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Historical Dataset Reconstruction and a Prediction Method of Solar 10.7 cm Radio Flux *

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Abstract We reconstruct the developing history of solar 10.7 cm radio flux (F10.7) since 1848, based on the yearly sunspot number and the variations. A relationship between the maximum and the linear regression slope of the first 3 years starting from minimum of the solar cycle is considered. We put forward a method of predicting the maximum of F10.7 by means of the slope-maximum relationship. Running tests for cycles 19 to 23 indicate that the method can properly predict the peak of F10.7.

Key words: Sun: activity — Sun: radio radiation — Sun: sunspots

1 INTRODUCTION

Electromagnetic wave radiates from the Sun over a wide range of radio band from millimeter to several tens of meters, mainly from the solar upper atmosphere (Lin 2000; Parker 2001). Solar 10.7 cm radio flux (F10.7), measuring the radiation at frequency 2800 MHz, is a key parameter when describing the radiation intensity of the quiet sun, and in the study of the solar upper atmosphere (Lin 2000). With an intensity on the order of $10^{-22}\,\mathrm{Wm^{-2}\,Hz^{-1}}$, the F10.7 reflects well the variations in the ionosphere (Wu et al. 2004).

Like the sunspot relative number F10.7 is also a useful index of solar activity. The research and prediction of F10.7 are useful in many fields, such as the safety of spacecraft, safety of space and air travel, meteorological research and service, etc. F10.7 is always an input parameter when calculating the atmosphere density for orbit determination in aerospace and when predicting the influence of the ionosphere on communication.

Much attention has always been paid to the variation of F10.7 (Rajesh 2007). The methods of its prediction are continually being improved along with the improvement in data analysis techniques. Xanthakis & Poulakos (1985) proposed a method of predicting the total radio-flux based on the sunspot number. They presented a detailed statistical analysis of the daily values of F10.7 as well as the corresponding Zürich numbers resulting in the establishment of a certain relation between the two. Miao et al. (2003) obtained smoothed monthly mean sunspot numbers of cycle 23 by the method of similar cycles, and then predicted F10.7 according to the statistical relationship between the sunspot number and F10.7. By using historical data of past solar cycles, they similarly predicted the smoothed monthly mean F10.7 of cycle 23. Some researchers (Zhong et al. 2005) applied the singular spectrum analysis method in combination with the similar cycle method to predict F10.7.

In this paper, we focus on reconstructing the historical dataset of F10.7 since 1848, based on the relationship between the variation of annual solar F10.7 and the sunspot number. Moreover, we try to construct a method of predicting the maximum of F10.7, based on a relationship between the characteristics of the ascending part of the solar cycle and the maximum flux.

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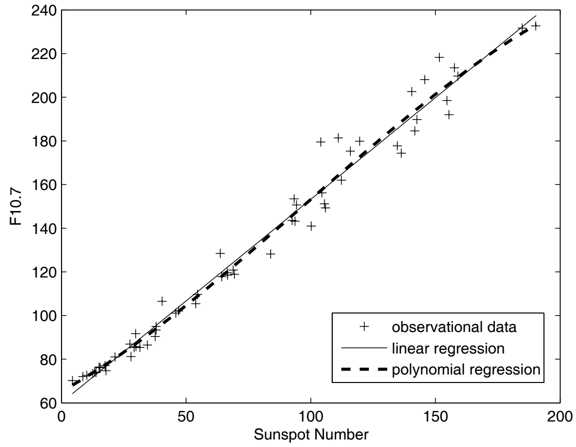

Fig. 1 Relationship between F10.7 and sunspot number.

2 METHOD OF RECONSTRUCTION

F10.7 and relative sunspot numbers in 1-year intervals are obtained from the Solar Data Services of National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (NGDC), for the periods 1947–2005 and 1848–2005, respectively.

There is a good correspondence between F10.7 and sunspot number. The flux-sunspot correlation coefficient (about 0.9893) for the period 1947–2005 is far above the 99% significance level. Figure 1 gives the scatter plot of yearly sunspot number against F10.7, further illustrating the pronounced synchronous fluctuations that they experience. F10.7 is steadily increasing along with the increasing sunspot number and the relationship is approximately linear. Considering the characteristics, we tried two transfer equations, one a simple linear regression and one a polynomial regression. We shall be choosing a proper transfer equation to be used for the reconstruction.

2.1 Linear Regression

Figure 1 shows the result of a linear regression analysis of the observational data. The solid line is the regression line with equation

$$\mathrm{Flux} = 0.932\mathrm{SN} + 60.054\,, \tag{1}$$

where Flux is the reconstructed F10.7 series, SN is the yearly sunspot number since 1947.

The complex correlation coefficient is 0.9892 between the reconstructed and observational series. R^2, the coefficient of determination, equals to 0.9786. F-test value is 2606.6 at a confidence level of P >99.99%. The standard deviation is 7.22.

2.2 Polynomial Regression Analysis

We also applied a polynomial regression for the sunspot number–F10.7 correlation. See the dashed line in Figure 1. Its equation is

$$\mathrm{Flux} = -1.28 \times 10^{-5}\mathrm{SN}^3 + 3.76 \times 10^{-3}\mathrm{SN}^2 + 0.633\mathrm{SN} + 65.209\,, \tag{2}$$

with F= 884.8 at confidence level P >99.99%. The standard deviation is 7.03.

The complex correlation coefficient of the regression equation is 0.9898 and R^2 is 0.9797. Although R^2 is nearly the same as in the linear regression, the polynomial regression provides a better fit especially at the two ends. The standard deviation is also smaller than that of the linear regression.

2.3 Reconstruction

A useful long-term database should not only yield improved understanding of the solar activity itself, but also contribute to the prediction of the maximum and minimum epochs of F10.7. Now, compared with

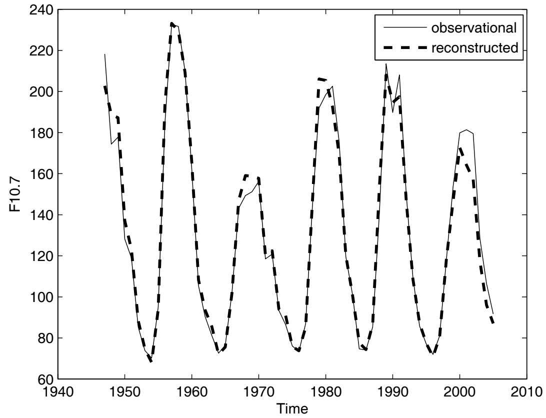

Fig. 2 Observed and reconstructed F10.7.

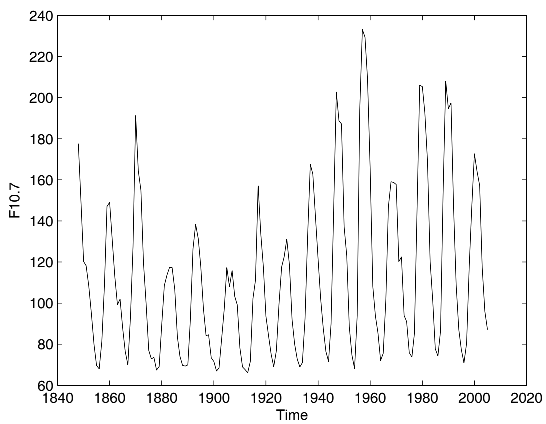

Fig. 3 Reconstructed F10.7 in the period of 1848–2005.

sunspot number, the observational dataset of F10.7 is shorter. Therefore, we expect to be able to reconstruct the F10.7 historical dataset on the basis of the longer series of sunspot relative numbers.

We first apply Equation (2) to reconstruct F10.7 using the yearly sunspot relative number since 1947 (Fig. 2). Note that most of the reconstructed values agree remarkably well with the observational values, and only a few values are significantly different. The largest error is in 2002, when the reconstructed value is smaller than observational value by about 22.3. However, substantial discrepancies do not exist. On the whole, the reconstruction series tallies well with the observational datasets.

The time history of F10.7 from 1848 to 2005 was reconstructed based on Equation (2). As seen in Figure 3, the minima of the solar radio flux were commonly around 70, while the maxima varied from $\sim$110 to $\sim$230.

3 PREDICTION

3.1 The Relationship between the Slope b and Maximum M_f since 1947

For predicting the maximum, we focused on an analysis of the ascending part of every solar cycle of F10.7 since 1947. To obtain more accurate values for the slope, we needed more values. We could not use four values, because, in some solar cycles, such as the 19th, F10.7 reached the maximum in the fourth year. By means of linear regression analysis of F10.7 on m, m+1 and m+2 starting from minimum, we could obtain the slope. Applying the same method to all the solar cycles since 1947, we obtained the slope series,

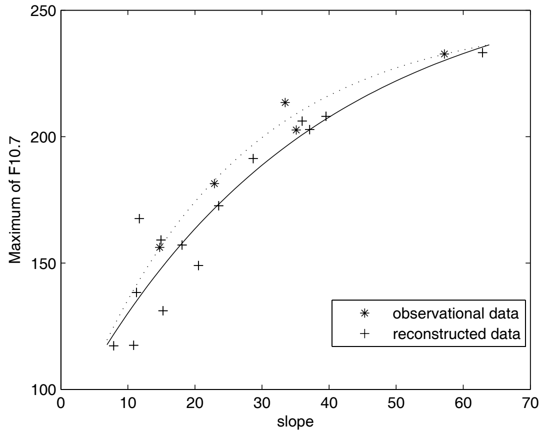

Fig. 4 Correlation between the maximum M_f and the slope b, since 1947 (dotted line) and since 1848 (solid line).

b. We denote the series of maxima since 1947 as M_f. Figure 4 is a Scatter plot between the slopes b and the maxima M_f. Note that the smaller the slope, the smaller the flux, and vice verse, and we have the exponential relationship represented by

$$M_f = -171.72 \times e^{(-b/23.62)} + 247.84\,. \tag{3}$$

3.2 The Slope-Maximum Relationship

As mentioned above, the history of solar radio flux observations is not very long: there are only observational records for about five solar cycles since 1947. Statistically the relationship between the slope and the maximum we presented will be considerably improved, if we could use a larger body of observational data. With this aim in mind, we combined into one set, two data sets of F10.7. (1) The set from 1848 to 1946 reconstructed with the above method. (2) The observed set of 1947–2005. Thus, we obtained a new series of 158 years from 1848 to 2005. We applied the same method as in Section 3.1 to analyze the new F10.7 series and we obtained the following-relationship between the maximum M_f and the slope b:

$$M_f = -187.72 \times e^{(-b/33.26)} + 268.55\,, \tag{4}$$

See Figure 4. The shape of the relationship is the same as before, only the numerical coefficients are a little different. This confirms the results presented on the relationship between the maximum and the slope. With this relationship, we could calculate the maximum of F10.7 as soon as we know the first three yearly numbers.

3.3 Testing the Method by Simulated Prediction

To assess the reliability of the method of prediction, we made a test using the same method described in Sections 3.1 and 3.2. For the series of 1848–1995, obtained after deducting the 23 $^{\text{rd}}$ cycle (1996–2005) from the series 1848–2005, we obtained an exponential relationship. Then, inserting the slope obtained by linear regression of the first three yearly values of the 23rd cycle in the exponential function, we obtained the maximum of the cycle about 173.1±13.5. The real observational value is 181.4, well within the limits of our prediction.

Because only the series from cycle 19 to 23 of F10.7 is observational data, we performed a test on these cycles using the same method. For example, for making a prediction of the maximum of cycle 19, we first delete the cycles 19–23 from the total data series. Figure 5 plots the predicted values (dotted line) and the observed values (solid line). The standard deviation is 16.4. The results indicate that the method is practicable, and the simulative prediction is in a good coincidence with observed data.

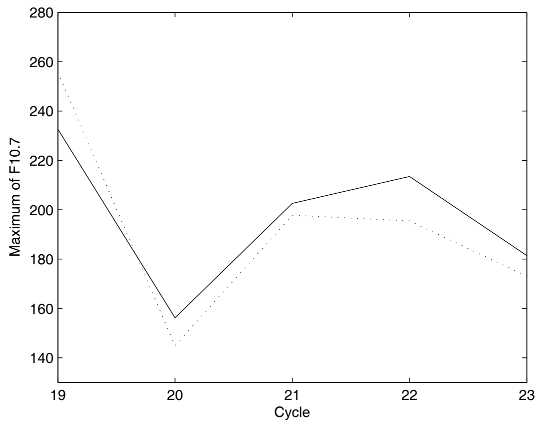

Fig. 5 Predicted values (dotted line) and observed values (solid line) of maximum of F10.7.

4 DISCUSSION AND CONCLUSIONS

There is a close correlation between F10.7 and the sunspot number. On the basis of yearly sunspot number, the developing history of F10.7 since 1848 is reconstructed. According to the relationship between the linear regression slope of the first 3 years and the maxima, we have constructed a method for predicting the maximum. A running test for cycles 19–23 has shown a good simulative prediction result. The analysis shows that the slope could better foresee the maximum of F10.7 in the cycle.

The real historical observational datasets of F10.7 are very limited. If we only use the real datasets, then it is not enough to establish the slope-maximum relationship. Therefore, in this paper we made use of both the real observational data series (1947–2005) and the reconstructed historical datasets (1848–1946). The extending of the data series by synthesizing the two sections enhanced the credibility of the slope-maximum method.

As a matter of fact, our method has certain limitations for some solar activity cycles, where F10.7 approaches maximum in the third year, for then our prediction would be just a short time ahead. However, our method does give a predicted value some time ahead, and the prediction error is relatively small. For major cycles the method can predict the maximum of F10.7 a good while in advance.

The above slope-maximum method for F10.7 prediction will be checked further in the coming 24^{th} solar cycle.

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