LONG-TERM FLUCTUATIONS OF SOLAR ACTIVITY DURING THE LAST THOUSAND YEARS

L. KŘIVSKÝ

Astronomical Institute, Czechoslovak Academy of Sciences, 251 65 Ondřejov, Czechoslovakia

(Received 1 March; in revised form 11 April, 1984)

Abstract. Long-term variations of solar activity during the last thousand years were derived from historical observations (by the naked eye) of large sunspots and from records of auroras at latitudes $< 55°$. The results shown in Figure 1 indicate very good agreement as regards the occurrence of maxima and minima of all three indices (sunspots, auroras, ^{14}C), and even between secondary fluctuations of the ^{14}C-curve, which were usually neglected in the presentation of the smoothed curve.

1. Introduction

Schove (1955) began to inquire into the problem of long-term fluctuations of solar activity of the last 1000–2000 years, using auroral records, and Kanda (1933) used records of large sunspots visible by naked eye for the same purpose. Of the other later and more significant investigations in this field one should mention the papers of Link (1964) and Eddy (1976) who included the work of number of authors on determining the content of ^{14}C in the tree-rings of very old trees in his synthesis; on a reverse ^{14}C scale the latter represents the level of long-term fluctuations of solar activity.

2. Data, Method, and Results

The purpose of the present communication is to demonstrate the long-term fluctuations of solar activity using newly collected data on naked-eye observations of large sunspots (Wittmann, 1978), on the one hand, and verified data on auroral observations at latitudes $< 55°$ compiled from all published catalogues (Křivský and Pejml, 1980), on the other. Both data series were treated using the same statistical method and the results were compared with the most recent detailed ^{14}C-curve derived from the tree-rings of very old trees (Stuiver, 1980).

2.1. Big sunspots

Wittmann (1978) compiled all the known and recorded naked-eye observations of large sunspots from various countries using historical sources. The observations from some countries are more or less random, from others they are nearly systematic, particularly from where attention was devoted to the Sun for religious and astrological reasons.

Sunspots can be observed by naked eye under dimmed glare of the solar disk (through haze or smoke), best after sunrise or before sunset when the area of the sunspot umbra exceeds 900×10^6 km^2 and the total area of the sunspot group 5700×10^6 km^2. The first observation was made in Greece in 466 B.C. and has been ascribed to Anaxagoras, the

Solar Physics **93** (1984) 189–194. 0038–0938/84/0931–0189$00.90.

last observation in Wittmann's catalogue being from 1638. In the second millenium, the recorded and preserved observations are so numerous (they mostly come from China and are the result of rather consistent observational effort and recording capability; the series is practically unaffected by the civilization factor) that they can be used without homogenization to construct the curve which would illustrate secular fluctuations of solar activity.

For the period in question, the years 1000–1640 (i.e. 641 years), the numbers of sunspot observations made in individual years were excerpted from the Wittmann catalogue so that they correspond to the occurrence of the sunspot phenomena in terms of their aggregate existence in solar rotations and not to days of observations. There were 93 such cases during the period involved. To express the long-term variations, 40-years sums of two series were made: one (series *a*) began in the year 1000, the other (series *b*) in 1020. The length of the interval was chosen with a view to the distribution of the data in the course of the years and to the period of known secular variations. The resultant curve was constructed from $\frac{1}{2}(\Sigma 40_a + \Sigma 40_b)$ (in each case from values adjacent in time) and located at the time centre between the single values $\Sigma 40_a$ and $\Sigma 40_b$, so that primitive gliding and smoothing were ensured. This statistical treatment was not even necessary, because both curves without any treatment displayed nearly the same pattern and extremes; the same method was used to treat the auroral observations (see below). This curve is marked 'Sunspots' in Figure 1.

The maxima '*M*' of the second millenium '2' are marked in the order they occurred in the millenium: *M*2–1 is a very conspicuous maximum around the year 1130, the subsidiary *M*2–2 is in the descending phase following *M*2–1 around the year 1210, the next *M*2–3, quite sharp but of short duration, around the year 1370, another smaller one *M*2–4 around the year 1610. The minima '*m*' of the second millenium '2' are also marked in the order they occurred in the millenium: *m*2–1 before 1030, the second subsidiary *m*2–2 (on the downslope) occurred about 1170, the third *m*2–3 is broader and is located between the years 1250–1330, the fourth *m*2–4 is between the years 1430–1510 (referred to as Spörer's) and the fifth *m*2–5 (referred to as Maunder's) after the year 1630.

The interval of extremes *M*2–1, *m*2–2, and *M*2–2 (1070–1230) as a whole could als be considered one large maximum with a subsidiary minimum *m*2–2.

2.2. C14 SOLAR ACTIVITY

The existence of the individual secular maxima and minima is indubitable with a view to the behaviour of the other indices, auroral and ^{14}C, and the quantitative characteristics of these extremes are most probably also real.

The comparison with the ^{14}C-curve (Stuiver, 1980), on which the location of the extremes agrees with those on the 'Sunspot' curve, indicates that the long-term fluctuations of the variable incidence of cosmic radiation at the Earth's atmosphere and the variable production of ^{14}C within the millenium are caused by the condition of solar activity as the primary process; disturbances in the Earth's magnetosphere and high atmosphere (which is represented by the curve of aurora occurrence) are derived which

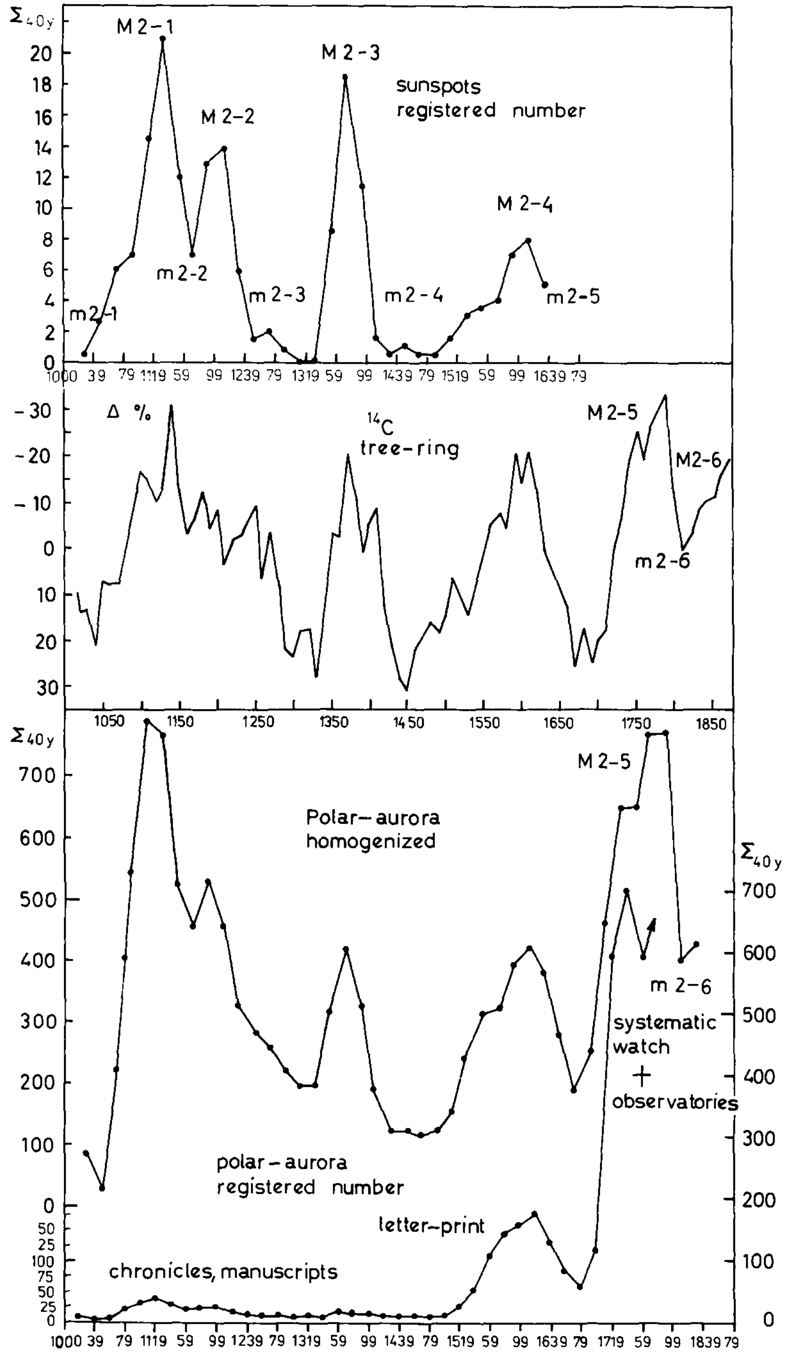

Fig. 1. Long-term fluctuations of three solar activity indexes: 40 years sums of sunspot observations by naked eye (statistically elaborated), maxima (M) and minima (m) with numbering are indicated; ^{14}C deviation in ‰ from tree-rings (Stuiver, 1980); 40 years sums of polar-aurora observations (statistically elaborated and homogenized) and 40 years sums of polar-aurora numbers without homogenization.

logically corresponds to the well-known mechanism of the causal sequence of the individual complex process (high solar activity-disturbance in interplanetary space-disturbances in the Earth's magnetosphere-aurora).

2.3. Polar Aurora

For processing the auroral data a catalogue was compiled (Křivský and Pejml, 1980) which contains the data observed and historically recorded auroras from the year 1000 to 1848 (with which H. Fritz's catalogue ends), mostly from geographic latitudes $< 55°$. This data catalogue (of verified aurora; uncertain cases, especially in Fritz's catalogue, were not considered) was compiled from a number of catalogues and observation sets (Fritz, 1873; Mossman, 1898; Spilger, 1939; Vyssotsky, 1949; Seydl, 1955; Matsushita, 1956; Link, 1961; Réthly and Berkes, 1963; Link, 1963, 1965; Křivský and Pejml, 1980).

During the whole period (1000–1848) 3110 days with auroras were confirmed, however, due to the civilization factors only 167 were observed from the year 1000 to 1499 (to the beginning of effect of letter-print). As a result of civilization factors the series is considerably inhomogeneous, although all the maxima and minima (see Figure 1, the bottommost curve), similar to those on the sunspot and ^{14}C-curves (Figure 1), can be seen on the curve of aurora days for the forty-year intervals which were not homogenized. We shal inquire into the civilization factors affecting the amount of observations and attempt to homogenize the series by defining them. The increase in the number of preserved reports of the occurrence of auroras is influenced by a number of factors, some of which act gradually, others very rapidly. There is the factor of the increasing number of chroniclers and popular scripturalists, and their contact with observers; the factor of increasing probability that chronicles and records will be preserved with time (both apply to the period 1000–1500); the letter-print factor acted rapidly (more frequent record of reports on events, together with more probability of conserving them until the present); enhanced interest in natural phenomena in connection with the Renaissance, with travelling and discovery developed more slowly; founding of stations and observatories, and their records, the use of calendars, newspapers and the higher informativeness associated with them, as well as the possibility of transmitting news from a larger area into the conservation centre (for recording in a chronicle or printing) all had a quick and substantial effect. Events of war in the main cultural centres of human society had a negative and temporary effect. The positive factors listed above are responsible for gradual, as well as rapid, irregular increases in the number of reports on conspicuous events such as the aurora.

In the attempt to homogenize the series of data, it was assumed that nearly all aurora were recorded roughly after 1700. The printing factor of the letter-print came to bear after the year 1500. The factors will be at roughly the same level during the period from the year 1000 to 1500 (see the bottom unreduced curve in Figure 1). Drawing on the factors mentioned above, the number of observations were adjusted by period as follows (a detailed justification is given in study of Křivský and Pejml, 1980): the forty-year sums of series '*a*' (beginning in the year 1000) for the period 1000–1519 were multiplied by the factor 23, for the period 1520–1559 by the factor 6.3, for the period 1560–1719 by the factor 2.4, no adjustment after 1720; the forty-year sums of series '*b*' (beginning with the year 1020) for the period 1020–1499 multiplied by the factor 24, for the period 1500–1539 by the factor 6.3, for the period 1540–1699 by the factor 2.7, no adjustment after 1700.

Forty year sums of two series were made as in the case of sunspots: one series began with the year 1000 (*a*), the other with the year 1020 (*b*). The resultant curve (Figure 1) was constructed from $\frac{1}{2}(\Sigma 40_a + \Sigma 40_b)$ (in each case from values adjacent in time) and the value obtained was located at the time centre between the single values $\Sigma 40_a$ and $\Sigma 40_b$, so that single gliding and smoothing were ensured. This statistical adjustment was not even necessary, because both curves, without any adjustment, displayed very similar shape. The resultant curve is marked 'polar aurora, homogenized' in Figure 1.

3. Discussion and Conclusion

One can see that all the maxima and minima on the sunspot curve are also on the auroral curve and that their positioning in time is identical; since data for a longer period were available, the maximum $M2$–5 (1730–1800) and the minimum $m2$–6 (after 1800) could be added.

The records of occurrence of auroras, adjusted for purposes of identifying long-term fluctuations, are evidently an index which expresses secular solar activity; this partial conclusion is substantiated by the aggregate occurrence of all main and subsidiary extremes also on the two other curves, which is in logically causal agreement with known individual complex phenomena and processes (high solar activity-disturbance in interplanetary space-disturbance in the Earth's magnetosphere-aurora).

The asset of this study is the more detailed behaviour of solar activity derived for the recent millenium from historical observations of large sunspots (by naked eye) and from records of observations of auroras at altitudes $<55°$. The results shown in Figure 1 show very good agreement between the occurrence of the maxima and minima of all three indices (sunspots, auroras, ^{14}C), including the subsidiary fluctuations on the ^{14}C-curve which earlier were usually ignored in presenting the excessively smoothed curve.

Since the auroral curve has displayed the same behaviour and the same occurrence of maxima and minima as the sunspot curve (which characterizes high solar activity and the mighty eleven-year cycles), one can claim that the long-term fluctuations in the occurrence of aurora, connected with magnetoplasmic disturbances of the Earth's magnetosphere, are of solar origin and not of autonomously magnetospheric origin. Since the behaviour of ^{14}C (reversed scale) is similar, it is clear that the modulated level of cosmic radiation, which is responsible for the variations of ^{14}C in tree-rings, simultaneously characterizes analogous disturbed conditions in interplanetary space, which have their primary cause in the Sun (Lin *et al.*, 1975).

These results, founded on the statistical treatment of long series of data, agree with individual processes and mechanisms, known earlier: large sunspot groups on the Sun with flares → magnetoplasmic clouds from the Sun into interplanetary space → these decrease the level of cosmic radiation penetrating to the Earth with in turn decreases the production of ^{14}C in the Earth's atmosphere – the clouds from the Sun simultaneously disturb the Earth's magnetosphere and thus create conditions for the generation of auroras (Fischer and Křivský, 1965).

References

Eddy, J. A.: 1976, *Science* **192**, 1189.

Fischer, S. and Křivský, L.: 1965, *Bull. Astron. Inst. Czech.* **16**, 316.

Fritz, H.: 1873, *Verzeichniss beobachteter Polarlichter*, Gerol's Sohn, Wien.

Kanda, S.: 1933, *Proc. Imp. Acad. Tokyo* **9**(7), 293.

Křivský, L. and Pejml, K.: 1980, 'Solar Activity, Aurorae and Climate in Middle Europe in the Last 1000 Years', preprint.

Lin, Y. C., Fan, C. Y., Damon, P. E., and Wallick, E. J.: 1975, *14th Int. Cosmic Ray Conf.* **3**, 995.

Link, F.: 1961, *Českosl. čas. hist. (Praha)* **9**, 559.

Link, F.: 1963, *Trav. de l'Inst. Géophys. de l'Acad. Tchécoslov. des Sci.*, No. 173 (1962), 297.

Link, F.: 1964, *Planet. Space Sci.* **12**, 333.

Link, F.: 1965, *Trav. de l'Inst. Géophys. de l'Acad. Tchécoslov. des Sci.*, No. 212 (1964), 501.

Matsushita, S.: 1956, *J. Geophys. Res.* **61**, 297.

Mossman, R. C.: 1898, *J. Scottish Meteorolog. Soc. Ser. III*, Vol. XI (13–16), 58.

Réthly, A. and Berkes, Z.: 1963, *Nordlichtbeobachtungen in Ungarn (1523–1960)*, Ung. Akad. d. Wissensch., Budapest.

Schove, D. J.: 1955, *J. Geophys. Res.* **60**, 127.

Seydl, O.: 1955, *Trav. de l'Inst. Geophys. de l'Acad. Tchécoslov. des Sci.*, No. 17 (1954), 159.

Spilger, L.: 1939, *Z. angew. Meteorologie* **56**, 371.

Stuiver, M.: 1980, *Nature* **286**, 868.

Vyssotsky, A. N.: 1949, *Medd. Lunds Astr. Obs.* **II-126**, 40.

Wittmann, A.: 1978, *Astron. Astrophys.* **66**, 93.