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Estimation of past solar and upper atmosphere conditions from historical and modern auroral observations

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Abstract. On the basis of the analysis of the data of auroral observations at middle latitudes during low solar activity, and modern spectrophotometric research, the feasibility of their joint use for the estimation of the level of the solar activity during periods without instrumental measurements is discussed. In this paper an attempt is undertaken to determine quantitative information on solar activity by comparing the data of visual auroral observations with the modern parameter of their luminescence.

Key words. History of geophysics (solar-planatary relationship) – Magnetospheric physics (auroral phenomena; solar wind-magnetosphere interactions)

1 Introduction

Long-term visual observations of the occurrence of auroras have revealed that their number changes considerably with time (Loysha et al., 1989; Schröder, 1984, 2001a). After the decrease in the number of observed auroras in the period of the Maunder Minimum, 1645–1710, the bright auroras of 17 March 1716 observed in middle Europe (figures of this unusual phenomenon are published in Schröder (1984, 2001b), Brekke and Egeland (1983), refocused attention on the problem of auroras (Schröder, 2001b). Although the observations of sunspots, displaying a level of solar activity, started in 1611, and gave us some idea of solar activity, systematic observations do not start until 1745. It soon became obvious that the frequency of occurrence of auroras simply displays variations in solar activity (Schröder, 1964). However, they were mainly used for definition of the times of minima and maxima of solar activity without the construction of quantitative algorithms to estimate the level of activity. In this paper an attempt is undertaken to determine quantitative information on solar activity by comparing the data of visual auroral observations with the modern parameter of their luminescence.

2 Data of the auroral observations

The data used in this study were the Wolf numbers W (a series of mean annual observations of the solar activity), and visual data of auroras during the interval 1750–1830. During that time span more or less regular aurora observations have been made in Europe (e.g. in Germany, Hungary, Austria) by several observers. On the other hand, it may be possible that in limited times auroras have not been noted due to the impact of cloud cover or state the loss of records (e.g. caused by wars).

In this time span the long minimum of solar activity (Dalton/Hallström-Minima 1790–1830) occurred during cycles 5, 6 and 7, when the mean annual Wolf numbers W at the respective maxima were 49, 49 and 72 (Waldmeier, 1955). The appropriate variations in solar-aurora relations are compared with the numbers of cases N of annually registered auroras. Thus, the depth of minima was slightly less in the Spörer (1420–1540) and Maunder (1645–1710) periods (Schröder, 1984).

Table 1 lists the number of available data. The visual observations were made mainly at middle latitudes in central Europe (geographical latitudes ∼48°–58° N, geomagnetic ∼48°–58° N). Single observations have been neglected. Table 1 includes only data which have been observed from at least two stations independently. In these time spans (18th/19th centuries) the auroral reports are mostly missing, not only in Europe, but also in America; only a few reports are available of spans of reduced auroral activity available (see also Link (1962, 1977)). There are few reports during periods of lower auroral intensity (Dalton, 1873; Fritz, 1881; Lampadius, 1806; Cramer, 1785; Busse, 1815; Parrey, 1819). For example, in 1804, in Abo and Manchester, Hallström and Dalton found only a very small number of reports about auroras. During their travels to northern high latitudes Haussmann and von Buch also noted very few auroras at this time (Ideler, 1832). On the other hand, it is of interest that the number of observed auroras increased before 1793 and after 1819. In later years, for example, for the period 1830–1836, very extensive and bright auroras were noted by Argelander in Finland.

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Table 1. The mean annual visual observations of the auroras N at the middle latitudes of Europe and mean annual levels of the solar activity W during 1780–1829.

Years	N	W
1780	16	85
1781	33	68
1782	34	38
1783	33	23
1784	10	10
1785	15	24
1786	83	83
1787	76	132
1788	56	131
1789	56	118
1790	39	90
1791	14	67
1792	10	60
1793	1	47
1794	4	41
1795	0	21
1796	0	16
1797	0	6
1798	0	4
1799	1	7
1800	0	14
1801	0	34
1802	1	45
1803	3	43
1804	1	48
1805	2	42
1806	1	28
1807	0	10
1808	0	8
1809	0	3
1810	0	0
1811	0	1
1812	0	5
1813	0	12
1814	3	14
1815	0	35
1816	1	46
1817	7	30
1818	5	30
1819	0	24
1820	20	16
1821	24	7
1822	6	4
1823	0	2
1824	3	9
1825	6	17
1826	6	36
1827	18	50
1828	1	64
1829	8	67

Here it is necessary to emphasize that although the 18th and 19th centuries marked a period of increasing interest in solar-terrestrial physics, the study of auroras and the Sun were not mainstream areas for research by the astronomers of those times. For the span from 1793–1818 only a few positive sightings of auroras are available from European latitudes. Scientific studies would certainly have been disrupted by the wars and conflicts of the time, although spectacular auroral displays would always have aroused interest.

We note in this period some widespread auroras on 29 January, 2 March, 28 July and 25 November 1780, 30 January, 15 February, September 25 and 15 October 1781, 29 March and 24 April 1783, 15 November 1784, 19 and 22 March 1786, 13 May, 13 July, 31 October and 26 November 1787, 11 February, 23 August and 21 October 1788, 22 April 1804, 8 February 1817 and 25 September 1827.

Table 1 also gives the mean annual Wolf numbers W according to Waldmeier (1955).

On the basis of the data presented in the Table 1, the following approximate relationships between the mean annual numbers of visually observed auroras N and Wolf numbers W were obtained

$$N = (21 \pm 1) \cdot \frac{W}{100} \cdot \left(1 + \frac{W}{100}\right)$$

and

$$W = (23 \pm 1)\sqrt{n} - 50.$$

These allow for the estimation of levels of solar activity for those periods of time when there are data on visual auroral observations at middle latitudes.

3 Characteristics of auroras

Active spectrophotometric researches of auroras at middle latitudes which were carried out in the period of the International Geophysical Years (1957–1959), have revealed the more important factors controlling their occurrence. The accepted system of estimation of brightness of auroras in International Brightness Coefficients IBC (Chamberlain, 1961) means that the auroras noticed at middle latitudes are usually visible in the middle of the night at zenith angles 60–70° and have a brightness of I or II IBC. Thus, they are evident only under conditions of good visibility and have basically diffuse and weak ray structures of green and violet colour. Only the auroras of III and IV IBC exhibit distinctly the well-known auroral phenomenon. This conclusion follows from figures presented in Schröder (1984), Brekke and Egeland (1983).

Typically low-latitude auroras have very often a red colour and are caused by the 630 nm emission of atomic oxygen. Their occurrence is closely connected to a high level of the solar activity (Schröder, 1964; Truttse, 1968a, b, 1969). The empirical relationship obtained by Truttse is:

$$\log I_{630} = (F_{10.7} - 157)/50 - (\phi - 34)D_{st}/1460\,,$$

where the intensity I_{630} is expressed in Rayleighs, $F_{10.7}$ is the solar radioflux, D_{st} is the index of geomagnetic disturbance, ϕ is geomagnetic latitude. Since the thermospheric temperature where there is 630 nm emission is directly proportional to the index $F_{10.7}$ (for example, CIRA, 1972), the importance of this relationship is that the brightness of red auroras grows exponentially (decimal) with the level of the solar activity.

According to the Jacchia formula (Jacchia, 1979),

$$D_{st} = -6.5\,\mathrm{Sh}(0.535\,K_p).$$

Spectral auroral measurements at the mid-latitude station Zvenigorod (geographical coordinates 55.7° N, 36.8° E) for the period 1957–1966 (i.e. solar cycle 19) have shown that within high solar activity, auroras were observed visually 42 times, whereas the spectral data on amplification of the emissions registered them 663 times. Within a sunspot minimum auroras were seldom observed visually, though the index K_p once reached 9. At the same time spectrographically registered amplifications of emissions were obtained on 56 occasions (Shefov and Yurchenko, 1970). During moderate geomagnetic storms (K_p<5–6, intensities of the red 630 nm emission near the horizon basically did not exceed 10 kilo Rayleighs, and in the zenith were no more than 5 kilo Rayleighs (Shuiskaya, 1970). At this time the intensity of the 557.7 nm emission for the appropriate conditions were 3–5 and 0.5–0.8 kilo Rayleighs, respectively. It will be completely coordinated to estimations, which can be obtained through the given formulas.

As the theresholds of visual sensitivity of green and red radiations of the auroras were, respectively, about 1 and 10 kilo Rayleighs, it means that under conditions of unforeseen visual observations at middle latitudes, the registered auroras should be III or IV IBC, with their share in total actually occurring amplifications of an atmospheric luminescence being ~7–10%. Only at special purposeful observations are the visual registration of auroras of I and II IBC possible.

As the longest series of measurements of the solar activity are the Wolf numbers W, for an estimation of the mean annual indices $F_{10.7}$, it is possible to use the above mentioned formulas (Vitinsky et al.,1986) for mean annual $F_{10.7}$<154 and W<100

$$F_{10.7} = 71.74 + 29.70(W/100) + 51.46(W/100)^2\,.$$

Thus, for the middle latitudes, and the level of solar activity in the considered period of visual observations, the estimations of brightness of expected auroras in the atomic oxygen 630 nm emission are:

$\log I_{630} = 2.34$ for $\Phi \sim 48°$ N;
$\log I_{630} = 3.24$ for $\Phi \sim 58°$ N;
or $I_{630} < 220$ Rayleighs in the zenith for $\Phi \sim 48°$ N;
$I_{630} < 2200$ Rayleighs in the zenith for $\Phi \sim 58°$ N.

Therefore, red auroras may only appear very seldom for $W<40-50$. (The intensity of red oxygen emission 630 nm exponentially (decimal) depends on the index of solar activity. Therefore, for W smaller than 40–50 it is smaller than some hundreds of Rayleighs and these intensities are lower than eye sensitivity.) The intensity of auroras in the emissions 1NGN_2^+ 391.4 nm and 427.8 nm and atomic oxygen 557.7 nm are approximately the same. For $D_{st} \sim 100-150$ the intensities of 557.7 nm emission are less than 1000 Rayleighs (Truttse, 1968a, b). It is also lower than the threshold of sensitivity of the eye. Hence, according to the above-mentioned threshold sensitivity of visual observations, such auroras are inaccessible to registration.

Special interest is focussed on cases of observations of intensive low-latitude auroras, such as that during the solar maximum of 1870 (W~139, estimated $F_{10.7}$~176). From available figures their brightness in two red arches, apparently reached 1 mega Rayleighs, which is comparable to the auroras during solar cycle 19. On the basis of the work of Truttse (1968a, 1968b, 1969) the exospheric temperature at this time apparently could have reached ~1400 K. Estimations of the level of solar activity in the past based on the frequency of observed auroras were undertaken earlier by Schröder (1964, 2001). However, in this work information was given only for years of minima and maxima of the solar activity.

4 Conclusion

The use of data of the visual observations of low-latitude auroras in the era before instrumental observations, and the allocation among them of information on colour structure of a luminescence (some examples are given in Eather, 1980; Brekke and Egeland, 1983), together with statistical data of the spectrophotometric measurements saved in the IGY period, allows estimations to be made of the level of solar activity on the basis of the number of observed auroras. Furthermore, through estimations of brightness of a luminescence it is possible to determine levels of helio-geophysical disturbances. Unfortunately, the deficiency of modern atlases showing auroral structures (e.g. International Auroral Atlas (1963), Kaneda et al. (1968)) for these purposes is the absence in them of information on dates and helio-geomagnetic conditions of the observed forms of auroras. This deprives us of the opportunity of comparing the real forms of auroras with visual stretches of earlier observed phenomena.

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