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   interference of local aerodynamical effects. Some other
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Variations of solar EUV, UV and ionospheric foF2 related to the solar rotation period

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Abstract. Spectral analysis of daily values of various solar indices viz. sunspot number, 10.7-cm flux, H Lyman-α and -β, specific He, Fe and Mg lines and solar X-rays was carried out for two selected intervals. During interval A (May–August 1978, 123 days) the solar indices showed a prominent periodicity near 27 days, while during interval B (January–May 1979, 151 days) the solar indices showed a prominent periodicity near 13 days. For the same intervals, *foF2* (max) and *foF2* (average) during 1000–1500 LT were similarly analysed for the locations Cachoeira Paulista, SP, Brazil (23°S, 45°W), and Okinawa (26°N, 128°E) and Kokubunji (36°N, 139°E) in Japan. The 27-day and 13-day periodicities in solar indices were reflected in the *foF2* series, but in different relative proportions at the three locations, probably due to the interference of local aerodynamical effects. Some other periodicities were common to solar indices and *foF2*, while some others were present in the solar indices but not in *foF2*, or vice versa.

1 Introduction

Relationships between solar indices (mainly sunspot numbers and 10.7-cm flux) and ionospheric parameters on long-term scales have been reported earlier (e.g. Smith and King, 1981). Recently, Rishbeth (1993) reported relationships between day-to-day ionospheric variations and solar indices (sunspots and 10.7-cm flux) during two very strong 27-day rotations in November–December 1979. In this note, we report results of a spectral analysis of the daily values of several solar indices viz. sunspot numbers, 10.7-cm flux, Ca K Plage, photospheric 2050 Å, H Lyman-α and -β, specific He, Fe and Mg and O lines and solar X-rays, and ionospheric *foF2* at Cachoeira Paulista, SP, Brazil, (23°S, 45°W), and Okinawa (26°N, 128°E) and Kokubunji (36°N, 139°E) in Japan, during two selected intervals of several months each. The various solar indices arise from emissions from different parts of the solar atmosphere (the photosphere, chromosphere, and corona), and will have different relationships (perhaps none) with ionospheric *foF2*. Our purpose is to see which periodicities observed in which solar indices are reflected in the ionospheric data.

2 Data

Hinteregger (1981) has given plots of daily values of several solar indices (obtained from the AE-E satellite) for 1978–79. From these we selected data for May–August 1978 as our interval A, since during this interval the solar indices had a prominent wave with a period of about 27 days. Similarly, from Donnelly *et al.* (1986) we selected data for January–May 1979 as our interval B, since during this interval the solar indices had a prominent wave with a period of about 13 days. Data for other solar parameters were obtained from Solar Geophysical Data, while X-ray data were obtained from Wagner (1988). For ionospheric parameters, we examined both *foF2* (max), i.e. the maximum value of *foF2* during the LT interval 1000–1500 h, and also *foF2* (average) for the same interval. The geomagnetic activity during these intervals was low, hence complications from storm-time effects on *foF2* are not expected to be significant.

3 Method of analysis

Power spectra were obtained by maximum entropy spectral analysis (MESA) (Ulrych and Bishop, 1975). Since MESA does not give amplitude estimates accurately (Kane, 1977; Kane and Trivedi, 1982), it was used only to detect possible periodicities T_k ($k = 1{-}n$), and these were

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then used in the expression

$$f(t) = A_0 + \sum_{k=1}^{n} [a_k \sin(2\pi t/T_k) + b_k \cos(2\pi t/T_k)] + E$$
$$= A_0 + \sum_{k=1}^{n} r_k \sin(2\pi t/T_k + \phi_k) + E, \quad (1)$$

where $f(t)$ is the observed time series and E is the error factor. The best estimates of A_0, (a_k, b_k), (r_k, ϕ_k) and their standard errors, were obtained by a least-square fit using multiple regression analysis (Bevington, 1969). Amplitudes exceeding 2σ are significant at a 95% (a priori) confidence level.

Before applying this method, one needs to check whether the data have any long-term (linear or parabolic) trends, and if so, to correct for these by estimating the trends by standard regression analysis and subtracting this from the original data.

4 Results for interval A (May–August 1978)

The various solar indices were obtained from Hinteregger (1981). For ionospheric parameters, detrending may be necessary as shown in Fig. 1a. This shows a plot of *foF*2 (max) at Cachoeira Paulista for May–August 1978, and their long-term variation represented by the thick line, obtained by fitting a degree-two polynomial. When the thick line values are subtracted from the original values, the difference obtained is shown in Fig. 1b. There is still much scatter, which is minimized by evaluating 3-day running averages (the thick line in Fig. 1b). These running averages were used for spectral analysis. This was carried out for four ionospheric time series, i.e. the unsmoothed and 3-day smoothed values of both the maximum and average of the detrended *foF*2 values from 1000–1500 LT.

Plots of the various solar indices are shown in Fig. 2 for May–August 1978, and in Fig. 3 for January–May 1979. Some indices are missing in one interval and present in the other, but this is not important as we will not compare the results of the two intervals. In each plot several features (maxima and minima) seem to be common to all indices, indicating that these are present in all regions of the Sun. Others are peculiar to some indices only, indicating their localised nature.

Figure 4 shows the spectra, i.e. the amplitudes versus periodicities T (days) for May–August 1978 (interval A). The abscissa scale is chosen as $\log_{10} T$, to give equal percentage spacing for all T. The top four plots refer to the four ionospheric series at Cachoeira Paulista. Whereas there are many peaks significant at a 2σ (a priori) level, indicated by the hatching, the two very prominent periodicities are $T = \sim 15.4$ and ~ 25.6 days. In the other plots, there is a prominent periodicity at $T = \sim 25$ days for almost all indices except the O IV Group (554 Å), for which two periodicities ($T = 24.0$ and 29.5 days) are indicated. All these could be considered to be due to the solar rotation. However, there are only small peaks at $T = \sim 18$ days, and still smaller ones at $T = \sim 13.5$ days, though strong periods around 14 days have been reported elsewhere for various solar indices at other times (e.g. Donnelly and Puga, 1990). There are some peaks, e.g. $T = 5.8$ and 7.6 days, which seem to be significant in the ionospheric parameters but not in the solar indices. Conversely, some solar indices show a peak at $T = \sim 33$ days which is reflected only in the ionospheric parameters at Okinawa. On the other hand, $T = \sim 40$ days is seen in the

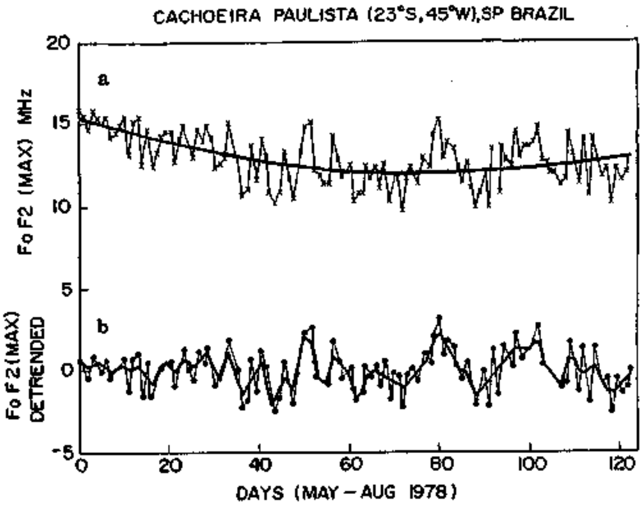

Fig. 1a and b. *foF*2 (max) at Cachoeira Paulista SP, Brazil 23°S, 45°W, during interval A (May–August 1978, 123 days). **a** Daily values and their long-term trend (*thick line*), obtained by a polynomial fit. **b** Detrended *foF2* (max) and their smoothed values (*thick line*)

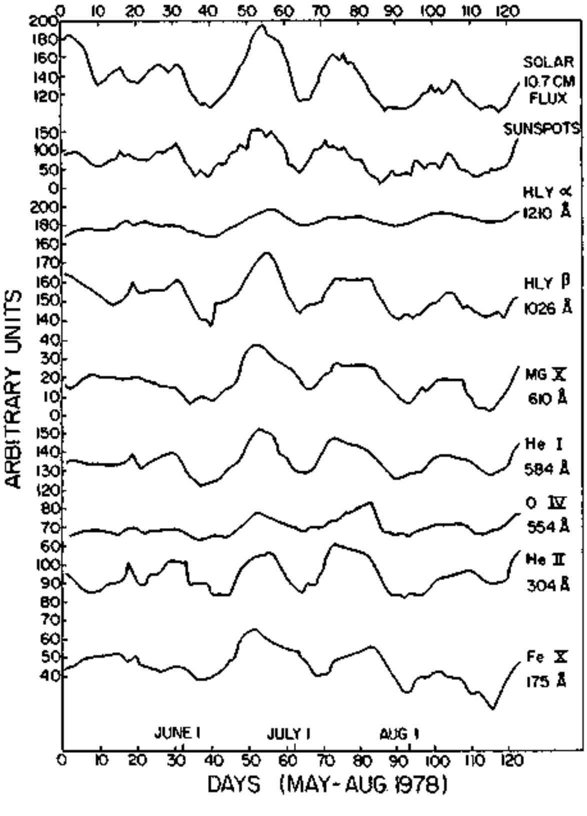

Fig. 2. Plot of the 123 daily values of the various solar indices for May–August 1978

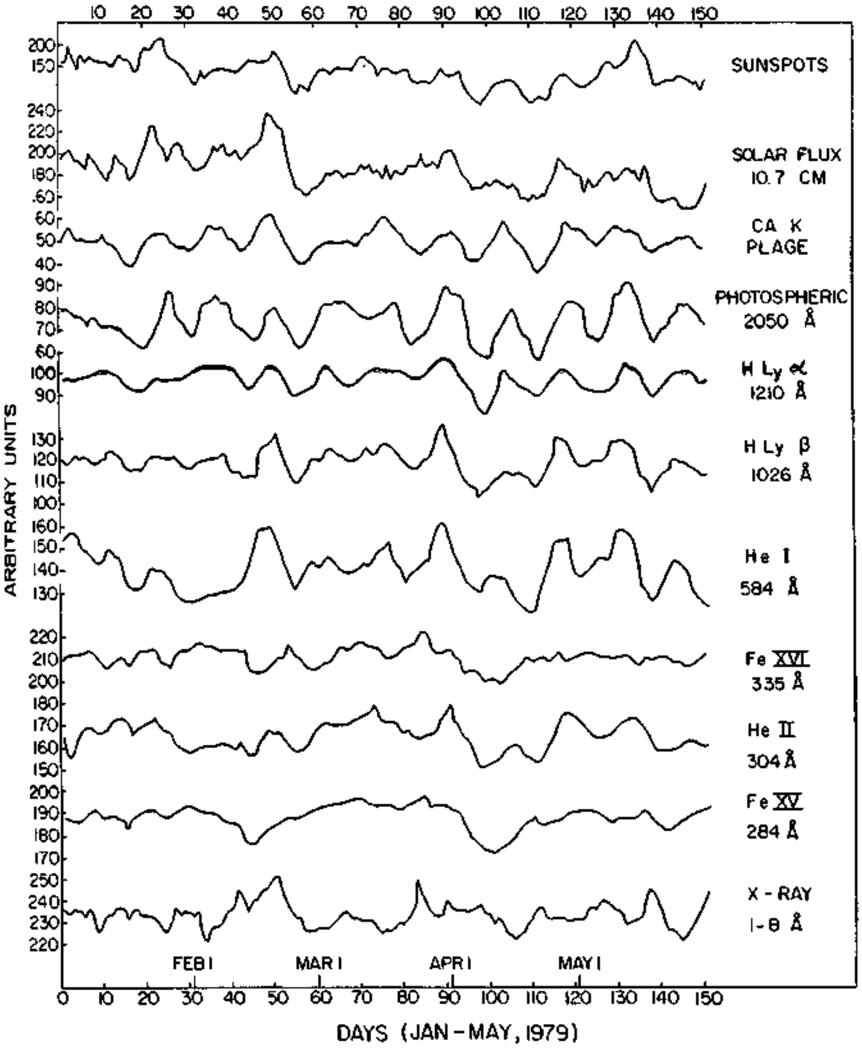

Fig. 3. Plot of the 151 daily values of the various solar indices for January–May 1979

ionospheric parameters and in some solar indices (sunspots, 10.7-cm flux, H Ly α, Fe X), and may be peculiar to this interval. Rishbeth (1993) obtained correlation coefficients of + 0.11, + 0.59, and + 0.01 between sunspot numbers and *foF*2 at Port Stanley, Slough, and Huancayo, respectively. We made a similar analysis for our ionospheric parameters and various solar indices for this interval. Almost all correlation values were low, though positive. This was probably because not all periodicities were common and of equal importance. In the case of ionospheric parameters, dynamic effects connected with the atmosphere will cause variations unrelated to solar rotation, which will reduce the correlations. Experimental inaccuracies in the ionospheric data should also reduce the correlations. Also, some days were slightly magnetically disturbed and may have produced small strom-time F-region variations not directly related to solar indices.

5 Results for interval B (January–May 1979)

Figure 5 shows spectra for the 151-day interval January–May 1979. The ionospheric parameters (top four plots) show two prominent peaks at $T = \sim 24.7$ and ~ 28 days. In some solar indices both of these are prominent, but in others only one appears, or both are weak or absent. In general, the 24.6-day periodicity seems to match, but there is no clear, consistent agreement on 28 days. Conversely, all solar indices have a prominent peak near $T = 13$ days but the ionospheric parameters show peaks at $T = 12$, 15 or 18 days, but not at 13 days (in this region, the accuracy of peak detection by MESA is good enough to see this difference). Also, all the solar indices have peaks in the range $T = 40$–50 days but the ionospheric parameters do not show this strongly.

Since many peaks are common to almost all solar indices, "consensus" spectra can be created. These were obtained by choosing peaks which were prominent in at least four solar indices. Figure 6 shows the "consensus" spectra for solar indices and *foF*2 (max) for Cachoeira Paulista, Okinawa and Kokubunji for interval A (May–August 1978) in the upper half, and interval B (January–May 1979) in the lower half. For interval A (Fig. 6a), the solar indices show prominent peaks at $T = 25$ and 70 days, smaller peaks at $T = 13.5$ and 10 days. For ionospheric *foF*2 (max), $T = 25$–26 days is seen

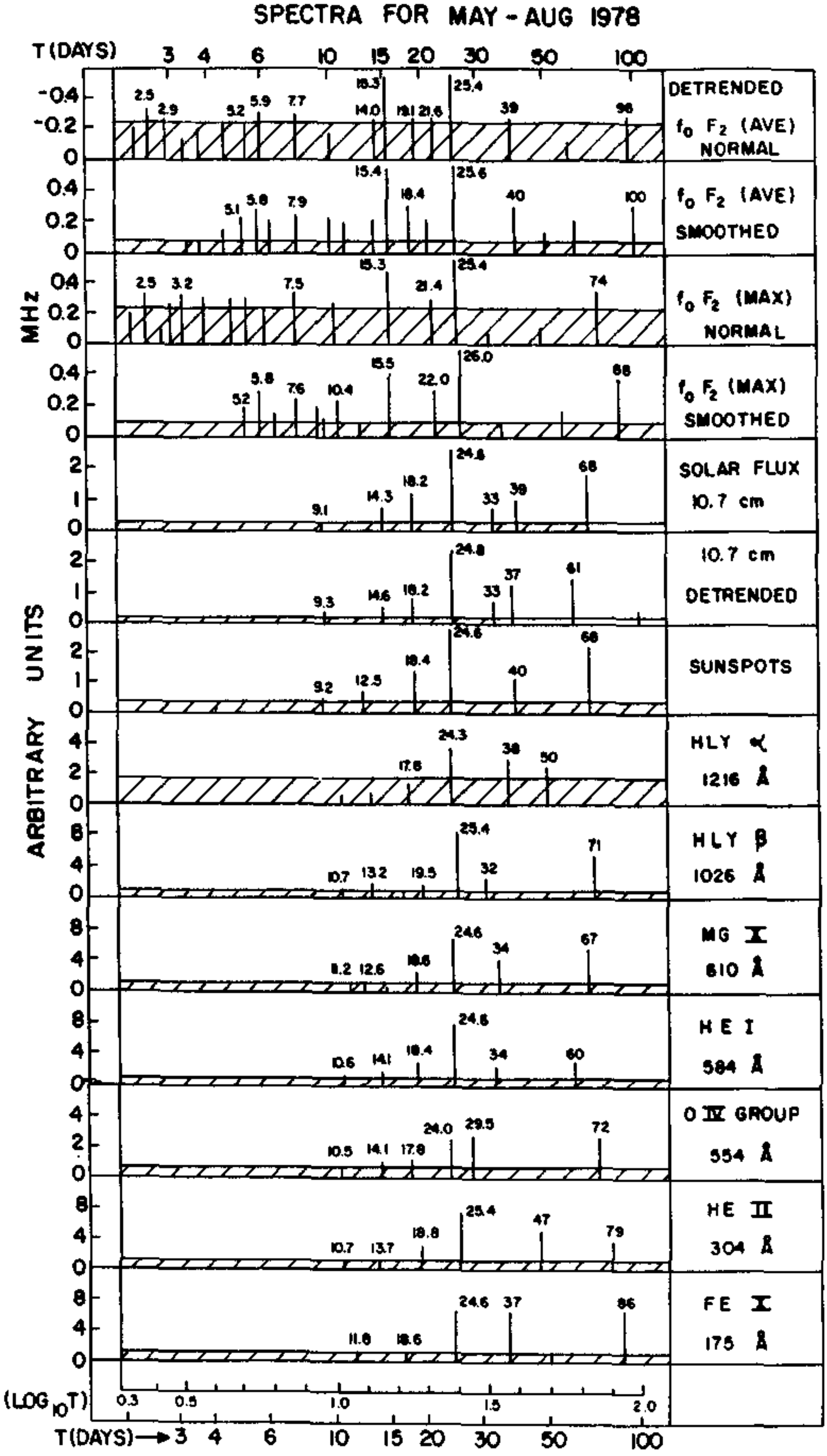

Fig. 4. Spectra (amplitudes versus periodicity T in days) for interval A (May–August 1978, 123 days) for the ionospheric parameters at Cachoeira Paulista (*top four plots*) and for various solar indices. The abscissa scale is in units of $\log_{10} T$

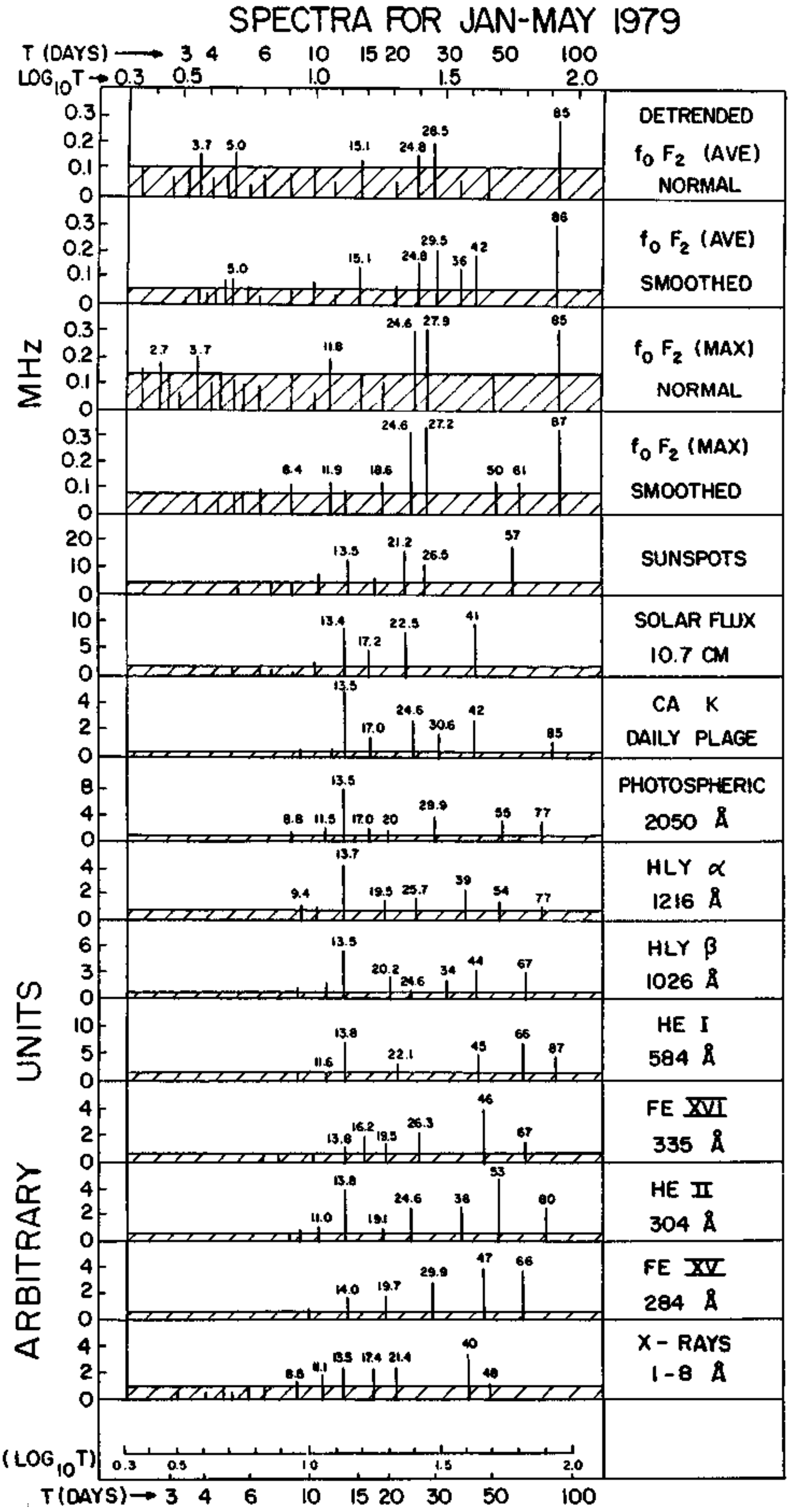

Fig. 5. Spectra for interval B (January–May 1979, 151 days)

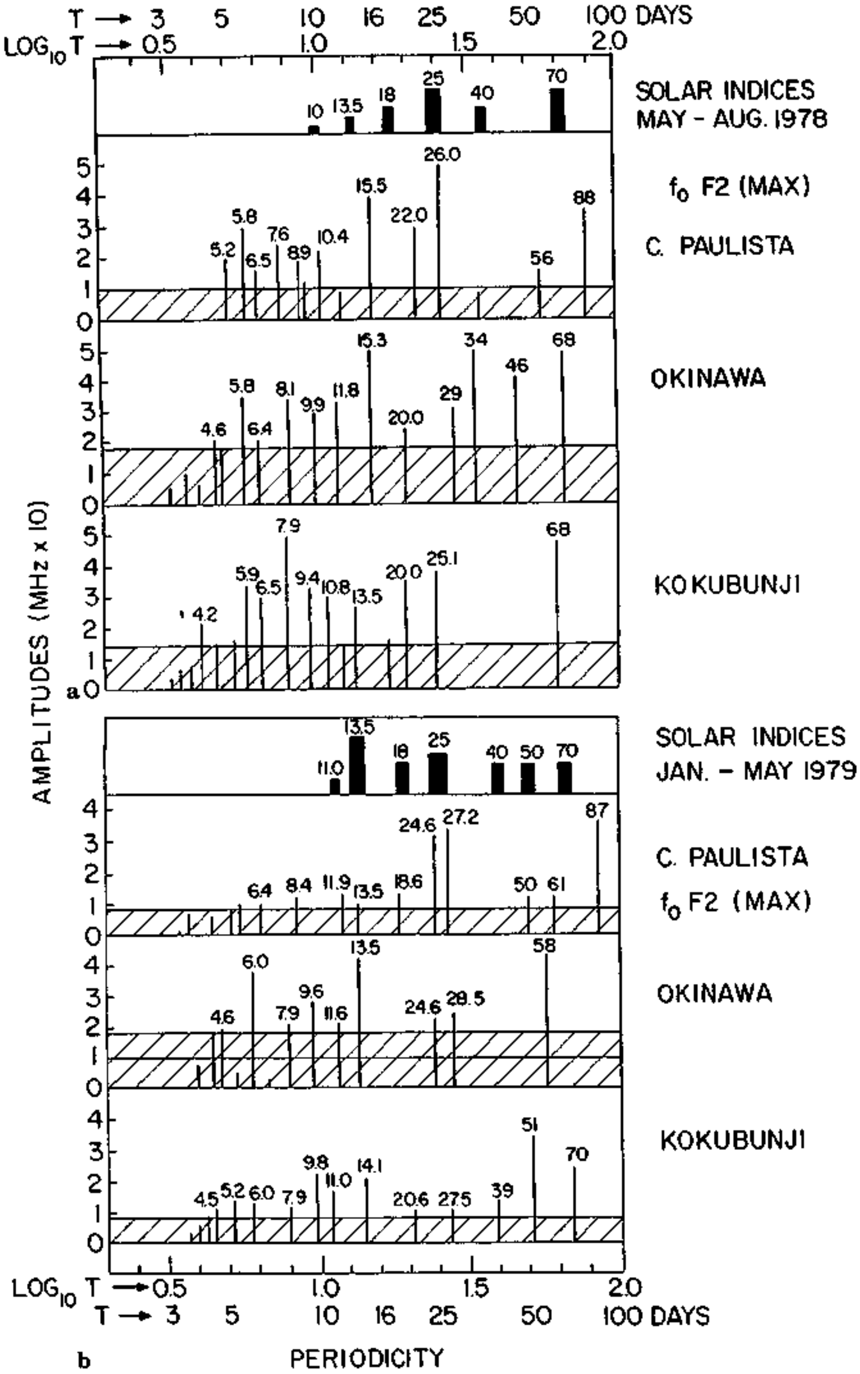

Fig. 6a and b. Spectra for solar indices (summary) and *foF*2 (max) at Cachoeira Paulista (23°S, 45°W), Okinawa (26°N, 128°E) and Kokubunji (36°N, 139°E) for **a** interval A, 123 days, May–August 1978, and **b** interval B, 151 days, January–May 1979

prominently at Cachoeira Paulista and Kokubunji, but Okinawa shows $T = 29$ days. All locations show large peaks near $T = 67$–72 days, but these may not be reliable and are absent in the very important He II 304 Å data. A peak at $T = 15$ days is seen at Cachoeira Paulista and Okinawa, but not at Kokubunji. The peak at $T = 18$ days seen in solar indices is not seen in *foF*2 (max) at any location. Conversely, lower periodicities ($T = 5.8$ and 7–8 days) are seen in *foF*2 only and are probably of terrestrial origin (perhaps related to planetary waves).

For interval B (Fig. 6b), solar indices show strong peaks at $T = 13.5$ and 25 days. In *foF*2, $T = 13.5$ days is seen prominently at Okinawa, less prominently at Kokubunji, and negligibly at Cachoeira Paulista. $T = 25$ days is seen prominently at Cochoeira Paulista, moderately at Okinawa, and negligibly at Kokubunji. $T = 50$–70 days is seen at all locations.

6 Conclusion and disucssion

Our results indicate that the solar index peaks near 27 days and 13 days are reflected in different proportions in the ionospheric parameters at different locations, probably due to the interference of local aerodynamical upheavals. Peaks at $T = 4$–8 days appear in the ionospheric parameters only, and could be of terrestrial origin.

For ion production in the ionospheric F- and E-regions, the most important solar EUV radiation is in the range 100–1026 Å. For the ionospheric D-region, H Lyman-α (1216 Å) is the major source. Thus all solar indices shown in Figs. 2 and 3 are not expected to be equally important for the ionosphere. For the F2-region, 200–800 Å radiation is much more important (e.g. He II, Fe XV, ,Fe XVI, and He I). In particular, He II 304 Å is very important for the thermospheric maxium temperature. All these indices may not always be well correlated with each other. The solar source regions for the various UV radiations range from the upper photosphere to the region of the photosphere-chromosphere temperature minimum, while EUV source regions range up to the corona (Donnelly *et al.*, 1986). Thr UV spectrum has absorption lines and continua, and the strong absorption lines originate in the chromosphere. The EUV flux consists mainly of emission lines and emission continua. Donnelly and Puga (1990) have studied the power spectra for solar UV, EUV and X-ray fluxes. The 27-day and 13-day peaks have different relative strengths for different solar indices, as can also be seen from our Figs. 4 and 5. In particular, the 13-day peak is weak in the coronal flux of Fe XV and XVI EUV lines, while it is strong in He II 304 Å. The ionospheric parameters do not seem to be related to the solar indices for all periodicities. Thus, besides the effect of solar input, *foF*2 might be affected by other factors, probably aerodynamic effects in the Earth's atmosphere, which might have their own characteristic periodicities. For example, the non-solar period of about 16 days observed in both the intervals could be due to a middle-atmospheric planetary wave of tropospheric origin, as was found in the E- and F2-regions above Huancayo (Peru) by Forbes and Leveroni (1992). The latter authors point out that free Rossby (resonant mode) oscillations with periods 2, 5, 10 and 16 days may regularly penetrate from the stratosphere into the ionosphere/thermosphere.

Intervals A and B analysed here had rather low geomagnetic disturbance levels. However, in general ionospheric parameters are strongly correlated with magnetic disturbances and their effect needs to be considered, when prominent. The present analysis was restricted to two short selected intervals. The analysis needs now to be extended to other suitable intervals.

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