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SOLAR INDICES AND SOLAR U.V.-IRRADIANCES

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Abstract—Solar radio fluxes, Zurich relative sunspot number R_Z, and Solar CaII plage indexes daily values for the period 1957–1980 are analyzed in order to test the stability of the series with respect to time and solar activity. It is found that between the series of the 3, 8 and 10 cm radio fluxes and the series of R_Z no significant trend with time, solar activity or solar cycle exists when mean values for periods of the order of one year are considered.

Then, the daily solar u.v.-irradiances measured since 1969 for H-Lyman-alpha and-beta, the HeI-resonance line and HeII-Lyman-alpha are compared with the 10.7 cm radio fluxes and adjusted. After adjustment, the behaviour of the four series of irradiances with respect to the 10.7 cm flux shows a similar structure as the behaviour typical for the series of the 3 cm or the 8 cm fluxes.

This adjustment allows the determination of the slope of the mean variation of the u.v.-irradiances with solar activity. The increases from solar minimum to solar maximum related to the minimum values are respectively: 60% for H-Lyman-alpha, 80% for H-Lyman-beta and 90% for HeI and HeII.

INTRODUCTION

The emission in the u.v. and X-ray regions of the solar spectrum, which is responsible for the photoionization and photodissociation processes in planetary upper atmospheres, has been the subject of various rocket and satellite observations for several years. However, the exact relationship between such u.v. and X-ray emissions and the various solar indices is still a subject of discussion. The sunspots, solar plages and radio fluxes have been introduced as solar indices and accepted or rejected according to the authors. Therefore, a study in which the observational data are analyzed in order to infer time-average values or to deduce correlations or trends remains an essential problem of solar variabilities related to atmospheric processes.

The object of this study is to show first that there is an internal consistency in the available series of solar radio fluxes in the microwave region when their mean values at different levels of solar activity during periods of the order of one year are considered. On the other hand, since it is known that the measured spectral irradiances in the u.v. domain may be subject to errors, because of degradation of the calibration constant, a practical way of compensating a possible drift must be found. For example, if a linear variation in time of the sensitivity of the equipment is assumed, it is possible to use the observed solar u.v. fluxes and to modify them so as to show the same consistency as the radio fluxes observed in the cm spectral range. When such a comparison is made for all levels of solar activity, it leads to an estimation of the trend of the variation of any specific irradiance with solar activity. However, an absolute calibration is still needed in order to adapt to an exact value the regression law which is obtained.

SOLAR RADIO FLUXES

The basic data for an analysis of solar indices are: the daily fluxes (expressed in units = 10^{-22} W m^{-2} Hz^{-1}) on 10.7 cm (National Research Council, Ottawa, Canada) and on 3, 8, 15 and 30 cm (Research Institute of Atmospherics, Toyokawa, Japan) from May 1957 to December 1980; the Zurich relative sunspot numbers R_Z; and the Solar CaII Plage Indexes (Swartz and Overbeek, 1971 and National Geophysical and Solar–Terrestrial Data Center (NGSDC), Boulder, U.S.A.). It must be noted that the radio fluxes have been the subject of extensive studies in order to reach a fair order of compatibility (Tanaka *et al.*, 1973).

A test of the stability of the series of data with respect to time and solar activity can be made in two ways which are explained below.

A first test involves a graphical comparison of radio fluxes as illustrated for 3 and 10 cm in Fig. 1. The abscissae are the numbers of days counted from the beginning of the period under test and the ordinates are

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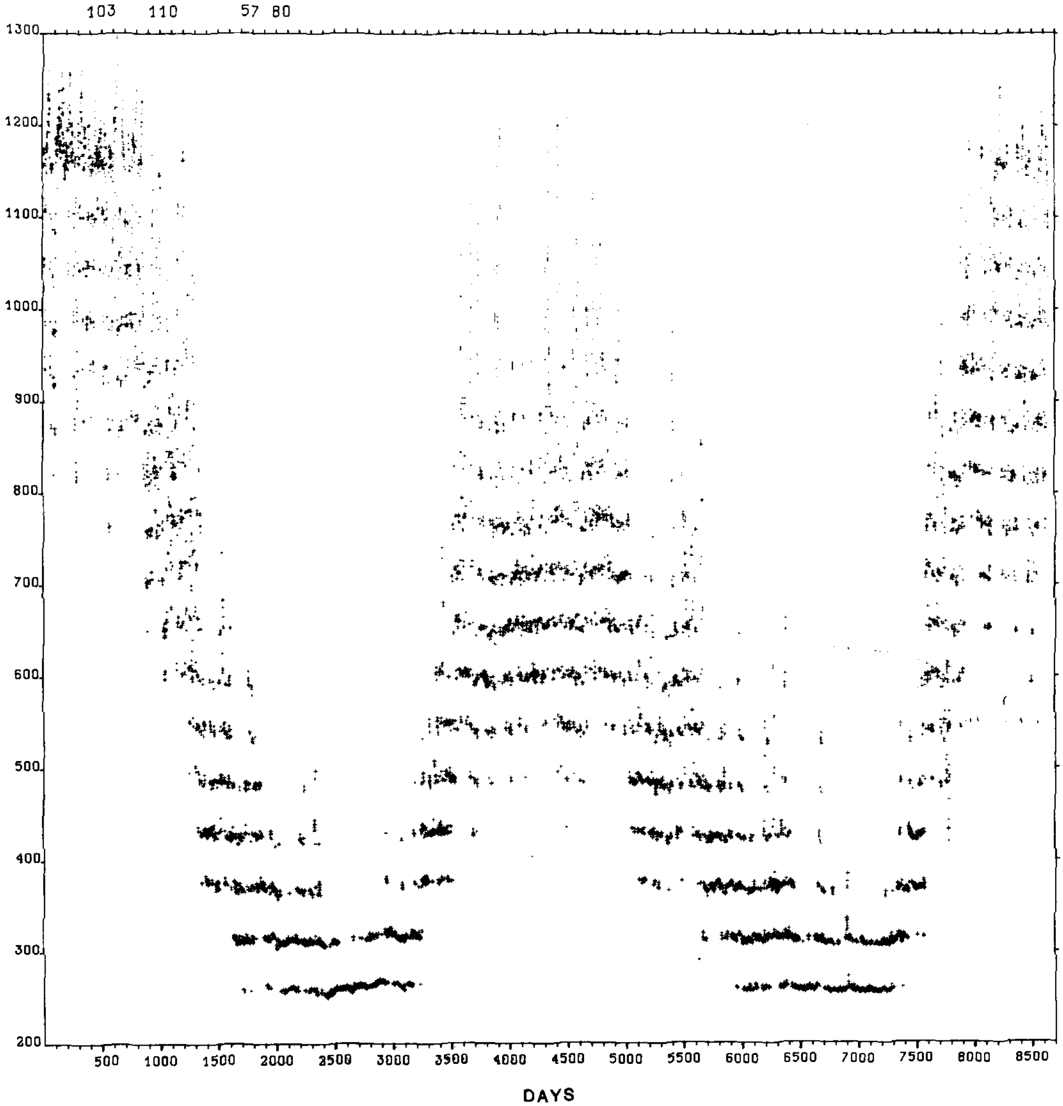

Fig. 1. Daily solar radio fluxes at 3 cm vs time from 1957 to 1980.
Vertical classification for different specific solar activity values defined by $F_{10.7}$, the solar radio flux at 10.7 cm; each class is given for intervals $F_{10.7} \pm 5$ for successive increments of 50 units of the 3 cm radio flux.

the 3 cm fluxes for various values of the 10 cm flux. When the 10 cm flux is between 65 and 75, the ordinates are the values of the 3 cm flux; the ordinates are incremented by 50 when the 10 cm flux is between 75 and 85; and so on. For a coefficient of correlation equal to unity, such a representation would lead to horizontal and parallel groups of points. In Fig. 1, the various bands are nearly horizontal for all levels of solar activity and there is no difference between the different cycles in either the rising or the decreasing part of each cycle. The conclusion is, therefore, that no long-term trend corresponding to a drift exists between these two series of fluxes.

A second numerical test involves the determination of mean values of data belonging to different classes of solar activity. The ratios of the values for periods of 18 months to the average value for the same level of solar activity during the whole period of 24 years have been used here. The numerical results of Table 1 show that for each period and for all levels of solar activity the

TABLE 1. RATIOS (IN %) BETWEEN THE MEAN VALUES OF THE 3 cm RADIO FLUXES FOR SUCCESSIVE PERIODS OF 18 MONTHS FROM 1957 TO 1980 AND THE AVERAGE VALUE FOR THE WHOLE PERIOD OF 24 YEARS CORRESPONDING TO ALL LEVELS OF SOLAR ACTIVITY DEFINED BY THE 10.7 cm SOLAR RADIO FLUX

	Classification†																		
Period*	070	080	090	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
01												099	099	099	100	100	100	099	100
02								100	099	099	100	100	100	099	100	099	101	102	101
03			101	100	101	100	101	102	104	102	103	104	106						
04	100	100	099	099	099	097	098												
05	100	099	099	100															
06	102	102	102	102	101														
07			103	101	102	101	100	100	101	101	100	102							
08						100	100	100	100	099	100	101	102	100	101				
09					102	101	101	100	100	101	101	100	102	103					
10			102	100	100	099	099	099	099	098	099	099	099						
11	100	100	100	099	099	099	099	100	102	102									
12	100	100	100	100	101	098													
13	099	099	099																
14	099	099	099	100	100	099	100	100	100	099									
15					101	101	100	099	099	099	099	099	100	101	100	101	099	100	
16								097	098	098	098	098	097	099	098	098	099	099	099

*01–16 correspond to 16 periods of 18 months = 24 years between 1957 and 1980.
†070–250 are solar radio fluxes at 10.7 cm; classification: $F_{10.7} \pm 5$ units.

ratios correspond to 1.00±0.03. Such a result leads again to the conclusion that there is no long-term trend and indicates also the type of distribution of ratios which is typical of a close connection between two series of data.

Similar results are obtained in the comparison of the 8 and 10 cm fluxes. However, differences showing cyclic effects occur at 15 cm and are more apparent at 30 cm and these may be related to the relative importance of the coronal part in the microwave emission. An analogous analysis has already been made by Nicolet (1963).

On the other hand, the analysis of the Wolf numbers indicates no long-term trend, but shows an important dispersion of the ratios for low solar activity. As far as the solar calcium plage indexes are concerned, the values from 1958 to 1970 (Swartz and Overbeek, 1971) are about 20% greater than the values reported after 1970 in the NGSDC booklets.

It can be concluded, therefore, that there is no significant trend with time, solar activity level or solar cycle in the three series of radio fluxes at 3, 8 and 10.7 cm when mean values for periods of the order of 1 year are considered.

The regression analysis of the daily radio fluxes, F, between 1957 and 1980 (8640 values), of the Zurich relative sunspot numbers, R_Z (8640 values), and of the Solar CaII plage indexes, CA^+ (7720 values), leads to the following formulas for both the daily values and the 27-day running means; CC is the correlation coefficient and D is the standard deviation.

	CC	D
$F_{03} = 255.5\left[1+0.255\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.973	8.58
$\bar{F}_{03} = 255.7\left[1+0.253\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.986	5.68
$F_{08} = 72.4\left[1+1.18\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.994	5.25
$\bar{F}_{08} = 72.9\left[1+1.17\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.998	2.98
$F_{15} = 50.2\left[1+1.63\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.993	5.57
$\bar{F}_{15} = 49.6\left[1+1.67\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.996	3.75
$F_{30} = 42.3\left[1+1.41\left(\frac{F_{10.7}-65}{100}\right)\right]$	0.977	7.28
$\bar{F}_{30} = 40.7\left[1+1.53\left(\frac{\bar{F}_{10.7}-65}{100}\right)\right]$	0.990	4.57
$R_Z = 5.6+111.7\left(\frac{F_{10.7}-65}{100}\right)$	0.962	17.54
$\bar{R}_Z = 6.7+109.9\left(\frac{F_{10.7}-65}{100}\right)$	0.988	8.79
$CA^+ = 4.0+45.4\left(\frac{F_{10.7}-65}{100}\right)$	0.910	10.70

A more detailed analysis of these results will be given in another paper.

SOLAR U.V.-IRRADIANCES

Extensive series of daily solar irradiances in the u.v. domain of the solar spectrum have been published since 1969. They have been collected by satellites such as OSO-5 (Vidal-Madjar, 1975; Vidal-Madjar and Phissamay, 1980), AEROS-A and B (Schmidtke, 1978, 1979), AE-E (Hinterregger, 1981a) and recently SME (Rottman *et al.*, 1982). We shall consider here observations of H-Lyman-alpha (121.6 nm), H-Lyman-beta (102.6 nm), the HeI-resonance line (58.4 nm) and HeII-Lyman-alpha (30.4 nm).

As already pointed out (Bossy and Nicolet, 1981), not all the observed solar irradiances of H-Lyman-alpha can be considered as homogeneous data. Figure 2 is an illustration of five series of observations compared with the 10.7 cm radio flux and Fig. 3 is an application to these observations (excluding the observations of SME) of the method which has been used in Fig. 1 for the 3 cm radio fluxes. In Fig. 3, the solar activity classes are 65–85, 85–105,... for the 10.7 cm flux and the increment for each class corresponds to 30.

It must be pointed out that the first series of OSO-5 observations has already been adjusted by Vidal-

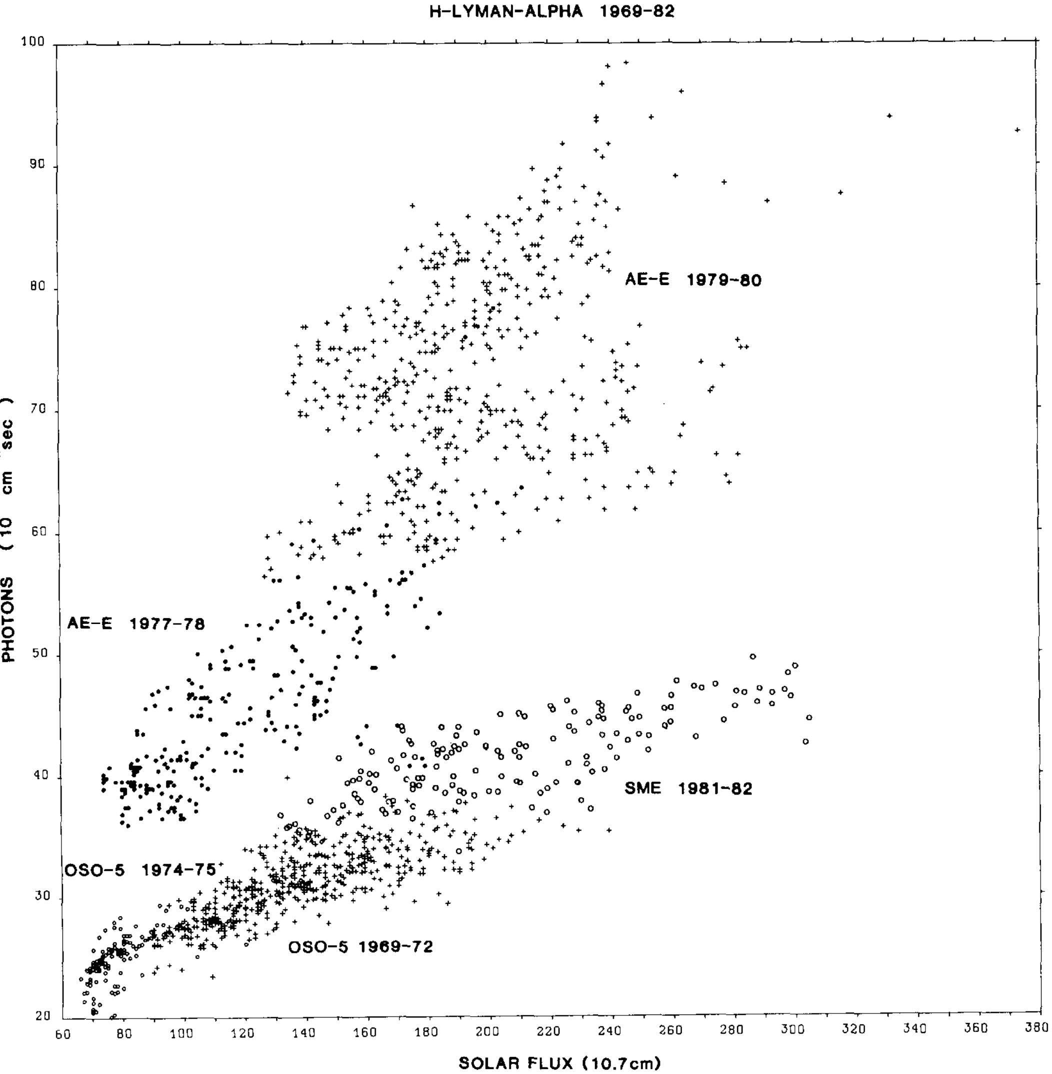

FIG. 2. OBSERVATIONS OF THE SOLAR IRRADIANCES OF THE H-LYMAN-ALPHA VS THE 10.7 cm SOLAR RADIO FLUX. Five groups are shown: OSO-5 (1969–1972) and (1974–1975), AE-E (1977–1978) and (1979–1980), and SME (1981–1982).

Madjar (1975) in order to take into account the decrease of sensitivity of the equipment, estimated to a round figure of 10% per year. In addition to such a constant drift, Fig. 3 shows for this series parallel groups of points with a residual negative slope (about 3% per year) during the 900 first days and afterwards a positive slope up to the end of the series. The structure of the second series of OSO-5 (Vidal-Madjar and Phissamay, 1980) is less regular since it corresponds to a period of minimum solar activity. As far as the data of AE-E (Hinteregger, 1981a) are concerned, they are here divided into two groups before and after January 1979 when the data were produced by two different parts of the equipment. In the first AE-E group, there is an almost stable period of 200 days, followed by a strong negative slope during about 100 days and by a pronounced increase up to the end of 1978. The second AE-E group begins with a jump of about 20% followed by an increase during about 100 days and then a decrease during a similar period of time. Then, after a new increase, a last period of 450 days begins where a negative slope is present. At the end of this second group, the values are almost of the same order of magnitude as the data obtained at the end of the first

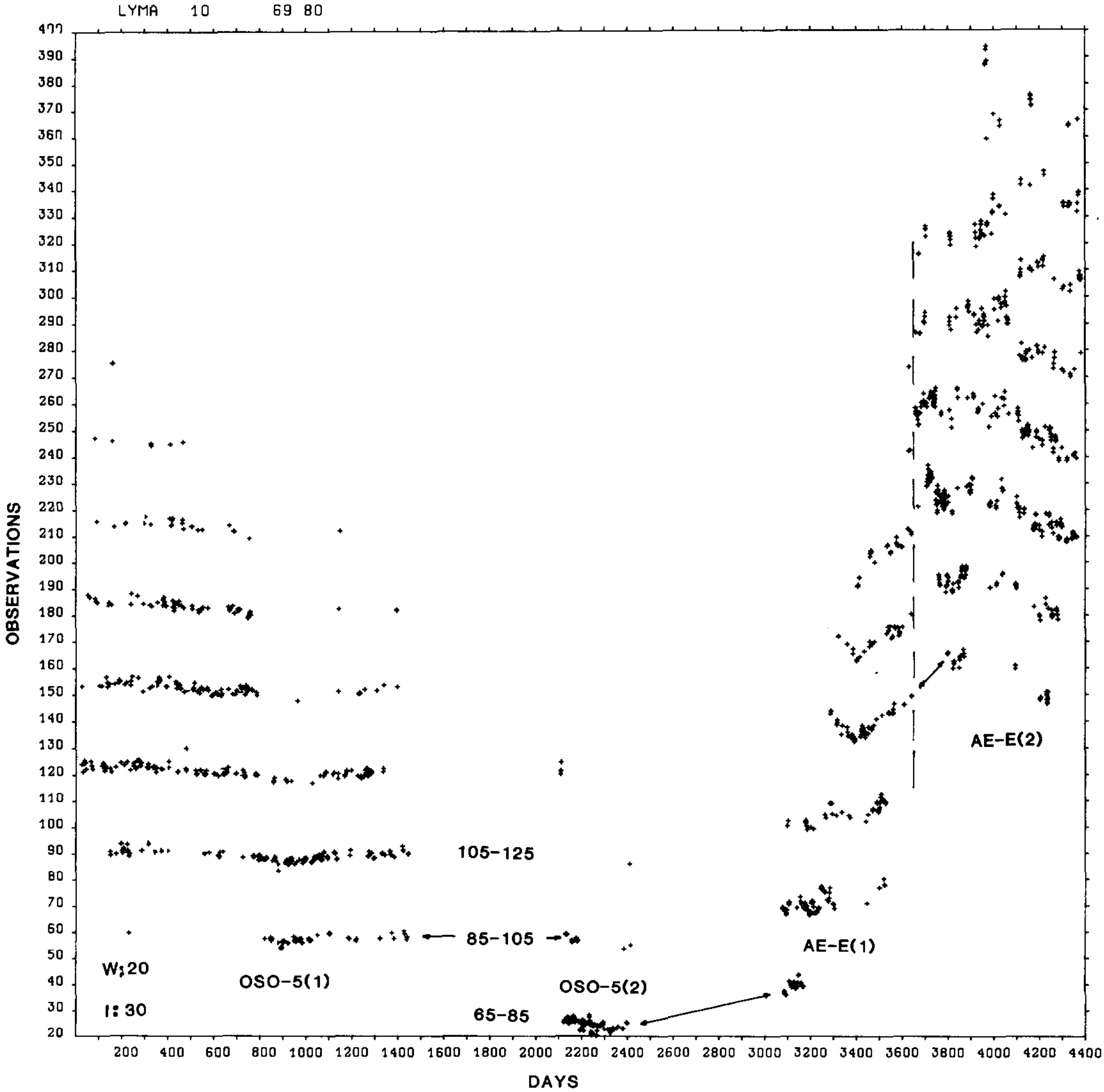

Fig. 3. Daily H-Lyman-alpha irradiances (represented in the same way as for the observational data given in Fig. 1) vs time from 1969 to 1980.

Vertical classification for different solar activity values defined by $F_{10.7}$; each class is given for intervals of $F_{10.7} \pm 10$ with increments of 3×10^{-11} photons cm^{-2} s^{-1} of H-Lyman-alpha.

group. This last fact has already been pointed out by Hinteregger (1981b).

All these features are mainly due to instrumental effects which may correspond to a variation of the calibration factor due to instrumental degradation. In fact, the parallelism in the various trends for all levels of solar activity is a clear indication that they correspond to drifts due to decreases or to increases in the instrumental sensitivity. Therefore, in order to remove these various drifts in a simple way, it has been assumed that during a certain number of time intervals (a maximum of 20 has been considered), the sensitivity varies linearly with time. When this assumption is correct, all the slopes become zero and the points must be distributed along horizontal lines. Moreover, the distribution of the ratios must look like the typical distribution of Table 1.

Table 2 shows the ratios for the solar irradiances, observed at H-Lyman-alpha computed for the various time intervals which have been adopted in the adjustment; the first line corresponds to the observational data and the second line gives the result obtained after adjustment. All the adjusted ratios lead to 1.00±0.03 with a distribution similar to the distribution obtained with the radio fluxes. The corresponding graphical result is illustrated in Fig. 4 which may be compared with Fig. 3.

Thus the inconsistencies of the H-Lyman-alpha series can be explained mainly by differences in the absolute calibration and by additional instrumental drifts with time.

The adjusted H-Lyman-alpha irradiances (assuming that the first data of OSO-5 were correctly calibrated) are represented in Fig. 5, which must be compared with

TABLE 2. H-LYMAN-ALPHA IRRADIANCES.

Ratios (in %) between the mean irradiances for various observational periods (01–14) of OSO-5 and AE-E and the mean irradiance deduced from the data from 1969 to 1980 corresponding to all levels of solar activity defined by the 10.7 cm radio flux from 75±10 to 255±10. First line: ratios deduced from published data and second line: ratios deduced from adjusted data.

	Classification											
Period	075	095	115	135	155	175	195	215	235	255		
01			093 100	080 100	069 100	058 101	052 098					
02		077 099	084 100	072 098	067 102						OSO-5	1969–1972
03		081 101	086 100	074 099	065 099							
04	084 099	080 099									OSO-5	1974–1975
05	137 102	116 099	123 098									
06		130 097	138 100	115 102							AE-E	1977–1978
07			144 102	122 100	108 098	092 099						
08							116 100	107 100				
09					150 101	130 100	120 099					
10				180 100	157 100							
11						128 099	116 098	110 100	114 102		AE-E	1979–1980
12					150 103	125 101	113 101	109 100	102 097			
13						110 099	102 101	093 099	095 099			
14				144 096	127 100	105 101	097 100	087 099	087 100	090 098		

the corresponding Fig. 2 for the observational data.

The regression analysis of the adjusted data leads to the straight line

$$F_{\text{Ly-}\alpha} = 2.91\left[1+0.20\left(\frac{F_{10.7}-65}{100}\right)\right] \times 10^{11} \text{ photons cm}^{-2}\,\text{s}^{-1}$$

with $N = 1406$ observations, a correlation coefficient $CC = 0.87$ and a standard deviation $D = 0.16$. The coefficient outside the brackets depends on the absolute calibration adopted for a quiet sun. Less than 6% of the data are outside the 10% domain on either side of the regression straight line.

The slope coefficient 0.20 obtained here is significantly lower than the value 0.44 published earlier by Bossy and Nicolet (1981). Such a difference corresponds to an improvement in the analysis resulting from detailed consideration of the ratios which leads to a much more refined adjustment, especially of the highest values of AE-E. This new value of the slope coefficient fits well with the slope obtained by the regression analysis of recent data of SME for $F_{10.7}$ between 130 and 300 from 13 October 1981 to 25

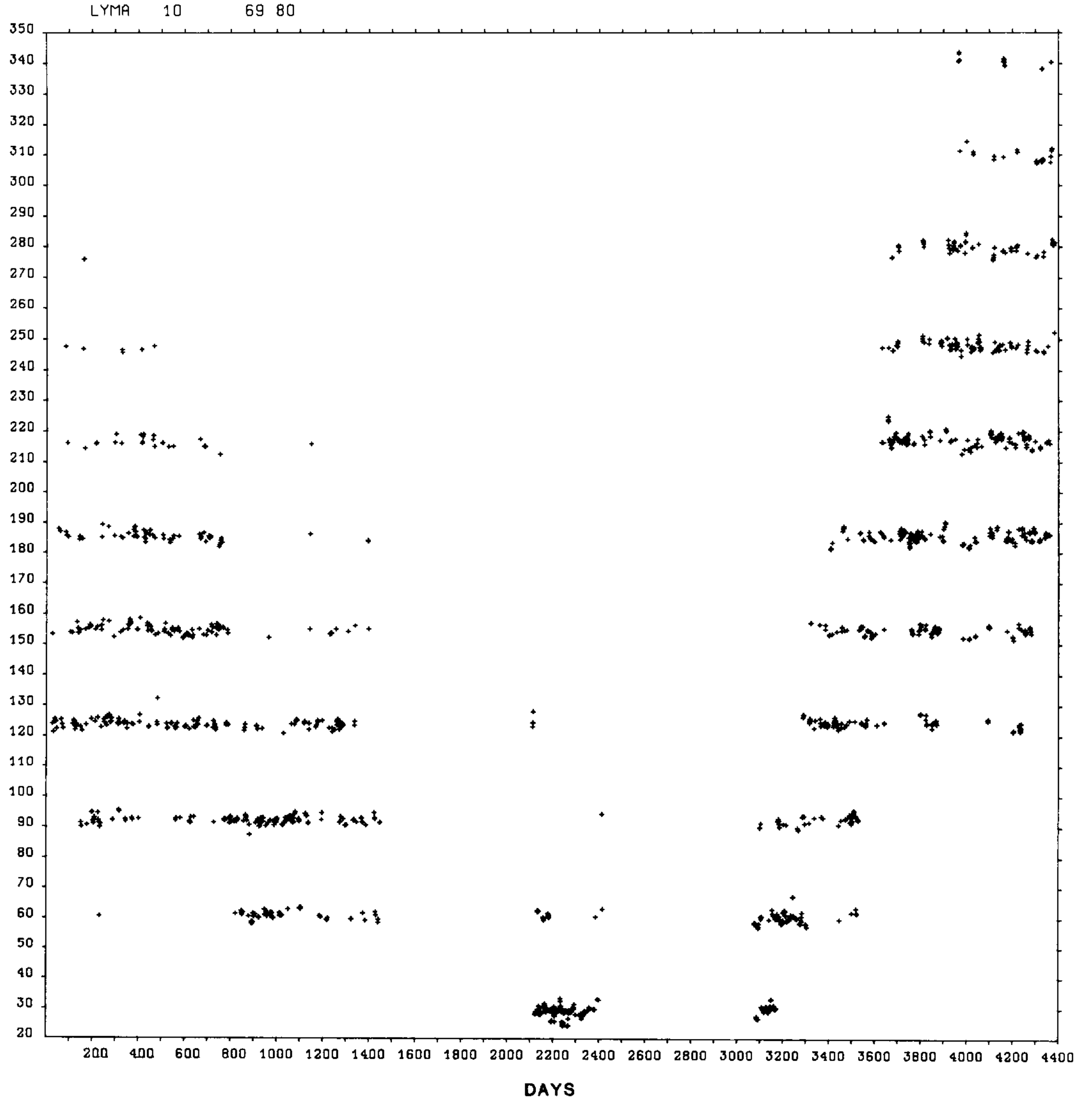

FIG. 4. ADJUSTED H-LYMAN ALPHA DATA FROM 1969 TO 1980. Parameters are the same as for Fig. 3.

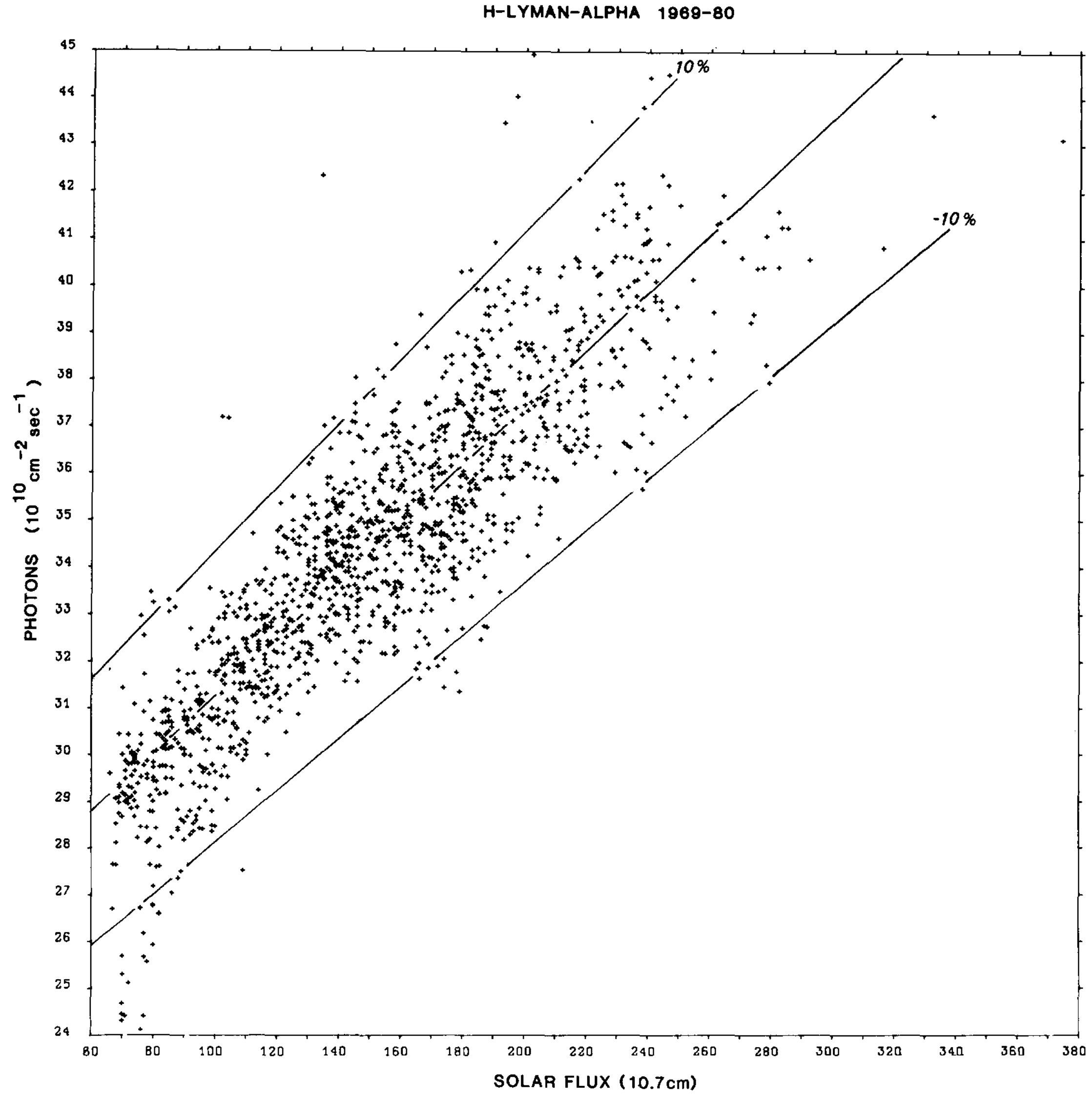

Fig. 5. Adjusted daily values of H-Lyman-alpha irradiances from 1969 to 1980 vs the daily 10.7 cm solar radio fluxes.

March 1982 (Rottman, private communication, 1982)

$$F_{\text{Ly-}\alpha} = 3.32\left[1+0.18\left(\frac{F_{10.7}-65}{100}\right)\right] \times 10^{11} \text{ photons cm}^{-2}\,\text{s}^{-1}.$$

These parameters are very close to the values 3.44 and 0.16 obtained by Rottman *et al.* (1982) using a shorter series of SME observations. The difference between 2.91 based on OSO-5 and 3.32 deduced from the values of SME is related to the problem of the absolute calibration.

An identical analysis can be made with success for the irradiances of H-Lyman-beta, the HeI-resonance line and HeII-Lyman-alpha measured by AEROS-A in 1973 (Schmidtke, 1978), AEROS-B in 1974–1975 (Schmidtke, 1979) and AE-E from 1977 to 1980 (Hinteregger, 1981a). The results of the regression analysis for these last three irradiances are as follows (in units of 10^9 photons cm^{-2} s^{-1})

$$F_{\text{Ly-}\beta} = 3.54\left[1+0.27\left(\frac{F_{10.7}-65}{100}\right)\right],$$

$$N = 1053,\ CC = 0.93,\ D = 0.20$$

$$F_{\mathrm{HeI}} = 1.58\left[1+0.32\left(\frac{F_{10.7}-65}{100}\right)\right],$$

$$N = 960,\ CC = 0.92,\ D = 0.12$$

$$F_{\mathrm{HeII}} = 7.10\left[1+0.28\left(\frac{F_{10.7}-65}{100}\right)\right],$$

$$N = 1135,\ CC = 0.93,\ D = 0.45.$$

Again, the adjusted data are mainly confined between the two lines at ± 10% from the regression straight line.

In the present adjustment procedure, the choice of the time intervals and of the rate of variation with time of the sensitivity is essentially based on the features of the graphical representation, but the scaling factors are obtained by a numerical analysis. Since some subjectivity is involved in the choice of the time intervals, various approaches may lead to differences in the slope of the regression straight line; however, these remain less than 10%.

Finally, when the values of the radio fluxes at 10.7 cm differ by nearly 300 units between solar minimum and solar maximum, it can be concluded that the corresponding variations of the irradiances are, with a precision of 10%, about 60% for H-Lyman-alpha, 80% for H-Lyman-beta (the value of 185% obtained by Nicolet and Bossy (1981) was based on the non-adjusted series of AE-E) and 90% for HeI and HeII, respectively.

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