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Extension of the F10.7 index to 1905 using Mt. Wilson Ca K spectroheliograms

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Abstract. The F10.7 index provides a daily record of solar microwave emissions, which vary in rough proportion to the projected area of bright magnetic structures called plages and network, and also sunspots, on the sun's disk. The daily observations used to form the index only began in 1947. Recently, we digitized the archive of daily Ca K spectroheliograms obtained at Mt. Wilson Observatory between 1905-1984, and measured the area variations of plages and enhanced network, on these photographic plates. We calibrated these variations against the F10.7 index between 1947-1984, so we are able to construct a full-disk proxy of F10.7 extending back to 1905. The behavior of this extended index indicates that UV irradiance levels achieved near the peaks of sunspot cycles 15, 16, and 17 between 1915-1945, were 25-40% higher than would be estimated from behavior of the Zurich sunspot number, R_z.

Introduction

The variation of solar microwave emissions at 10.7 cm has been monitored on a daily basis since 1947, as a widely used measure of solar activity, complementary to the Zurich sunspot number, R_z. The 10.7 cm microwave emissions arise mainly from regions of intense magnetic field in the solar chromosphere and transition region, associated with the morphological structures called plage and network, and also from sunspots (e.g. Tapping, 1987; Bastian et al., 1996; Schmahl and Kundu, 1995). Therefore, the F10.7 index is particularly useful as an index of variations in the sun's ultraviolet light emissions (e.g. Donnelly et al., 1983), which arise predominantly from the plage and network structures, and vary mainly due to changes in their projected area on the solar disk (e.g. Lean, 1987). It is superior in this use to the CaK plage index (Swartz and Overbeek, 1971) because it covers the full disk, i.e., it captures the contribution to UV emissions arising from changes in the chromospheric network, as well as from changes in the active region plages. This close connection to ultraviolet solar spectral irradiance variation makes the F10.7 index a standard input to models of both the neutral atmosphere and ionosphere (e.g. Hedin, 1982; Bailey and Balan, 1996; Roble and Ridley, 1994).

Studies of global change require a reliable proxy of solar ultraviolet outputs prior to 1947, when the F10.7 index was initiated. The best such proxy are measurements of the projected areas of bright chromospheric magnetic structures imaged on spectroheliograms obtained in the resonance line of Ca II (the Ca K line). Daily measurements of the bright Ca K plages seen in active regions began at McMath-Hulbert Observatory in 1947, at about the same time as the F10.7 index was initiated in Ottawa. However, no regular Ca K data were available prior to that year.

Recently, we digitized the daily Ca K spectroheliograms taken at Mt. Wilson Observatory (MWO) between 1915-1984, and measured the daily active region plage areas, corrected for foreshortening (Foukal, 1996, hereinafter referred to as Paper I). Since that work we have extended this digitization to include an earlier set of MWO plates beginning in 1905. The MWO plates also show the bright chromospheric network, whose area variations contribute to the slow variation of UV (and microwave) fluxes over a solar cycle (e.g. Lean, 1987). In this paper, we describe our measurement of the combined area variation of plages and network on these spectroheliograms, the calibration of these area variations against the F10.7 index between 1947-1984, and the generation of a proxy F10.7 index for the previous years 1905-1946. Finally, we compare its behavior to the area variation of active region plages alone, and also to R_z.

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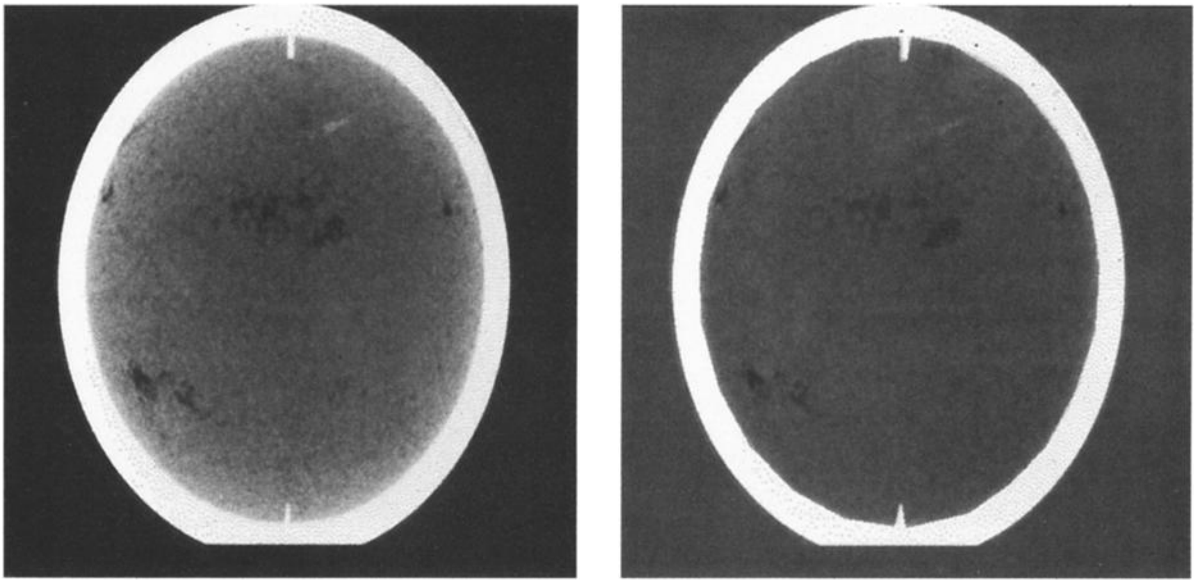
Data and Reduction Procedures

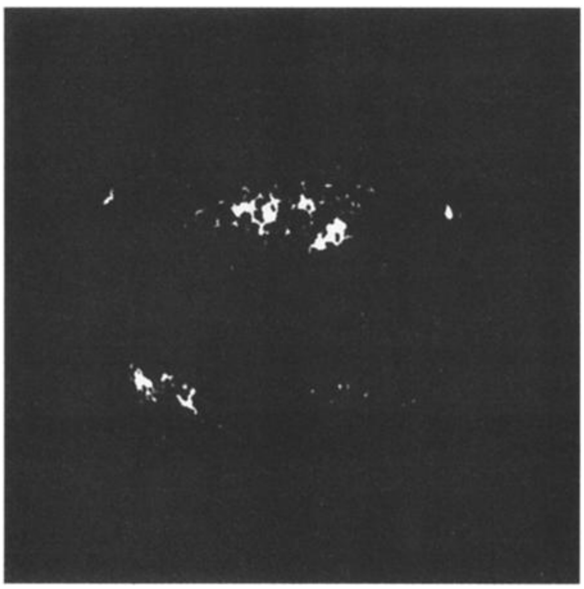
The data set of MWO Ca K spectroheliograms and their digitization using a CCD camera, were described by Foukal (1996). Fig 1(a) shows one of the digitized images. We see examples of bright active region plages, and also of localized enhancement (i.e. broadening) of the chromospheric network around active regions which covers the whole disk. We focus here on the reduction procedure followed in deriving an index, A_{pn}, which includes variations in area of not only the bright plages measured in Paper I, but also of the most obvious network enhancements.

The reduction was carried out on images of photographic density (rather than calibrated intensity) because i) no calibration density wedges were imprinted on the MWO spectroheliograms taken before 1962, ii) the density wedges beginning in 1962 often did not cover the full range of densities achieved in the brighter plages, and iii) the area variations of interest here are measured as accurately on density images as in intensity images, so the time consuming intensity calibrations provide no advantage. Systematic variations of plage or network brightness may also occur, but their measurement would require more accurate photometry than can be achieved on the archival photographic images analyzed here.

Our measurement of A_{PN} was carried out using IDL image processing software, proceeding as follows: i) the digitized density image is displayed on a crt, a line is drawn around the solar limb using a cursor, and the number of pixels, N, in the solar image is calculated; ii) solar limb darkening is removed by constructing a template of each image with the active regions excised and replaced by smoothed interpolation of the nearby disk; this template is then subtracted from the image itself (Fig 1(b) shows this subtracted image); iii) a quiet region of area approximately 5-10% of the solar disc is chosen on the subtracted image, and its rms density variation is calculated; iv) this rms value, multiplied by a constant chosen by inspection and iteration, is used to set a density threshold above which structures are called "plage and enhanced network". An image of these structures (Fig 1(c)) is displayed side-by side with the subtracted image, so that the operator can check whether the multiplier chosen captures the visual appearance of plage and enhanced network adequately (most of the images required no adjustment of the multiplier); v) the number of plage and enhanced network pixels, N_{AN}, is divided by the



(a) (b)



(c)

Figure 1. Panel (a) shows a digitized MWO CaK spectroheliogram; panel (b) shows the same image after subtraction of limb-darkening; panel (c) shows the areas chosen as plages and enhanced network.

total number of disk pixels, N, to yield the normalized, projected area, A_{PN}, of plages and enhanced network.

Since the lifetimes of plages and enhanced network exceed the period of solar rotation, reduction of four evenly spaced images per month was considered sufficient to monitor the long-term variations in A_{PN} required for global change studies. The leading source of error in A_{PN} is the subjective definition of enhanced network. This uncertainty is most serious in defining the level of activity minima, when no substantial plages are seen, and small changes in the operator's definition of network enhancements can lead to relatively large percentage variations.

Results and Discussion

Fig 2 shows the 1905-1984 monthly mean time series of A_{PN}, together with the corresponding time series of A_p. Their comparison shows that inclusion of the enhanced network significantly increases the amplitude of the seven smaller cycles relative

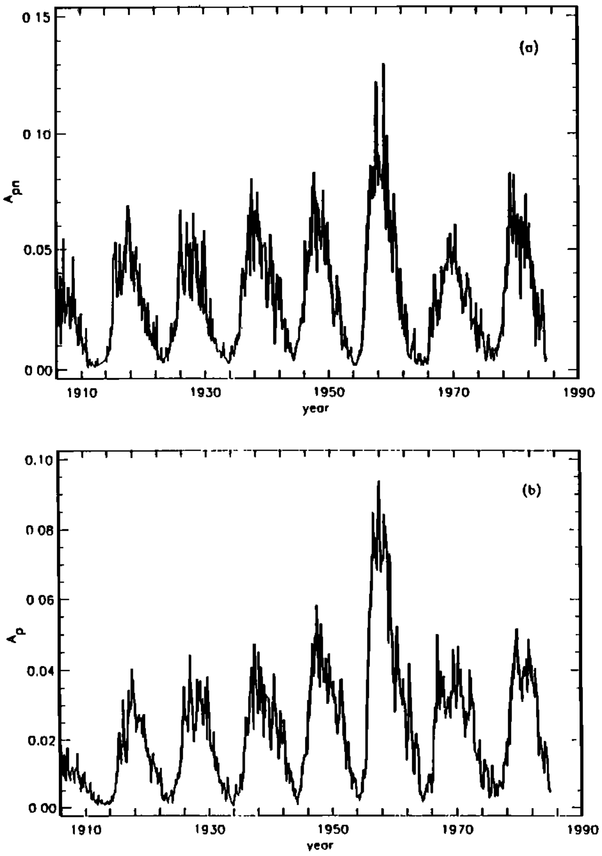


Figure 2. Time series of monthly means of (a) A_{PN}; and (b) A_p, for cycles 14-21. A monthly mean of A_{PN} is based on only 4 measurements; a full set of daily measurements was used to form monthly means of A_p. The ordinates are fractional areas of the projected disk.

to cycle 19, the largest. That is, the largest cycle (19) is magnified least (by about 15%), with progressively more magnification for the smaller-amplitude cycles, the amplitudes of cycles 14 and 15 being approximately doubled in A_{PN}. The uncertainty in A_{PN} around activity minima, mentioned above, is approximately ± 0.0025 in the disk-area units used in Fig 2, therefore too small to contribute significantly to this trend.

The most likely explanation of this trend is that, as more active regions crowd the active latitudes, progressively less of the solar disk area remains for enhanced network. Whatever the explanation of the trend may be, inclusion of even the most evident variations in network area considered here can add a contribution to the total area variation of Ca K structures comparable to that of active region plages.

A scatterplot of monthly mean F10.7 versus monthly mean A_{PN} for the years 1947-1984 (not shown here) exhibits a correlation coefficient of 0.93, compared to 0.87 when A_p is used. This shows that inclusion of the enhanced network improves the correlation between an index based on areas of Ca K structures, and the F10.7 index, which would be expected, since the microwave flux arises from the network as well as plages (e.g. Bastian et al. 1996). The regression relation between F10.7 and A_{PN} is found to be: $F10.7 = 617 + 1.12 \times 10^4 A_{PN}$.

In Fig 3, we show the "extended" time series of monthly F10.7 for 1905-1984 calculated from the time series of A_{PN}, using the regression relation given above. We also show the measured F10.7 monthly means for 1947-1984 for comparison. The two curves of measured and A_{PN}-generated F10.7 agree very well over the 1947-1984 period. Specifically, the enhancement of cycles 18, 20, and 21 relative to 19, and also the enhancement of cycle 21 relative to 20, both of which are the result of including network variation in A_{PN} as noted above, significantly improve the ability of the A_{PN}-generated F10.7 to match the behavior of the measured F10.7. Comparison of A_p with A_{PN} in Fig 2 shows that an F10.7 curve based upon A_p would exhibit a much greater amplitude of cycle 19 relative to 18, 20, and 21, and also a more closely similar amplitude of cycles 20 and 21, than are seen in the time series of measured F10.7 plotted in Fig 3.

In Fig 4 we compare the 1905-1984 behavior of our extended F10.7, with the Zurich sunspot number. A 13-month running mean has been applied to display the relative cycle amplitudes more clearly. This figure shows that in our extended F10.7 index, the amplitudes of cycles 15, 16, and 17 are enhanced by between 25-40%, compared to their relative amplitudes in R_z. This enhancement is too large by a factor 3-5 to be explained by the uncertainties in extended F10.7 around activity minima, mentioned earlier.

Summary and Conclusions

Using the MWO Ca K images we have digitized, we are able to measure variations of plage area, and of enhanced network area, and use them to construct an index, A_{PN}, of total area variation of solar chromospheric structures. Comparison of the "full-disk" index A_{PN}, with the index A_p of plage area alone, shows that inclusion of even the variations of the most enhanced network can make a contribution to a cycle's amplitude, comparable to that of active region plages. This result is consistent with previous findings (e.g. Foukal and Lean, 1986; Lean, 1987; Foukal et al. 1991) that network-associated contributions to variations in both total and ultraviolet irradiance are comparable in magnitude to the plage-associated variations.

We have also shown that the time behavior of this full-disk index A_{PN} correlates significantly better with the F10.7 index (which is also "full-disk"), than does the index, A_p, of active region plage area alone. This improved correlation would be expected, since 10.7cm microwave emission arises from the network as well as from active region plages.

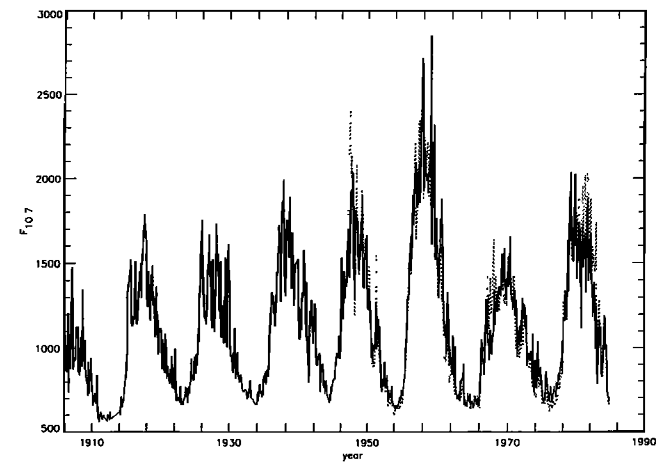
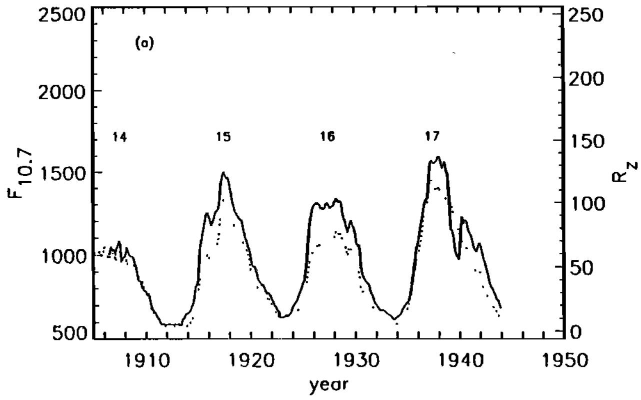


Figure 3. Time series of monthly mean extended F10.7 from 1905-1984 (solid line). The dotted line shows monthly means of measured F10.7 between 1947-1984. The ordinate is in microwave flux units.



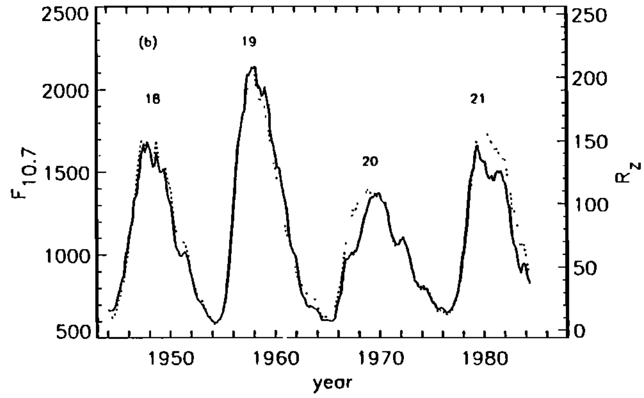


Figure 4. Running means (13-month) of our extended F10.7 index for 1905-1984 (solid), and of the Zurich sunspot number, R_z (dotted). Sunspot cycle numbers are marked 14-21.

The most evident difference between our extended F10.7 index and R_z, is in the enhancement of our index between 1915-1945 relative to 1905-1914 and 1946-1984, when compared to R_z. Therefore, backward extension of aeronomy models developed using the behavior of F10.7 measured since 1947, would require use of F10.7 values 25-40% higher than those estimated from R_z, between 1915-1945. The new index should also provide an improved discriminant of solar signatures in long-term trends of important atmospheric species, such as ozone (e.g. Dütsch et al., 1991).

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