | 0.79    | 0.79    | 0.80    | 0.70    | 0.72    | 0.74 | 0.54 | 1.00    |      |         |
| F10     | 0.90    | 0.93    | 0.93    | 0.80    | 0.82    | 0.89 | 0.67 | 0.82    | 1.00 |         |
| Sunspot | 0.92    | 0.94    | 0.93    | 0.86    | 0.87    | 0.92 | 0.77 | 0.79    | 0.95 | 1.00    |

value are averaged, one will probably see a reduction in slope (non-linearity) near  $F10 = \sim 200$ . The overall correlations were  $\sim 0.6$  and therefore, a straight line fit could be considered as probably valid. However, while plotting the points, it was noticed that the points during 2000-2002 (marked by crosses) lay mostly above those for 1996-1999 (dots) and could be on the upper branch of a hysteresis pattern as indicated by

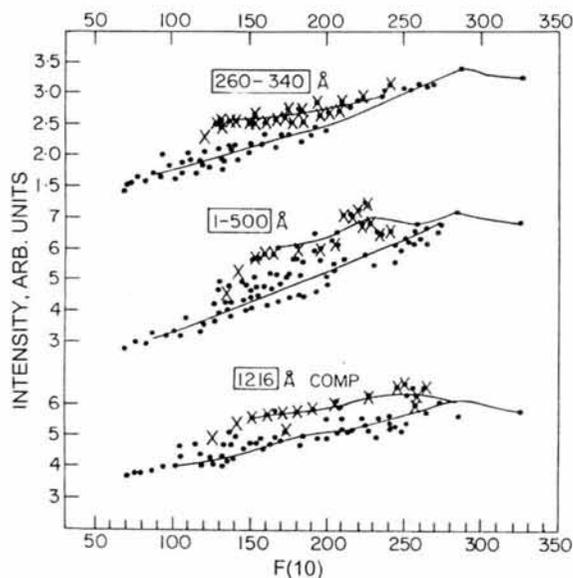


Fig. 7—Plots of the daily values of SEM/SOHO EUV and Composite Lyman alpha, versus F10, during 1996-2001

the lines. This is, of course, subjective, but the main effect seems as a hysteresis pattern.

There were several intervals of continuous days when F10 values exceeded 200. Plots for four intense events of about 30 daily values each are shown in Fig. 8, as for (a) July 2000, maximum F10 = 325 on 12 July 2000, (b) September 2001, maximum F10 = 286 on 28 Sept. 2001, (c) 15 Mar.-15 Apr. 2001, maximum F10 = 273 on 28 Mar. 2001, (d) May 2000, maximum F10 = 268 on 17 May 2000. In Fig. 8, F10 values exceeding 200 are shown black, and values for other indices during the same interval of large F10 values are shown hatched. The following may be noted:

- (a) During July 2000, all indices showed increases during 8-26 July, though the maxima were not at the F10 maximum of 10 July. Thus, there were no saturation effects.
- (b) During September 2000, F10 values had two maxima, a smaller one on 8 September and a larger one on 28 September. During the first maximum, other indices did not show large increases, but during the second maximum, other indices showed very large increases, indicating no saturation effects.
- (c) During 15 Mar.-15 Apr. 2001, all indices showed increases during 24 Mar.-4 Apr., though the EUV

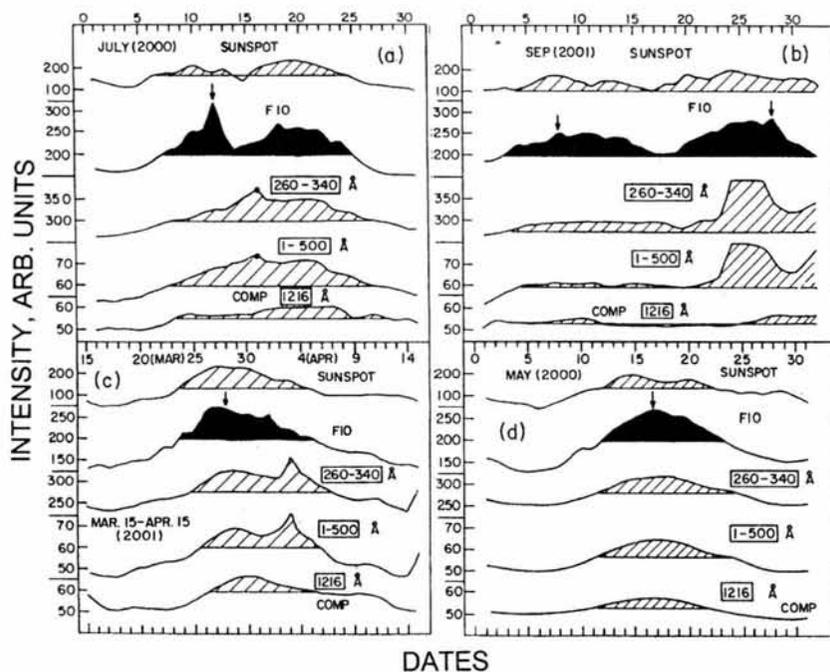


Fig. 8—Plots of the daily values of sunspot number, F10, SEM/SOHO EUV and Composite Lyman alpha during (a) July 2000, (b) September 2000, (c) 15 Mar.-15 Apr 2001, and (d) May 2000. The portion when F10 exceeded 200 is shown black and the same interval in other indices is shown hatched.

maxima occurred on April 3 and not on 28 March.

- (d) During May 2000, all indices showed increases during 12-23 May, with maxima near 17 May.

Thus, in these four events having largest F10 values exceeding 200, all indices showed similar increases, and no saturation effects.

**5.2 Monthly values and 12-month moving averages**

Figure 9 shows a plot of monthly values of SEM/SOHO EUV versus F10. The F10 range is of course, smaller, only 70-230. The scatter is large and there is no indication of a saturation effect or a hysteresis loop. Figure 10 shows the plots for the 12-month moving averages. The full lines are for EUV versus F10 and there is no saturation effect (F10 values are all below 150), but there are hysteresis effects. To check whether EUV showed hysteresis when plotted versus UV, EUV is plotted against Composite Lyman alpha as crosses. In contrast to the range of 150% for F10 increase from 1996 to 2000,

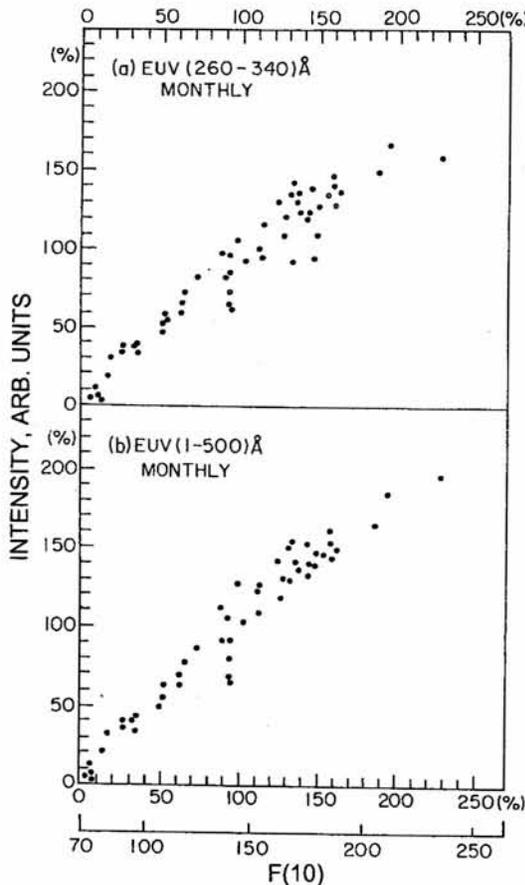


Fig. 9—Plots of the monthly values of SEM/SOHO EUV versus F10 during 1996-2001, (a) for 260-340 Å and (b) for 1-500 Å

the Lyman alpha increased only by ~50%, but the hysteresis effect is seen. To check whether Lyman alpha had a hysteresis effect with respect to F10, the bottom plot (open circles) is for Lyman alpha versus F10 and shows a small hysteresis effect.

As in the case of the AE-E data, the hysteresis could occur if the peaks are de-phased and/or the profiles are different at the solar maximum. Figure 11 shows the plots of (a) monthly values and (b) 12-month moving averages for 1996-2001. In (a), the monthly values have considerable fluctuations during 1999-2001. Several peaks (marked by dots) are common to all indices, though their relative proportions are different for different indices. The inter-correlations were excellent (+0.93 or more). In (b), sunspots and F10 had flat maxima during Feb-

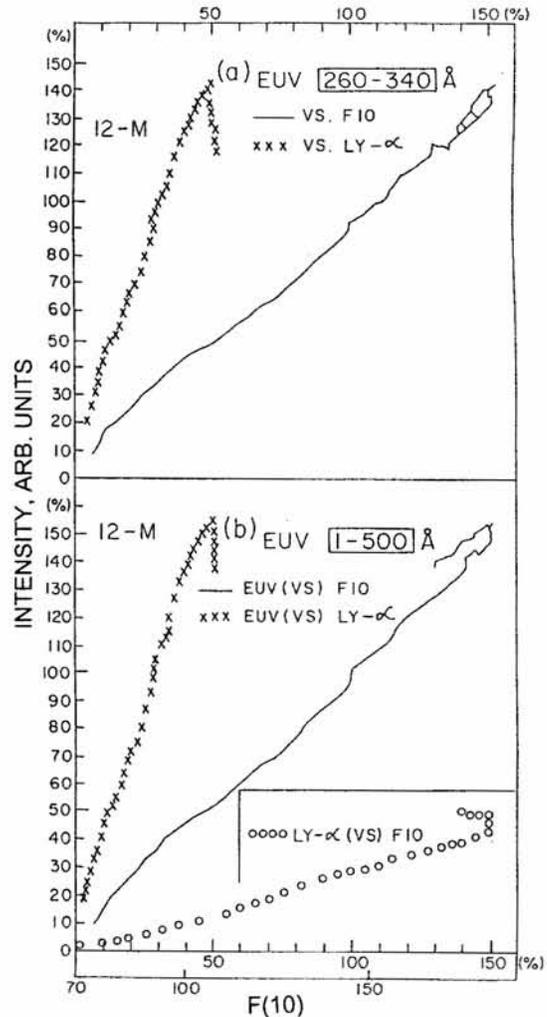


Fig. 10—Plots of the 12-month moving averages of SEM/SOHO EUV versus F10 (full lines) and versus Composite Lyman alpha (crosses), during 1996-2001. (a) for 260-340 Å and (b) for 1-500 Å [In (b), the open circles show a plot of Composite Lyman alpha versus F10.]

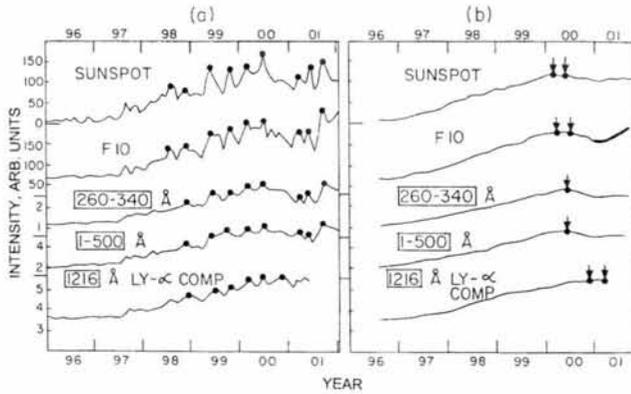


Fig. 11—Plots during 1996-2001 of (a) the monthly values and (b) the 12-month moving averages, of the sunspot number, F10, SEM/SOHO EUV and Composite Lyman alpha [Peaks are marked with dots.]

Jul. 2000, while EUV had maxima in July 2000 while Composite Lyman alpha had a flat maximum later in December 2000. Thus, some differences are observed.

The EUV (12-month moving averages) started decreasing in the end of 2000 and 260-340 Å dropped by ~10%; meanwhile, the F10 dropped by ~8% but was showing a recovery (see the thick lines in 2000-2001 in (b)). It is this difference in behaviour (F10 oscillating near solar maximum while EUV decreasing after the peak) that leads to the hysteresis patterns. This occurred in 1981 (cycle 21) and again in 2001 (cycle 23). A large hysteresis loop extended to a large range of F10 would imply that for the same moderate values of F10, the EUV could have different levels depending upon whether the solar cycle is in the upswing or downswing. In that case, the regression coefficient relating F10 to EUV would be different for the upswing and downswing.

## 6 Conclusions and discussion

It has been reported in earlier literature that for values of the solar 2800 MHz radio flux (10.7 cm, F10) exceeding 200, solar EUV values show saturation effects. This aspect was examined using EUV data obtained by the AE-E satellites during 1977-1981 and the SEM/SOHO satellite data from 1996 onwards to date. The following was noticed:

(a) There were several intervals when continuous daily values of F10 exceeded 200. In some of these, the corresponding EUV values showed saturation effects in the AE-E data, but in the SEM/SOHO data, the EUV values accompanied the F10 variation patterns, indicating no saturation effects. For monthly values as well as

the 12-month moving averages, no saturation effects were seen, but this could be because the F10 values rarely exceeded 200.

(b) In both AE-E data and SEM/SOHO data, there were some indications of probable hysteresis effects near solar maximum, with slight differences in the evolution of the EUV and F10. Either their peaks were slightly displaced with respect to each other, and/or their evolution profiles were different, the F10 remaining steady for several months after peaking (flat peak), while the EUV started decreasing soon after peaking.

Whenever EUV data are missing, the F10 is often used as proxy. The present analysis shows that a simple regression between F10 and EUV may be satisfactory only during the rise and fall of a solar cycle, and there too, the regression coefficients may be different for the upswing and downswing of the solar cycle. During months of solar maximum, the relationship gets distorted and because of its lingering near the peak for several months, the F10 may give overestimates of EUV.

As inputs in the terrestrial atmosphere, one needs irradiance models. These involve (i) Reference spectra, i.e. the flux versus wavelength, and (ii) formulae for their variations with solar cycle. Prior to AE-E, reference XUV-EUV spectra were based on rocket observations. Donnelly and Pope<sup>31</sup> gave a reference spectrum for moderate solar activity (F 10 = 150). Using the AE-E data, Hinteregger *et al.*<sup>9</sup> 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<sup>32</sup>, Schmidtke *et al.*<sup>33</sup>, Richards *et al.*<sup>8</sup>, and various models by Tobiska and his colleagues (Tobiska and Epravier<sup>34</sup> and references therein). All these empirical models were derived from the AE-E data and used F10 as proxy for EUV.

However, when 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<sup>23-25</sup>, a big, collaborative project was planned and started in 1998 and has resulted in SOLAR2000 (Tobiska *et al.*<sup>35</sup>). Here too, F10 is used as proxy for EUV. As far as we know, the likely de-phasing between F10 and EUV near solar maximum and the EUV hysteresis effect for moderate F10 values is not being taken into account. If true, the EUV estimates soon after the solar maximum could

be in error by a few percent even in the most up-to-date SOLAR2000 model.

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