Regular observations of the geomagnetic field at the Ógyalla observatory (present-day Hurbanovo) near the turn of the 20th century, including magnetic storms accompanied by auroras in March 1894, September 1898, and October 1903

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Abstract: From 1893 to 1905, the values of the geomagnetic field recorded three times a day are available from the Ógyalla magnetic observatory. We introduce these unique records, and at the same time, we provide an analysis of three noteworthy magnetic storms from this period, namely the events on 30 March 1894, 9 September 1898, and 31 October 1903. In addition to violent magnetic variations, remarkable auroras were observed in Central Europe during these events. The analysed events indicate that the source of the most intense, potentially dangerous geomagnetic disturbances can be the electric currents of the auroral oval or the field-aligned currents connected to the auroral oval.

Key words: geomagnetic data, magnetic observatory, magnetic storm, auroral oval

1. Introduction

As high technologies proliferate on Earth and in near-Earth space, the advanced society needs deeper knowledge of space weather. Geomagnetic activity is an aspect of space weather that affects many technological systems, as it is well-known. Examples of such jeopardized systems are represented

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by electric power distribution networks and telephone and telegraph lines (*Boteler et al., 1998; Ribeiro et al., 2016; Love et al., 2019; Hapgood, 2019; Boteler, 2019; Rajput et al., 2021; Buzulukova and Tsurutani, 2022)*. From this point of view, we are most interested in the most extreme phenomena. However, there are few samples of such extreme events in the modern digital age; therefore, we need to study instructive events from a little more distant history, too. Luckily for the researchers, there are also some records of the geomagnetic field from before the digital and space age.

The study of the geomagnetic activity requires systematic observations of the geomagnetic field at magnetic observatories. The first such observatory was founded by Carl Friedrich Gauss and Wilhelm Weber in Göttingen in 1833, the impetus for that having been provided by Alexander von Humboldt (*Schröder and Wiederkehr, 2002; Linthe, 2007*). Several dozen other magnetic observatories were built in the 19th century. Nonetheless, many have been shut down over time or moved to different locations, most often due to increasing artificial magnetic disturbances caused by the growth of settlements and industrialization. For the sake of completeness, we note that observations of the direction of the geomagnetic field began earlier. In London and Paris, the magnetic declination started to be recorded in the 16th century (*Malin and Bullard, 1981; Alexandrescu et al., 1996*). The inclination has been observed in London since the 16th century (*Malin and Bullard, 1981*) and in Paris since the 17th century (*Alexandrescu et al., 1996*).

At the end of the 19th century, the Ógyalla Central Observatory for Meteorology and Geomagnetism started its activity, too. Another frequently used spelling of the observatory name was Ó-Gyalla, the later name was Stará Ďala, and the present-day name is Hurbanovo. Its coordinates are 47.88° N and 18.19° E (geographic latitude and longitude, respectively). The founder of the observatory was Nicolas de Konkoly. This distinguished scientist used several variants of his name, depending on the language in which the document was written: He wrote his name as Konkoly Thege Miklós in Hungarian. In German, he used Nicolaus Thege von Konkoly and, in later years, Nikolaus Thege von Konkoly. In English-written official correspondence, he preferred the variant Nicolas de Konkoly. Konkoly was then the director of the Royal Hungarian Central Institute for Meteorology and Geomagnetism in Budapest (the term Royal Hungarian assigned governmental bodies of the Kingdom of Hungary, which was a part of the Austro-Hungarian Empire, being a dual monarchy). When planning the location for the new observatory, he carefully chose a place that he assumed would be spared for a long time from artificial disturbances such as that threatened the operation of some other observatories (*Marczell, 1900*). Ógyalla – Stará Ďala – Hurbanovo is the oldest still operating magnetic observatory in Central and Eastern Europe (*Hejda, 2007*).

Thanks to its location, the Ógyalla observatory filled the gap in geomagnetic observations in Central Europe. According to *Marczell (1900)*, Ógyalla took over the role of the geomagnetic observatory in Vienna because the industrialization and growth of the city of Vienna no longer allowed to meet the requirements for the accuracy of measurements necessary to obtain new knowledge about the complicated geomagnetic phenomena. That is also one of the main ideas of this paper: we will present geomagnetic observations in the part of Europe that was little covered by observatories near the turn of the 20th century. At the same time, our ambition is to contribute to the interpretation of a few geomagnetic disturbances from this period; it will be an interpretation of old observations from the point of view of current knowledge.

Our paper has the following structure: Section 2 is devoted to the data on the horizontal intensity, declination and inclination observed at Ógyalla. The period between June 1893 and December 1905 is covered. We describe the observatory equipment and present the data preserved in printed yearbooks. Section 3 focuses on three magnetic storms (in 1894, 1898, and 1903), during which the geomagnetic field disturbances and auroras were observed. In Section 4, we conclude that the most dangerous geomagnetic disturbances at middle latitudes may be related to the electric currents of the auroral oval or the field-aligned currents connected to it. This idea is not new (e.g. *Vennerstrom et al., 2016; Cid et al., 2015*), but its general acceptance needs to be supported by an adequately large set of intense or even better extreme events of extreme events that confirm it. Old observations of intense magnetic disturbances, which we present in this work, can also serve this purpose, and this is one of the intended contributions of our article. At the same time, by studying the three disturbances, we try to show that the data made available from the beginnings of the Ógyalla observatory can still be valuable even today.

2. Geomagnetic field records from 1893 to 1905

In the following text, we will briefly describe the equipment of the Ógyalla magnetic observatory near the turn of the 20th century in the context of the history of this scientific workplace. Subsequently, we will introduce the data files with three elements of the geomagnetic field, which we publish in the supplement of this article. We will also add a unique analogue record of the magnetic storm that occurred on 30 November 1903.

2.1. The observatory near the turn of the 20th century

As mentioned in Section 1, when establishing the Ógyalla magnetic observatory, it was expected that the locality would protect observations from artificial disturbances. At the same time, Konkoly's decision about the magnetic observatory location was influenced by two other important factors: (1) his private observatory already existed in Ógyalla at that time (*Šišulák and Pastorek, 2022*), so there was already a kind of infrastructure for scientific observations, and (2) Ógyalla was in the previous two decades a place where some geomagnetic measurements were carried out (*Konkoly, 1898, pp. 44–51; Marczell, 1900*). These measurements were performed by Konkoly in the early 1870s at the request of Guido Schezl, who was the first director of the Royal Hungarian Central Institute for Meteorology and Geomagnetism in Budapest (*Csontos et al., 2007*). Observations were carried out with a Lamont variation device in a wooden hut in Konkoly's park, and absolute measurements were made in a nearby field tent. Thanks to these first measurements, the geomagnetic conditions at Ógyalla were well-known before building the magnetic observatory.

When the measurements initiated by Schenzl had accomplished their purpose, they were ended. However, as soon as Konkoly took over the position of director of the Institute in Budapest on 21 September 1890, he moved the Lamont variation stations from Budapest to Ógyalla and began new systematic geomagnetic observations at Ógyalla (*CIM&EM, 1893; Konkoly, 1898, pp. 44–51; Marczell, 1900*). At first, they were carried out in the old way under the methodical guidance of Ignácz Kurländer, Konkoly's predecessor in the director's office, who was already retired.

In 1895, Konkoly ordered the construction of a small absolute pavilion with an octagonal plan (*Konkoly, 1898, pp. 44–51*). The reader can find a photo of this small building in (*Prigancová and Vörös, 2001, p. 13, Fig. 2 therein*). The observatory was equipped with two theodolites for absolute geomagnetic measurements. The first of them was the field instrument Small Lamont; it was repaired and modified in 1894 by the Viennese mechanic Hermann Schorss according to the plans of Liznar and Konkoly. The second theodolite was of the Meyerstein type, and also this device was improved by Schorss. We did not find in the literature when exactly the Meyerstein theodolite was modified, but we know (*OGY, 1898*) that, from 1897, the absolute measurements were made twice a month with the Lamont as well as Mayerstein theodolites. So, at that time, both the instruments were already adjusted. The absolute measurements of inclination were performed with the Dover inclinatorium (*Konkoly, 1898, pp. 44–51*). An interesting piece of information about the professional staff of the observatory was provided by *Marczell (1900)*. He wrote that, since 1895, Lajos Steiner took over the geomagnetic observations in Ógyalla.

Marczell (1900) described the first years of observing with the Lamont variation instruments at the Ógyalla observatory. These instruments were transferred there from Budapest, from the ending Buda observatory, and they did not use any temperature compensation. Marczell was sent on a study trip abroad to gain experience and choose a suitable instrument for Ógyalla. In 1894, the observatory acquired new variation instruments of the Mascart type manufactured by the Carpentier company. However, they were installed only in November 1899 in the newly built variation pavilion, and the final adjustment of the instruments was done by Christmas 1899. The photo of the variation pavilion, built after Steiner and Marczell's plans and completed in 1899, still serves its original purpose. The reader can find the photograph of this building in (*Ochabová and Ochaba, 1977, p. 31, Fig. 2 therein*).

The Ógyalla observatory acquired two complete sets of the Mascart system in total – one for direct telescope observation, the other for photographic recording. Each set contained devices for measuring horizontal intensity, declination and vertical intensity. *Steiner (1900)* described their functioning as follows: The declination was observed with a declinometer with a magnetic needle suspended on a single fibre. To monitor the changes in the horizontal intensity, they used a bifilar magnetometer, the essence of which was a magnetic needle suspended on two fibres (for an explanation of the principle of the bifilar device, see e.g. *Hejda et al., 2023*). Variations in vertical intensity were observed using Lloyd's scales. From the first set of the devices, the values of geomagnetic elements were read using a scale and a telescope at specified instants three times a day: 7 a.m., 2 p.m., and 9 p.m. of Ógyalla Mean Time. In the second set, the telescope scale was replaced by a light source and a sensitive photographic plate. The source of light was a petrol lamp that emitted rays through thin slits. The rays reflected from the mirrors of the declinometer, bifilar magnetometer, and Lloyd's balances illuminated a photographic plate, which uniformly moved by a clockwork mechanism.

The above-described development of the geomagnetic observations in Ógyalla preceded the official opening of the state meteorological and geomagnetic observatory in Ógyalla on 30 September 1900, which was the day when the observatory was handed over to the state administration (*Ochabová and Ochaba, 1977; Prigancová and Vörös, 2001*).

About the following period, we will already mention only two pieces of equipment. In 1903, the observatory obtained the Wild theodolite, and the absolute measurements of declination and horizontal intensity with this new instrument started in 1905 (*OGY, 1907*). To measure the inclination, A. de Büky constructed a new instrument in which he combined the induction coil of Wild's device and the old Meyerstein theodolite (*OGY, 1907; Ochabová and Ochaba, 1977*).

The later development of the Ógyalla – Stará Ďala – Hurbanovo observatory is well described in (*Ochabová and Ochaba, 1977; Prigancová and Vörös, 2001*). Nowadays, approximately 150 years since the first systematic observations in Ógyalla, the observatory under the name Hurbanovo is part of the Earth Science Institute of the Slovak Academy of Sciences and international network INTERMAGNET.

2.2. Geomagnetic data for the years 1893–1905

From the yearbooks published in printed form by the Royal Hungarian Central Institute for Meteorology and Geomagnetism in Budapest, we have digitized the existing records of regular geomagnetic field observations (see Supplement), namely horizontal intensity and declination from June 1893 to December 1905 and inclination from January 1903 to September 1904 and from July 1905 to December 1905. These were instantaneous values observed three times a day at 7 a.m., 2 p.m., and 9 p.m. of Ógyalla Mean Time (i.e. local mean time). This time is ahead of the Universal Time (UT) by 1 h 12 min 45.6 s.

The Supplement only presents data up to the end of 1905. Since 1906, the publication of data in the yearbooks was changed in such a way that it was in line with the publications of the Potsdam observatory; hourly means began to be published (*Ochabová and Ochaba, 1977*). These are available in digital form in global data centres, e.g. *WDC for Geomagnetism Kyoto (2024)*.

3. Three geomagnetic events accompanied by auroras

Geomagnetic field records from the first years of operation of the Ógyalla observatory provide information on several interesting geomagnetic variations. Although these records have limitations – observations only three times a day, a magnetogram with gaps – they are still valuable information because, near the turn of the 20th century, the network of geomagnetic observatories was sparse in some locations on the globe, such as the Central and Eastern Europe. Using these data, we will try to contribute to the knowledge of the mechanisms of extreme magnetic disturbances. We will present a hypothesis based on the current theory of intense geomagnetic disturbances (Section 3.1). Subsequently, we will analyse three geomagnetic disturbances during which auroras were observed (Sections 3.2, 3.3, and 3.4). We will draw attention to the mutual features of these events and use them to support our hypothesis (Section 4). In doing so, we will also utilize geomagnetic and aurora observations from other parts of the globe besides the local ones.

3.1. Extreme mid-latitude variations: background information

Our hypothesis, for which we try to find support in observations, is that the most dangerous geomagnetic disturbances in the mid-latitudes may be related to the electric currents of the auroral oval or the field-aligned currents connected to it. As we have mentioned in Section 1, this idea is not new. Nevertheless, to strengthen its general acceptance, it would be helpful to find enough events observed in the past. Neither is it a surprising hypothesis since it is known (e.g. *Hayakawa et al., 2018a*) that, during magnetic storms, the auroral oval moves towards the equator, and auroras (usually red colour-dominated) appear in mid- and low latitudes. And therefore, the auroral-oval and field-aligned currents can even be present at middle or low latitudes.

We have used the term magnetic storm a little cagily up to now because the most dangerous geomagnetic disturbances are not necessarily magnetic storms defined via the intensification of the ring current. The development of the storm-time ring current is usually quantified by the Dst index (*Sugiura, 1964*) or its improved variants, e.g. the Dcx index (*Asikainen et al., 2010*). Traditionally, however, the term magnetic storm has meant intense geomagnetic disturbances without examining the relationship of these disturbances to the intensity of the ring current; the term magnetic storm itself was introduced by Alexander von Humboldt (*Korte and Mandea, 2019*) a long time before anything was known about the ring current. After this explanation, in the following text, we use the term magnetic storm in the latter, more traditional sense.

Vennerstrom et al. (2016) showed that, when considering all space weather effects of storms, the aa or Kp indices classify the extreme storms more adequately than the Dst or Dcx indices. For example, intensified auroral electric currents pose a more serious threat to electrical distribution and telecommunications networks than the enhanced ring current. We note that, unlike the Dst and Dcx indices, the Kp and aa indices express the level of global geomagnetic activity. The Kp index is a widely used three-hourly index, and it is calculated from local K indices (*Bartels et al., 1939; Mayaud, 1967*) determined at selected 13 magnetic observatories. Likewise, the aa index (*Mayaud, 1972*) is a three-hourly index, but it is calculated from a pair of near-antipodal magnetic observatories (one observatory in Europe, in Great Britain; the second observatory of the pair in Australia). Though we mention the Dst and Dcx indices as characteristics of the ring current and Kp and aa indices as a description of the overall geomagnetic activity in the middle latitudes, including the activity of the auroral oval, if it happened to occur in the mid-latitudes, note that only the values of the aa index have been determined (*Mayaud, 1972*) for the period we are interested in.

Despite the argument about the importance of electric currents associated with the auroral oval, the role of the ring current is not negligible. The values of the Dst index are related to how much the auroral oval moves to lower latitudes (e.g. *Yokoyama et al., 1998*). It means that the Dst index, to some extent, contains information about how close to the equator the electric currents of the auroral oval manifest themselves. The ring current and the phenomena in the auroral oval are thus related to each other in a certain way. For example, during substorms, particles from the plasma sheet are injected into the inner magnetosphere, which causes a growth of the ring current.

It is also interesting how quickly the auroral oval moves equatorward as geomagnetic activity increases and how quickly it shrinks back when the increased activity subsides. *Yokoyama et al. (1998)* found that during magnetic storms, the equatorward boundary of the auroral belt in the midnight sector reaches its lowest latitude approximately one hour before the Dst index reaches its minimum. It is similar to the time lag found between the peaks of the AE and Dst indices (e.g. *Davis and Parthasarathy, 1967; Loewe and Prölss, 1997*), the AE index mentioned here being a measure of global electrojet activity (*Davis and Sugiura, 1966*). Based on this, *Yokoyama et al. (1998)* concluded that the auroral boundary expands equatorward in association with an increase in auroral electrojet activity (i.e., not directly causally related to the intensification of the ring current); thus, the auroral oval expands rapidly.

On the other hand, the intensity of the ring current weakens more slowly than the intensity of the system of currents connected to the auroral oval (e.g. *Vennerstrom et al., 2016*), and even the auroral oval returns to its usual position slowly compared to the decrease in the activity of auroral currents *Yokoyama et al. (1998).* Yokoyama and his colleagues conclude that during the recovery phase the relationship between the Dst index and the position of the auroral oval is complicated and varies considerably for individual magnetic storms.

What magnetic latitudes (MLat) the auroral oval reaches, depending on the level of geomagnetic activity, is provided by, for example, *Yokoyama et al. (1998).* In order to minimize uncertainty, it is best to focus on the equatorward boundary of the auroral emission region, not on the equatorward boundary of the visibility of the aurora (*Yokoyama et al., 1998; Hayakawa* *et al., 2018a*). Yokoyama and his colleagues found the following for the position of the equatorward boundary of the diffuse auroral oval precipitation at midnight during the main phase of the magnetic storm: When Dst is above −50 nT, this boundary is generally between 65° and 55° Mlat (of corrected geomagnetic coordinates, CGM). When Dst drops below −100 nT, the auroral band moves significantly equatorward, below 50° Mlat. For each further decrease of 100 nT, the border of the auroral belt moves by about 6° to 7°.

The boundary of the diffuse auroral oval precipitation monitors the position of the inner edge of the central plasma sheet because it is generally assumed that the precipitating electrons in the diffuse aurora originate just in that central part of the plasma sheet (*Winningham et al, 1975; Makita and Meng, 1984; Yokoyama et al., 1998*). There is also a connection between auroras and the ring current because, together with the shift of the electron boundary, also ions penetrate inside the near-Earth region and strengthen the ring current (*Siscoe and Cummings, 1969; Nakai et al., 1986; Alexeev et al., 1996*).

Obviously, there are no in-situ space observations about interplanetary causes from the turn of the 20th century. However, SSC (storm sudden commencement) records (*Curto et al., 2007; Mayaud, 1973*) help us to create an idea about the physical conditions in the near-Earth space environment. It is now well known that the vast majority of the most intense magnetic storms are caused by disturbances in the solar wind during the passage of interplanetary coronal mass ejections (ICMEs), and a good indicator of the shock wave that accompanies the arrival of ICMEs is the occurrence of SSCs (*Vennerstrom et al., 2016*). Vennerstrom and his team found that a large portion of extreme storms are even produced by two or more, possibly interacting, disturbances in the solar wind.

In the following text, we will confront the described theoretical knowledge with three concrete magnetic storms accompanied by auroras.

3.2. The magnetic storm of March 1894

In Figure 1, in one of the panels, we see a record of the horizontal intensity at Ógyalla during the magnetic storm that began on 30 March 1894. The course in this coarsely sampled time series (3 values per day) looks like an

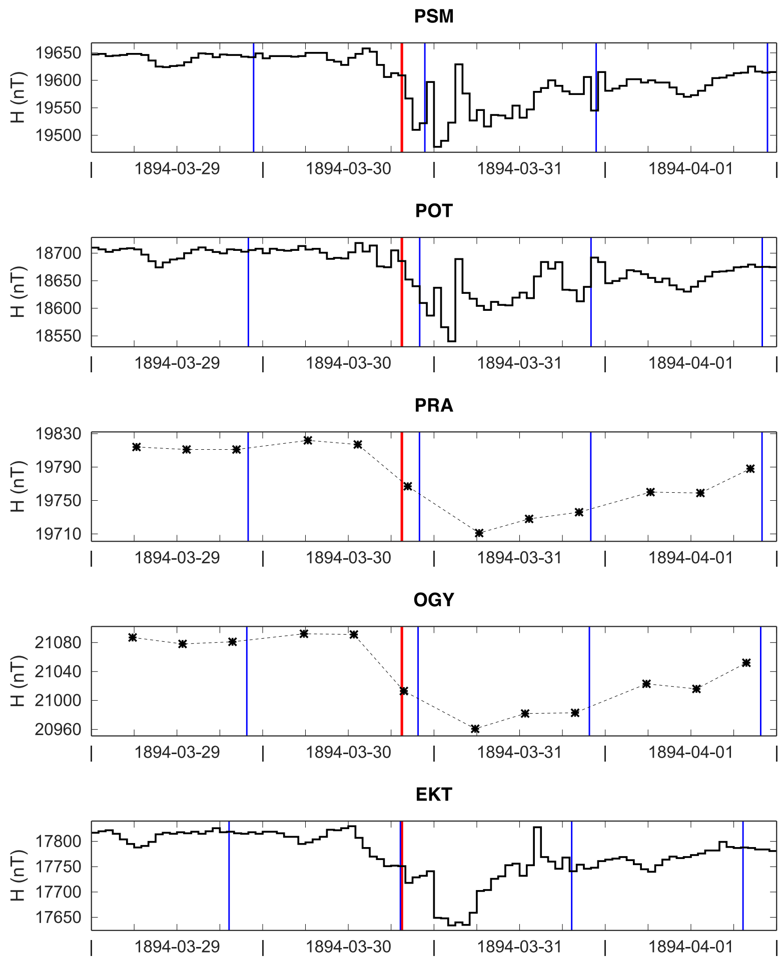

Fig. 1. Time series of horizontal intensity recorded during the geomagnetic storm of March 1894 at European observatories and the observatory EKT. The basic information on the observatories is in Table 1. The vertical red line indicates the occurrence of SSC. The blue vertical lines indicate the moments of magnetic midnights. Hourly means are shown for observatories PSM, POT, and EKT; momentary values are displayed for OGY and PRA.

ordinary geomagnetic storm caused by an intensification of the ring current. For comparison, series of horizontal intensity observed at other European observatories and the Ekaterinburg observatory (Asia) are also shown; the

Table 1. Information about the observatories whose data we used in this article: name and IAGA code, geographic coordinates (Lat, Long), geomagnetic coordinates (MLat, Mlong), and the moment at which magnetic midnight occurs for the given observatory, i.e. when the magnetic local time (MLT) is 0.00 MLT (data are hours of UT). The geomagnetic data, i.e. coordinates and magnetic midnights, are in the CGM system and refer to epoch 1900.0; the internet calculators by *Papitashvili (2023)* and *BGS (2023)* were used to determine them.

Observatory name	IAGA code	Geographic position		Geomagnetic coordinates		0.00 MLT
		Lat (°)	Long (°)	MLat (°)	MLong (°)	(h of UT)
Cheltenham	CLH	38.733	283.158	51.44	350.83	5.05
De Bilt	DBN	52.102	5.177	49.88	87.37	22.49
Ekaterinburg	EKT	56.827	60.632	50.40	131.98	19.30
Honolulu	HON	21.32	202.0	22.33	267.39	11.32
Ógyalla	OGY	47.88	18.19	43.12	95.95	21.78
Parc St Maur	PSM	48.809	2.494	46.92	84.08	22.73
Potsdam	POT	52.382	13.063	48.80	93.48	22.00
Prague	PRA	50.083	14.417	46.10	93.72	21.97
Sitka	SIT	57.067	224.67	60.14	275.48	10.33
Tokyo	TOK	35.685	139.753	29.12	207.78	15.16
Val Joyeux	VLJ	48.821	2.014	47.04	83.71	22.76
Vieques	VQS	18.15	294.55	30.83	2.94	4.13

hourly means used here[1] we obtained from *WDC for Geomagnetism Kyoto (2024)* and the instantaneous values for the Prague observatory from (*Hejda et al., 2021*). The vertical red line shows the instant of the occurrence of an SSC (according to *Mayaud, 1973*). The blue vertical lines show the moments when local magnetic midnights occurred in Ógyalla. To complement the information about the geomagnetic field in Fig. 1, we found two notes in the observational meteorological log from the Ógyalla observatory: on 30 March, they observed a magnetic variation with a varying geomagnetic field, and on 31 March, they observed a variation with an oscillating geomagnetic field.

Figure 2, top panel, shows the magnetic declination time series at Ógyalla for the same period as Fig. 1. Before the magnetic midnight between 30 and 31 March, the declination value is slightly higher than the other values.

[1] Based on the examination of the profile of the quiet diurnal variation, we concluded that the data of Ekaterinburg in the studied period in the cited source are likely reported for the local mean time. (It is not a surprise because the same practice was also at the Ógyalla observatory at the time.)

We have the following information about local aurora sightings during this geomagnetic event: *Seydl (1954)*, citing *Mitteilungen des Nordböhmischen Excursions-Klub's* (*NBEC, 1894*), states that, on the night between 30 and 31 March 1894, flaming rays of aurora borealis were seen in many places around Česká Lípa, North Bohemia. The aurora was so intense that people in some places called fire brigades. In Warnsdorf, the aurora was observed from 10 p.m. until 3 a.m. In Česká Kamenice, the aurora lasted from midnight to 2 a.m. The phenomenon was also sighted in Mariánské Lázně. The above times are local mean time, and the CGM latitudes of the places, which we calculated utilizing the calculator provided by *Papitashvili (2023)*, ranged from 46.24° N to 46.97° N.

From other parts of the world, let us mention Great Britain. It was reported from there that, during the aurora of 30 and 31 March 1894, various sounds produced by earth currents were heard in telephone sets on long telephone lines (*Preece, 1894*).

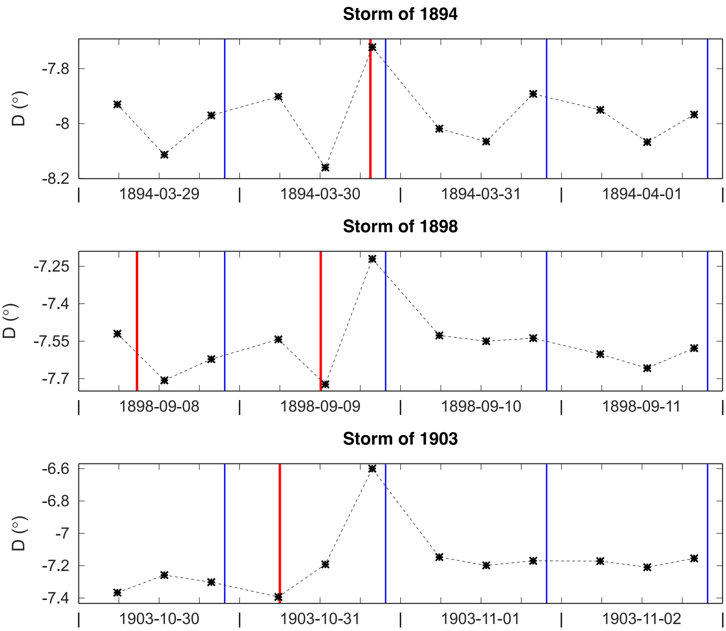

Fig. 2. Time series of magnetic declination (momentary values) at Ógyalla during the magnetic storms of March 1894, September 1898, and late October 1903. Vertical red lines indicate occurrences of SSCs. The blue vertical lines indicate the moments of magnetic midnights.

3.3. The magnetic storm of September 1898

About another event that occurred at the end of the 19th century, the observatory meteorological diary in Ógyalla records that northern lights appeared on the evening of 9 September 1898 between 9:44 p.m. and 11:00 p.m. of Ógyalla local time. The phenomenon showed itself mightiest at 10:08 p.m. At first, it was of an intense claret colour, then grey-green. The centre of it was a little to the NNW.

Also, the Prague observatory reported north lights from 8 p.m. until 10 p.m. (probably local time) on 9 September 1898 (*Weinek, 1899; Seydl, 1954*).

According to *Hrudička (1926)*, solar activity manifested itself as significant magnetic disturbances and interference with telegraph operations on 9 September 1898. The Northern Lights flared up that day at the NNE horizon in the form of a very intense red light between 8 p.m. and 9 p.m. that was visible at altitudes $15° - 20°$. The Northern Lights were observed in Bohemia and Moravia; for sure, people saw it in Třešť, Dačice, Jemnica, and Znojmo. Of the mentioned locations, the most equatorward is Znojmo, whose CGM magnetic latitude at that time was 44.50° N (calculator used: *Papitashvili, 2023*).

In addition to the observations on 9 September, *Seydl (1954)* quotes *Mitteilungen des Nordböhmischen Excursions-Klub's* (*NBEC, 1894*), who wrote that in Litoměřice (CGM latitude 46.63° N) they saw the aurora borealis on the following day, i.e. on 10 September 1898.

The record of the horizontal intensity at Ógyalla during the magnetic storm of 9 September 1898 is shown in one of the panels in Fig. 3. Again, at first glance, this time series shows an ordinary ring-current magnetic storm. For comparison, the figure displays the horizontal intensity at other European observatories and two Asian observatories; hourly means from the *WDC for Geomagnetism Kyoto (2024)* and momentary values for the Prague observatory from (*Hejda et al., 2021*) were used here. The sharp short-term positive variation recorded by the Asian observatories was not observed by the European observatories (including Ógyalla).

Figure 2 in the middle panel shows the time series of the magnetic declination at Ógyalla for the same period as Fig. 3. Before magnetic midnight between 9 and 10 September 1898, the declination value was higher than the other values.

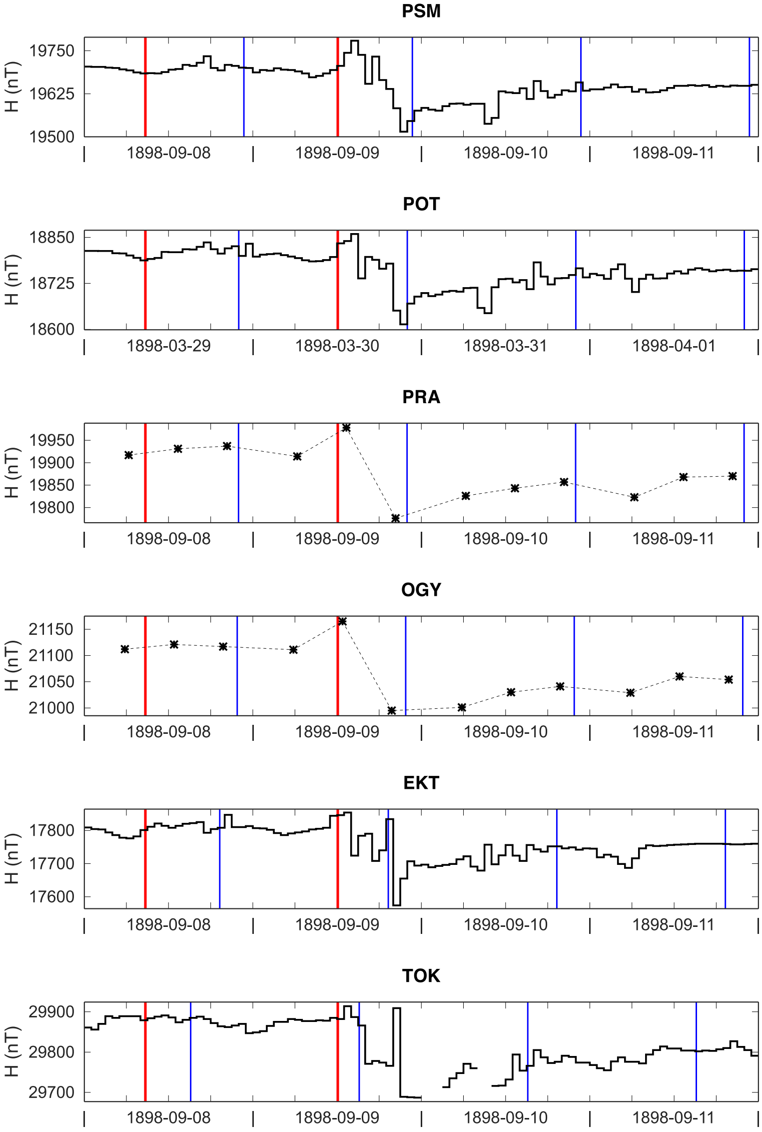

Fig. 3. Time series of horizontal intensity recorded during the September 1898 geomagnetic storm at European and Asian observatories. The basic information on the observatories is in Table 1. The vertical red lines indicate the occurrences of SSCs. The blue vertical lines indicate the moments of magnetic midnights. Momentary values are displayed for observatories OGY and PRA, and hourly means are shown for the other observatories.

3.4. The extreme magnetic storm of late October 1903

The magnetic storm that began at the end of October 1903 caught the attention of the scientific community because it occurred right after the minimum of the solar cycle no. 14, which until then was the weakest since the Dalton Minimum (e.g. *Ribeiro et al., 2016; Hayakawa et al., 2020*). Even though this storm occurred immediately after years of unusually low geomagnetic activity, it was the sixth most intense storm amongst the storms observed in the period 1868–2010 if ranked the magnetic storms according to the aa index, but taking into account also other relevant information (*Vennerstrom et al., 2016*).

Due to strange phenomena in some technological systems, the event also affected ordinary life. Geomagnetically induced currents (GICs) disrupted the railway system in London (*Hayakawa et al., 2020*). Telegraphic connections were spoiled in Australia, between European states, between Europe and Latin America, North America, and Algeria (*Finn, 1903; Lockyer, 1903; Boteler et al., 1998; Ribeiro et al., 2016; Hayakawa et al., 2020*). The impact on telephone lines was also observed; for example, an extreme voltage of 675 V was induced in the telephone cable near Chicago (*Hayakawa et al., 2020*).

Large-scale auroras accompanying the most violent part of this geomagnetic event were (as summarized in *Hayakawa et al., 2020*) observed in Russia, the USA, New Zealand and Australia. An overhead aurora was reported in Sydney (Australia, MLat 42.2° S). Hayakawa et al. (2020) used this data to determine the equatorward boundary of the auroral emission region as 44.1° of the invariant latitude (ILAT), following the procedure published in (*Hayakawa et al., 2018a*). We can compare this value with other extraordinary events. During the famous Carrington magnetic storm of 2 September 1859, the equatorward boundary of the auroral emission region was 32.7° ILAT (*Hayakawa et al., 2018a*). There was also a storm, which occurred on 4 February 1872, during which the equatorward boundary of the auroral emission region was only 24.2° ILAT (*Hayakawa et al., 2018b*).

The Ógyalla observatory had a magnetic latitude (CGM MLat) of 43° (Table 1), and therefore, at the time of the lowest descending auroral oval, the observatory found itself near the auroral oval. However, because the main phase of the storm occurred around 6 – 16 UT, i.e. during the day in Europe, European observers could only see the aurora borealis during the late part of the storm recovery phase (*Hayakawa et al., 2020*). Then, the aurora was already less dramatic. *Réthly and Berkes (1963, p. 102)*, quoting from *Büki and Marczell (1903); Steiner (1903)*, state that on 31 October 1903 at 7:54 p.m. of local mean time, despite the strong moonlight, a weak aurora was visible on the NE horizon at a height (elevation angle) of about $20-25°$. It spanned a width of 45°, was dark red, and had no structure. The phenomenon resembled twilight but was much more intense and did not reach the horizon. The glow moved westward and upward; at 8 p.m., the aurora was at a height of 40°, then gradually weakened and disappeared. Throughout the day, when the aurora appeared at Ógyalla, the magnetic instruments of the Ógyalla observatory showed very strong variations (Fig. 4).

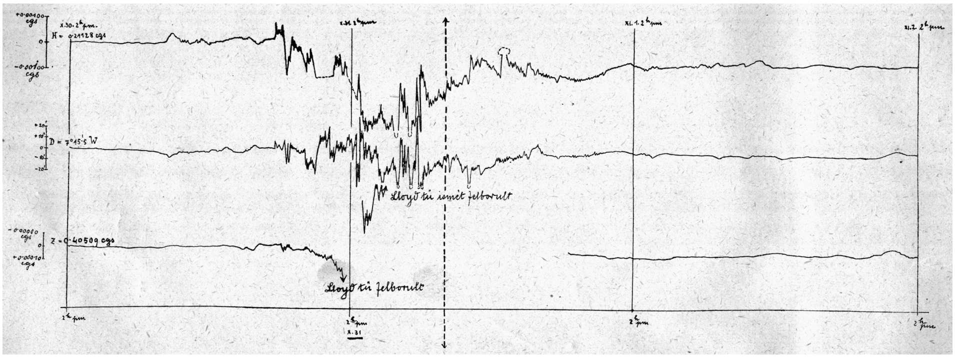

Fig. 4. Magnetogram from the Ógyalla observatory catching the geomagnetic storm at the turn of October and November 1903. The recorded elements of the geomagnetic field are horizontal intensity (H), declination (D), and vertical intensity (Z). The parts of the magnetograms where the light trace, recording the values of the elements, temporarily got outside the photographic paper are marked with round curves, drawn with dashed lines. The inscription "Lloyd tű (ismét) felborult." means that Lloyd needle (again) tipped over. Taken from *OGY (1904)*.

Large variations in horizontal intensity reaching or exceeding 500 nT have been reported from various parts of the world (e.g. *Okada, 1904; Bauer, 1904; Ribeiro et al., 2016*). Variations in declination were also remarkable, e.g. according to *Bauer (1904)*, at the Baldwin observatory, Kansas, the range of declination variation was up to 2°55′.

Variations in horizontal intensity observed at observatories that had sufficient data available without data gaps are shown in Fig. 5. The triangular symbols in the two afternoon data from Ógyalla on 31 October 1903 rep-

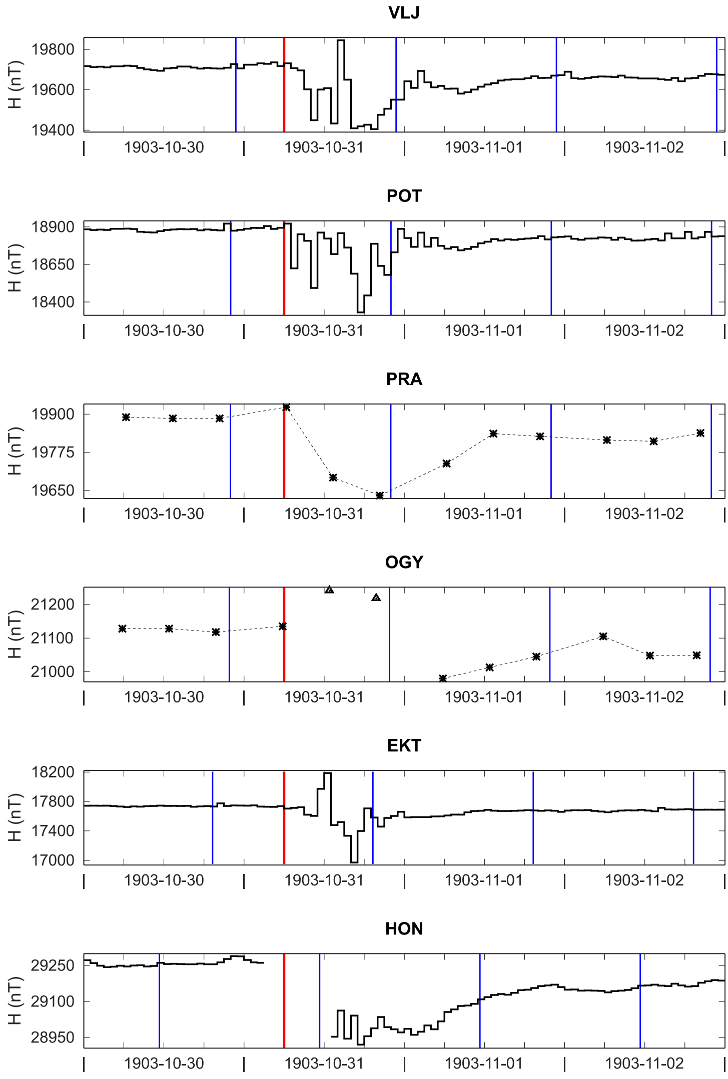

Fig. 5. Time series of the horizontal intensity recorded during the geomagnetic storm at the turn of October and November 1903 at European observatories and observatories EKT and HON. The basic information on the observatories is in Table 1. The vertical red line indicates the occurrence of SSC. The blue vertical lines indicate the moments of magnetic midnights. For observatories OGY and PRA, momentary values are shown, and for the other observatories, hourly means are displayed. The triangular symbols in the two afternoon readings at OGY on 31 October 1903 represent the lower limits of the values (i.e., the values were at least as shown in the figure).

resent the lower limits of the values at the given moments at 2 p.m. and 9 p.m. of local mean time, namely values $> 21,241$ nT and $> 21,218$ nT, respectively. In addition to the SSC that occurred within the displayed time window, SSCs also occurred earlier, namely on 25 October 1903 at 7.8 UT and 29 October 1903 at 10.1 UT (*Mayaud, 1973*). The variations in the relatively close observatories Prague and Ógyalla might seem to be inconsistent, but this is probably not the case. We interpret them as indicating the oscillatory nature of the variations, which was also observed by other European observatories, Val Joyeux and Potsdam.

Figure 2, bottom panel, shows the magnetic declination time series at Ógyalla during the event of 1903. Before the magnetic midnight between 31 October and 1 November, the declination value is much higher (namely by $36'$) than the other values.

4. Discussion and conclusions

The Ógyalla data from the turn of the 20th century, which we presented in our work and made available (in Supplement), have, in addition to their historical value, significance for present-day research on geomagnetic activity. We focused on three the then magnetic storms that accompanied auroras. Of the geomagnetic elements, horizontal intensity and declination are crucial for interpreting those intense events. For horizontal intensity, our findings were as follows.

In the 1894 event (Fig. 1), the observations at Ógyalla only confirmed what the other observatories observed. At the Parc St Maur observatory, which is the westernmost of the considered European observatories, a sharp and short-lived positive variation is visible around midnight between 30 and 31 March; a similar, but less significant variation can be seen at that time also in the hourly means of other observatories. Since the observatories here monitored only a relatively small part of magnetic longitudes, we cannot say whether that sharp variation was a local or global phenomenon. The overall longer-term decrease in horizontal intensity since the late evening hours of 30 March was a global phenomenon caused by the intensified ring current.

On the other hand, another short increase in horizontal intensity between 03:00 UT and 04:00 UT on 31 March 1894 was recorded by the European observatories Parc St Maur and Potsdam (no observation was made that time in Prague or Ógyalla). There was no indication of a similar variation at that time in Ekaterinburg. Therefore, it was probably a local phenomenon caused by sources other than the ring current. Since auroras were observed in Europe at the same time (Section 3.2), and thus the auroral oval must have been not very far from the places where the auroras were observed, we might interpret the geomagnetic variation as a consequence of the current system related to the auroral oval.

In the event from the year 1898 (Fig. 3), a clear profile of a ring-current magnetic storm can be seen at all observatories. However, Asian observatories showed additional positive sharp short-term variations not recorded at European observatories. Also, in this case, auroras were observed in Europe. Therefore, we could consider these variations as local variations, the cause of which might be found in the currents of the auroral oval or in the longitudinal currents connected to it.

The horizontal intensity in the extreme storm of 1903 (Figs. 4 and 5) shows, in each of the time series shown for the different observatories, in addition to the ubiquitous decrease caused by the storm-time ring current, also very different local patterns. Again, taking into account the auroras observed simultaneously with the magnetic storm, our interpretation is that those local variations were likely caused by the current system related to the auroral oval.

Based on the elevation angle of 40° under which the observers saw the aurora in Ógyalla, and following the procedure of *Hayakawa et al. (2018a)*, we calculated the ILAT (invariant latitude) of the equatorward boundary of the auroral emission region as 48.5°. Simultaneously with the occurrence of the aurora at Ógyalla, this phenomenon could be observed overhead (i.e. under 90° elevation angle) north of Ógyalla – at latitude 51.6°, approximately in the vicinity of the Polish city Ostrów Wielkopolski. The magnetic field line closest to the equator on which the aurora emission took place crossed the earth's surface at latitude 53.1°, approximately in the place of the Polish city Bydgoszcz, i.e. more than 400 km from Ógyalla.

The above value of 48.5° represents the equatorward boundary of the auroral emission region (*Hayakawa et al., 2018a*) on 31 October 1903 at around 8 p.m. of Ógyalla Mean Time, i.e. already at the time of the recovery phase of the magnetic storm. We cannot say with certainty that this is the equatorward limit of the auroral oval because the reports on the aurora in *Büki and Marczell (1903); Steiner (1903)* according to *Réthly and Berkes (1963, p. 102)* speak of a dark red glow that showed no structure. Thus, that glow might well be stable auroral red (SAR) arcs, which often occur several degrees closer to the equator than the auroral oval (*Rees and Roble, 1975; Hayakawa et al., 2018a*). The fact that they typically occur during the recovery phases of magnetic storms (e.g. *Hayakawa et al., 2018a*) also suggests that it could have been SAR arcs. Nevertheless, we tend to incline that the glow was a diffuse aurora since the phenomenon moved to the west and upwards, in the upward direction from 20°–25° to 40° in a few minutes, and we would expect a less dynamic development for SAR arcs. Either way, without spectroscopic observations, it is impossible to distinguish reliably between SAR arcs and ordinary auroras. However, such spectroscopic observations were not carried out in Ógyalla then.

We also could make a conclusion based on observations of declination. All three panels in Fig. 2 display a positive (eastward) variation briefly before the magnetic midnights when the auroras were observed. Our interpretation is that the declination was affected by occurrences of substorms. The thing is that there are intense upward-directed field-aligned currents in this pre-midnight sector during substorms. Because in all three events, Ógyalla was equatorward of the auroral oval during the Ógyalla nighttime, those field-aligned currents might cause the observed easterly deflection of the direction of the geomagnetic field.

GICs can have a decisive influence on the technological systems on the Earth's surface (see Section 3.4). At the same time, the intensity of GICs depends on the rate of change of the geomagnetic field. For the records of the horizontal intensity (Figs. 1, 3, and 5), we identified the source of the fastest changes. They seem to be the electric currents of the auroral oval or the longitudinal currents that feed into the auroral oval. It confirms our hypothesis in Section 3.1.

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