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Geomagnetic Activity at the Sodankylä Observatory, 1914–2010

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Abstract

We have studied the time variation of the geomagnetic field at the Sodankylä observatory based on activity indices derived from the magnetic recordings in 1914–2010. Magnetic activity was absolutely highest in autumn 2003 but has since then decreased to the lowest level for almost 100 years. The global magnetic activity shows similar trends and time variations as observed at Sodankylä.

*A comparison between manually derived magnetic indices (*K*) from Sodankylä (1996–2010) and computed ones (by an automatic algorithm) shows that there are no significant differences between the two indices. The manual production of the indices may well be replaced by the automatic one. However, there is a minor tendency that computer derived indices are slightly lower than the corresponding manually scaled values due to different data used for the scaling. Manually scaled* K*-values are produced from 15 s data (point values) when computer-produced values are derived from 10 s average data.*

Key words: geomagnetic activity, space weather, magnetic field, history, geophysical observatory

1. Introduction

In this paper, we utilize the magnetic activity index series consisting of daily *Ak*-numbers for analyzing variations in space weather conditions at Sodankylä since 1914. Comparisons are presented about differences between manually derived *K*-index numbers and those calculated by an algorithm developed at the Finnish Meteorological Institute (FMI) (*Sucksdorff et al.*, 1991).

Regular magnetic and meteorological observations started at the Sodankylä observatory (Geogr. Lat.* 67.4°N, Lon. 26.6°E) on January 1st, 1914. The site of the observatory was selected after a thorough magnetic survey in 1912 in the Sodankylä area at five possible locations (*Keränen*, 1973; *Simojoki*, 1978).

The history of the observatory goes back to the First International Polar Year, 1882–1883, when a full-scale geophysical and meteorological observatory was in operation (until 1884) about 5 km north of the present-day site (*Sucksdorff*, 1952; *Kataja*, 1973, 1999; *Nevanlinna*, 1999).

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* Corrected geomagnetic coordinates are 64.0°N; 107.0°E.

The main motivation of the establishment of the Sodankylä observatory was the need for continuous magnetic recordings supporting the magnetic mapping of Finland that started in 1910 (*Simojoki*, 1978; *Kataja*, 1999). This regional scale magnetic survey was a part of a worldwide project of a global magnetic study organized by the Carnegie Institution in the USA.

Recordings of the Earth's magnetic field vector at Sodankylä have been continued since 1914. A series of three-component magnetic data is thus available for about 97 years. Observations were temporarily stopped during the Finnish Civil War (1918) for a couple of months. The observatory was totally destroyed by German military forces in the World War II in 1944. It was rebuilt nearby to the original site after the war but the observations were stopped for about 15 months (*Sucksdorff*, 1952; *Kataja*, 1999; *Sucksdorff et al.*, 2001).

Magnetic recordings were carried out by photographic registrations on magnetograms up to 1996. Since then the variometers have recorded magnetic variations digitally. For characterization of the local space weather conditions, various magnetic activity indices have been determined daily from the Sodankylä magnetic data, as is the normal routine practice in at all magnetic observatories. Magnetic indices were scaled manually from magnetograms. They were printed in Sodankylä magnetic yearbooks together with magnetic data (see, the recent yearbook: *Kultima and Raita*, 2009). The indices published are the three-hour *K*-index and the daily *Ak*-number (for more information about the indices, e.g., *Menvielle and Berthelier*, 1991).

2. Magnetic recordings

Changes in the magnetic field were registered photographically by analog variometers since the beginning of the Sodankylä observatory 1 Jan 1914 up to 1996) (*Kataja*, 1973; 1999). The components* recorded were H, D and Z. After the wartime destruction of the observatory in 1944, new variation and absolute houses were set up in 1945. Magnetic registrations started again in January 1946 with a set of La Cour-type variometers. In 1953, these variometers were completed by three-component variometers: a normal variometer for regular magnetic variations, an insensitive one for magnetic storms, and a quick-run variometer for rapid changes (pulsations) in the magnetic field. The magnetic instrumentation was then well comparable with the international standards of the geomagnetic community in the 1950s. The baseline checks were made by the Danish QHM (for H), by the Askania declinometer (for D), and by BMZ (for Z) (for technical details, see *Wienert*, 1970; *Laursen and Olsen*, 1971; *Forbes*, 1987). Later in the 1960s a Helmholtz coil system together with a proton magnetometer for the total field (F) was applied for the determinations of the absolute level of the magnetic field components. In the 1980s a new type of an absolute instrument (a flux-gate sensor mounted on a non-magnetic DI-precision theodolite) was

*H is the horizontal component and Z the vertical component of the total magnetic field vector (F). D is the magnetic declination, i.e., the angle between the vector H (magnetic north direction) and the true north direction. The inclination (I) is the angle between H and F.

adopted for measurements of absolute values of D and I (*Forbes*, 1987; *Jankowski and Sucksdorff*, 1996). DI-flux instruments have now superseded the QHMs and similar devices based on suspended magnets.

Digital recordings of magnetic variations were started by a Polish torsion photoelectric magnetometer (TPM) in 1983 (*Jankowski and Sucksdorff*, 1996) but La Cour analog registrations were run simultaneously until the end of 1995. Today, there are three independent digital variometers recording magnetic variations with a 2 Hz sampling rate. Sodankylä also belongs to the international INTERMAGNET network (www.intermagnet.org) by sending daily magnetic field values to the network nodes. The observatory is also a member of the MIRACLE/IMAGE-magnetometer network (space.fmi.fi/MIRACLE) locating in Fennoscandia and Svalbard.

For further details of old and new magnetic instruments and data treatments, see *Wienert* (1970), *Laursen and Olsen* (1971), *Forbes* (1987) and *Jankowski and Sucksdorff* (1996).

Summaries of magnetic data collected during a year have been published in yearbooks since the beginning of the Sodankylä observatory. This tradition has been continued until today, and hourly, monthly and annual means of the magnetic field values will be found in printed form in yearbooks. In addition, some metadata information about the instruments is given as well as tables of magnetic activity indices. Real-time and older magnetic data in files are available through the Internet (www.sgo.fi).

3. Magnetic indices

Magnetic activity indices are discrete numbers derived from magnetic recordings by standardized methods. Their aim is to help monitoring magnetic transient variations and storms in various space weather conditions born in the magnetosphere and ultimately governed by the Sun in connection of solar-terrestrial interactions. Activity indices characterize the amplitude of magnetic disturbances in a time frame usually from an hour to one day. The most commonly used activity index is the Bartels' *K*-index introduced in the 1930s (*Bartels et al.*, 1939; *Mayaud*, 1980; *Menvielle and Berthelier*, 1991). It provides a homogeneous running record, in three-hour sequences, of magnetic effects of near-space electric currents caused by solar wind particles. *K*-indices are derived from magnetic recordings at a single site but a combination of *K*-indices with more global distributions yields new indices that describe planetary magnetic space weather conditions. These are *Kp*, *Am*, *Ap*, *aa*, etc. (*Menvielle and Berthelier*, 1991; *Rangarajan*, 1989). As magnetic indices are related to solar activity, they give proxy data about those solar processes that are relevant to the varying magnetic fields in space weather phenomena. Time series of magnetic indices tell us about cyclic and transient variations in the solar activity. Thus long lasting series of indices give important information about the Sun in the course of the 11-year sunspot cycle and beyond.

The longest uniform magnetic activity index series is the so-called *aa*-index. It is based on three-hour *K*-indices of two magnetic observatories located on the Earth almost antipodally in the UK and Australia. The *aa*-index series started in 1868 and it continues until present (*Mayaud*, 1980). Even further back in time goes an activity index series (*K* and daily *Ak*) derived from magnetic recordings at the Helsinki observatory, Finland, 1844–1912 (*Nevanlinna and Kataja*, 1993; *Nevanlinna*, 2004) and at Russian observatories since 1841 (*Nevanlinna and Häkkinen*, 2010).

First attempts to utilize Sodankylä magnetic data for deriving magnetic indices are from *Sucksdorff* (1942). He introduced an index (*Az*) calculated from the hourly range of the Z-component for 1914–1934. Sucksdorff's *Az* has not been utilized for other observatories but later he completed the Sodankylä *Az*-series up to 1944 (*Sucksdorff*, 1955). For Sucksdorff's other scientific works, see *Keränen* (1956), *Raita and Kultima* (2007).

During the IGY (International Geophysical Year, 1957-1958) and its extension IGC (*International Geophysical Cooperation*, 1959) a modification of the *K*-index (*Q*-index) was applied for 15-min intervals of magnetic variations (*Lincoln*, 1967). There were about 20 observatories around the polar regions scaling this *Q*-index for several years. At the Sodankylä observatory, the *Q*-index has been prepared and stored ever since the IGY.

Recently, new type of magnetic indices have been introduced that can be easily calculated from present day and historical magnetic data if available in numerical form in succession of at least hourly recordings. One of these is the daily IHV-index (Inter-Hourly Variability), which is a useful tool in studies of the long-term behavior of global geomagnetic variations in connection with solar activity reaching back to the 1830s (e.g., *Svalgaard and Cliver*, 2007). One of the advantages of the IHV-index compared with the traditional hand-scaled activity numbers (*K*-indices) is in its objective derivation. However, differences between activity time series of the two indices are not significant (Fig. 1). Magnetic data from Sodankylä, Nurmijärvi (Finland) and Helsinki observatories have been used among worldwide observatories in various studies based on the utilization of the IHV-index (e.g., *Mursula and Martini*, 2007; *Svalgaard* and *Cliver*, 2007).

In the 1950s routine determinations of daily Bartels' *K*-index were adopted at all geomagnetic observatories and the *K*-numbers were published in observatory yearbooks, as was the case at Sodankylä and Nurmijärvi observatories. Most of the world's observatories have calculated *K*-indices retrospectively using their old magnetograms in the archive. From Finland observatory *K*-indices are available as follows: Helsinki (1844–1897; *Nevanlinna*, 2004), Sodankylä Polar year station (1882–1883; *Nevanlinna*, 1999), *Sodankylä* (1914 – until present) and Nurmijärvi (1953 – until present) and some of the Finnish IMAGE-stations (Hankasalmi and Oulujärvi since the early 1990s).

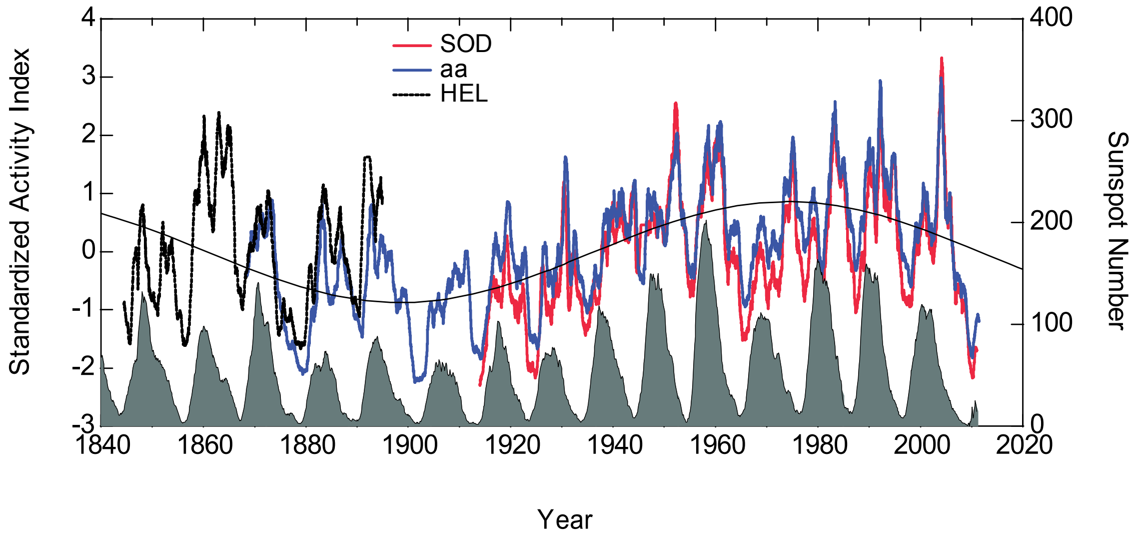

Fig. 1. Smoothed (365 d) and standardized daily means of *Ak*-indices from Sodankylä (SOD) 1914–2010, Helsinki (HEL) 1844–1897 and (standardized) global *aa*-indices 1868–2010. Sunspot numbers are depicted by grey area. The smooth curve is a sinusoidal fit of the *aa*-values showing an apparent period of about 150 years. Magnetic activity at Sodankylä was at the lowest level in late 2009 since the beginning of the magnetic observations in 1914.

Derivations of *K*-indices from analog magnetograms are based on a manual scalings where the magnetic field amplitude for each 3-hour sequence is determined by a special ruler (for more technical details, see, e.g. *Mayaud*, 1980; *Jankowski and Sucksdorff*, 1996). In the 1990s, when digital magnetic recording systems became more common in the magnetic observatories, automatic computer-based methods were developed and adopted for the *K*-index production. Today, most of the observatories record digital one-minute or denser values and produce the *K*-indices automatically. Many algorithms suitable for such calculations are available. Much effort has been put on for tests between manually derived *K*-indices and those calculated by computers (*Menvielle et al.*, 1995). A Finnish algorithm, the so-called FMI-algorithm, has been used since the 1990s for calculations of the *K*-indices from Nurmijärvi recordings (*Sucksdorff et al.*, 1991). Differences between computer-based *K*-indices and manual ones are usually small; about 70 % of all *K*-values agree and about 30 % differ by only ± 1 unit when the FMI-algorithm is used.

Fig. 1 shows a summary of the magnetic activity series of the smoothed daily index (365 d running means) from Sodankylä (1914–2010), Helsinki (1844–1897), and global *aa* (1868–2010). Daily indices in Fig. 1 have been standardized to *z*-scores by subtracting the mean value from each series and dividing the difference by the standard deviation. One can see that the time variations of all overlapping index series are rather similar to the 11-year sunspot variation. In the long-term behavior of the activity there was a minimum around 1900, a maximum in the mid of the 20th century after which the general trend of the magnetic activity has been slightly decreasing since about 1985. The Sodankylä *Ak*-index follows closely to the global *aa*-index and there are no significant changes in differences and in long-term trends between the two indices in the time interval 1914–2010.

It is interesting to note that the smoothed activity index (*aa* and Sodankylä *Ak*) reached an absolute maximum in autumn 2003 during the descending phase of the sunspot cycle 23, and the deepest minimum for about 100 years after the prolonged turn of the cycles 23 and 24 in 2009.

As is well known (e.g., *Kane*, 1997) the highest peak at the activity time series usually occurs in years just before or at the sunspot maximum and a couple of years after it during the descending phase of the cycle. The index series have thus dual peak structure during the 11-year sunspot cycle. The activity between two such peaks can be plunged deeper than in the preceding sunspot minimum as was the case in 1980.

The time period from about 1920 to 2010–2020 represents of an epoch called "Grand Maximum" (e.g., *Usoskin*, 2008; *Lockwood*, 2010) because the solar activity has been probably greater at that time than centuries to millennia before. According to the international solar activity prediction panel organized by NOAA (www.swpc.noaa.gov), the next sunspot maximum is expected to occur in 2013 and it will be lowest for about 100 years. Space weather conditions will probably be rather modest during the next ten years.

3.1 Computer production of Sodankylä activity indices

The analog magnetic recordings by the LaCour variometers were stopped at Sodankylä observatory in the end of 1995. Since then magnetic variations have been monitored digitally. However, *K*-indices have been determined manually after 1995 until now from magnetograms plotted from digital data with a 15-second sampling interval, which was available from the TPM magnetometer since 1983. In this way it is ensured that the Sodankylä activity series remains as homogeneous as possible when the index production method is kept unchanged. In order to reveal how much the manually produced indices (MK) differ from those obtained by an automatic FMI-algorithm (AK), we made a comparison between the two *K*-index series covering about 14 years (Jan 1996 – May 2010) comprising about 42 000 single *K*-index values. The result was that about 78.9 % of the AK and MK numbers were exactly the same. The difference was ± 1 unit in 20.8 % of the cases, and only 0.3 % more than 1. Fig. 2 shows the differences between MK and AK for each *K*-bin. One can see that for each MK-value when $K > 0$, the corresponding AK number is one unit smaller/greater in 5 – 25 %/5 % of the cases. This asymmetry in the *K*-value distribution means that there is a minor systematic difference between the MK and AK series. In the linearized daily activity index (*Ak*) this difference causes in most cases less than a 5 % decrease in the index when the calculated AK-values are compared with the MK-values. The main reason to the slight discrepancy between the AK and MK indices is obviously due to different data sets. The FMI-algorithm uses 10 s averages whereas Sodankylä magnetogram derivations of the *K*-indices are based on 15-s data.

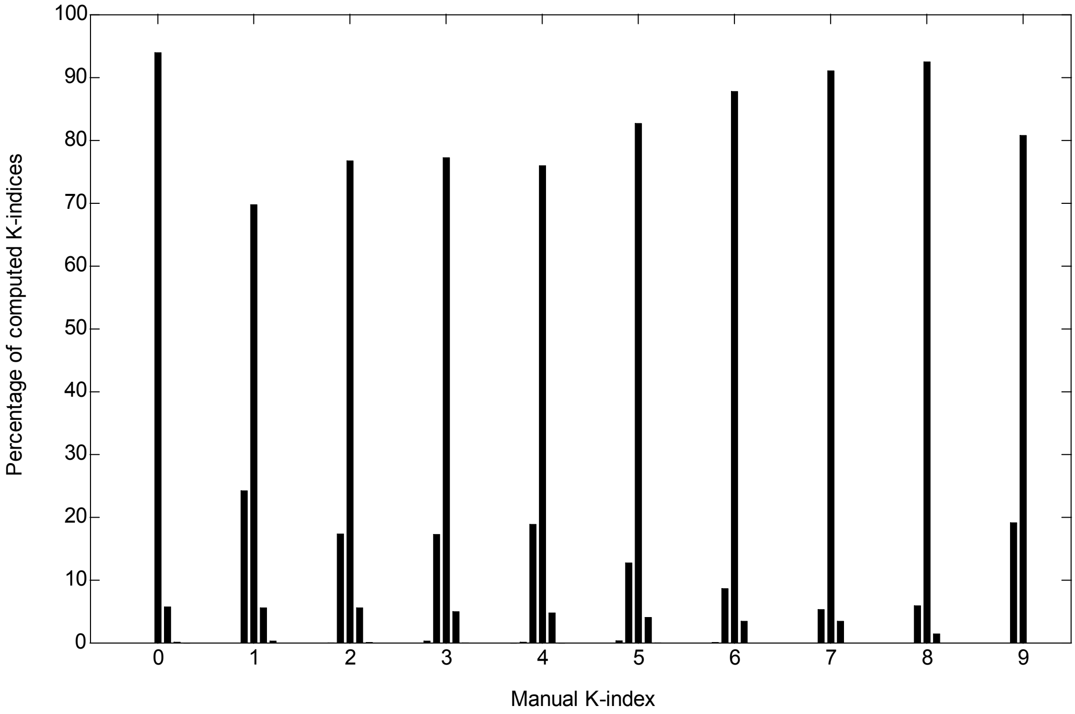

Fig. 2. Comparison between manual (MK) and computer produced (AK) *K*-indices at the Sodankylä observatory for the time frame Jan 1996 – May 2010.The bars at MK = 0, 1, ... , 9 give the percentage of AK-values that are equal to MK. The bar on its left/right side gives the percentage that the AK-value is one *K*-unit smaller/greater than MK.

3.2 Power spectra of activity time series

Fig. 3 shows an example of the power spectra of the activity index time series obtained by a Fourier-transformation. Given are the spectra based on the daily activity indices *aa* (1868–2010) and Sodankylä *Ak* (1914–2010). For comparisons between geomagnetic activity and its solar causes, a similar power spectrum from the solar wind velocity at 1 AU was reconstructed for 1965–2010 (data source: OMNIweb Data Explorer, http://omniweb.gsfc.nasa.gov/form/dx1.html). The power spectra have been calculated for the whole time period although a division according to 11-year sunspot cycles with ascending and descending sunspots would be a meaningful analysis too, as done by *Kane* (1997). However, the spectral spikes found here and shown in Fig. 3 represent standing signatures in the activity data that are stable throughout several sunspot cycles.

All three time series show major spectral spikes at the Schwabe sunspot cycle (9.2 – 10.9 yr), 5.0 – 5.3 yr, 1.3 – 1.5 yr, 26.6 – 27.5 d, 13.4 – 13.7 d, and 8.8 – 9.1 d reflecting basic characteristics in the solar activity behavior although the periods obtained here differ slightly from each other in the spectra. This is partly due to the different lengths and different spatial coverage of the original time series of activity indices. However, the periods found here correspond well to the results obtained from similar spectral analyses of activity index series (e.g., *Fraser-Smith*, 1972, *Delouis and Mayaud*, 1975, *Clua De Gonzales et al.*, 1993, and *Nevanlinna*, 2004).

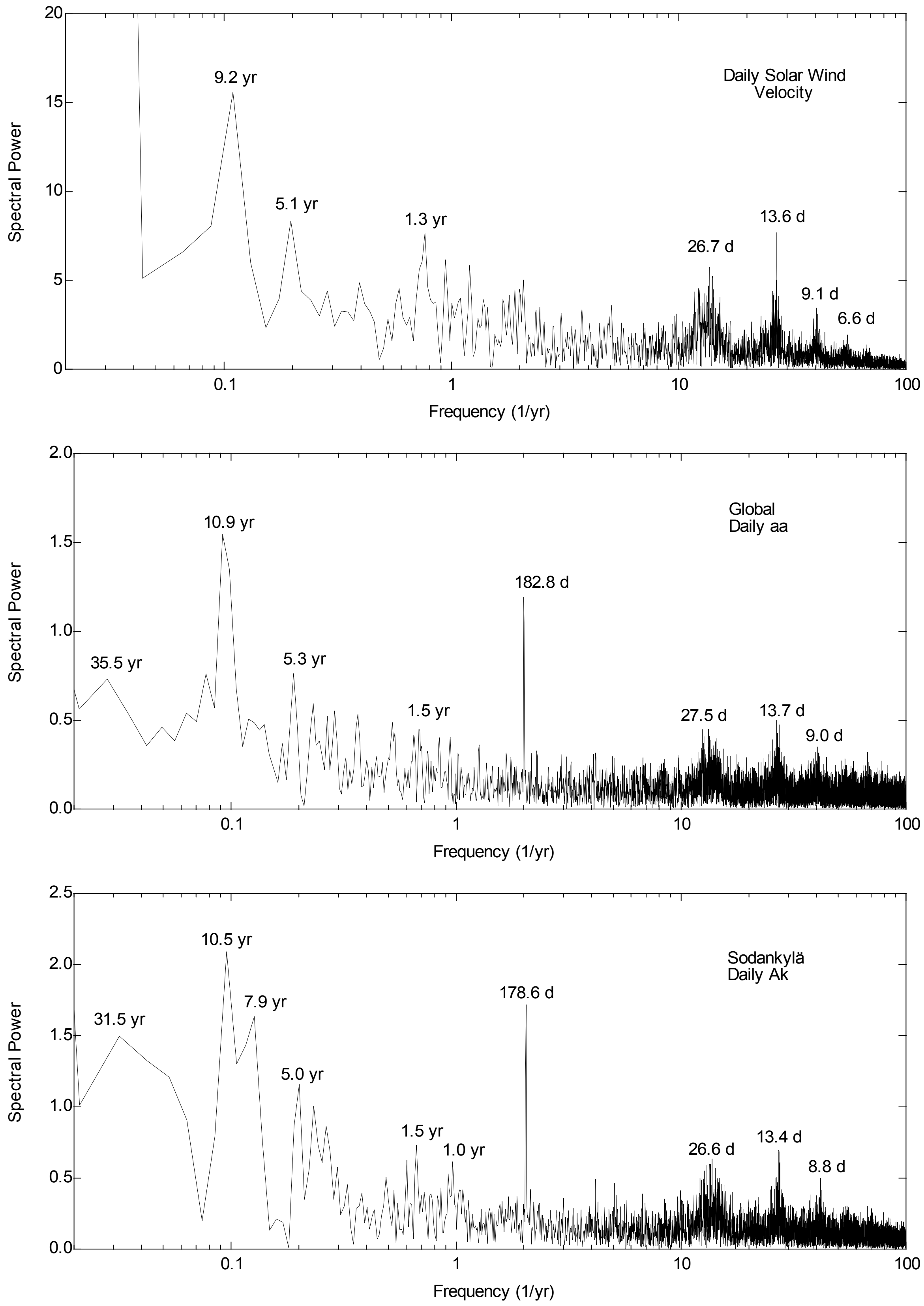

Fig. 3. Power spectrum of daily solar wind velocity (upper panel), global *aa*-index (mid-panel), and Sodankylä *Ak*-numbers (lower panel). Prominent spectral lines are attached by the period of the wave.

In the *aa*- and *Ak*-spectra, there are weak signals for periods longer than the double-sunspot cycle 22 yr similarly to what *Kane* (1997) has found. The spectral line about five years is connected with the dual-peak structure of the magnetic activity during the course of the sunspot cycle as shown in Fig. 1. In the dual activity behavior, the magnetic storms occur in at least two episodes with a time separation of about 4–6 years around the sunspot maximum year.

The spectral region between about 3 years to 1 year is very rich of lines in the geomagnetic activity spectral series as well as in the solar wind velocity spectrum. The period 1.3–1.5 yr found here and in other similar studies also revealed in many heliospheric parameters (e.g. solar wind speed, interplanetary magnetic field; see *Richardson et al*., 1994; *Clua de Gonzales et al*., 1993; *Mursula et al*., 2003, *Silverman and Shapiro*, 1983). These lines are quasi-periodic in such manner that they are not existing through the entire solar cycle and are weaker than average during low-activity sunspot cycles (*Kane*, 1997; *Mursula et al*., 2003). *Clua de Gonzales et al*. (1993) claim that this periodicity could be traced back to the sector structure of the interplanetary magnetic field.

There is rather a weak annual line visible at Sodankylä, which is absent in the *aa*-series. The annual variation is cancelled in the *aa*-index series because it is based on two antipodal observatories where the annual magnetic variation is in antiphase.

The strongest spectral line after the sunspot signal is the semi-annual wave seen only in geomagnetic activity data (Fig. 3). The existence of the semi-annual periodicity has been known since the early days of space weather studies in the beginning of the 19th century. It is caused mainly by the varying tilt of the Earth's magnetic dipole axis relative to the Earth-Sun line in the Russell-McPherron model (*Russell and McPherron*, 1973). The semi-annual wave has its minima at solstices and maxima at equinoxes.

In addition to the solar cycle and semi-annual periodicities, the solar rotation recurrence peak around 27 d is one of the most important feature in the geomagnetic activity variation as well as in the solar wind data. Actually, in the short period part of the spectrum there three are clusters of spectral lines centred at about 27, 13, and 9 days, respectively. The amplitude of the 13 d line is slightly greater than the two others.

Historically, the existence of the 27 d solar rotation periodicity of magnetic disturbances was recognized as early as in the 1850s and the first reports about the 14 d periodicity appeared in the early 20th century (e.g., *Chapman and Bartels*, 1940). Statistics of the 27 d and 14 d variations revealed in the magnetic recordings at Sodankylä were analyzed by Sucksdorff in his thesis about magnetic activity (*Sucksdorff*, 1942).

In the 1930s Bartels introduced M-regions as hypothetical (M for mysterious) solar sources of the recurrent magnetic activity (*Bartels*, 1934). Satellite missions in the 1970s revealed that M-regions are coronal holes from which enhanced solar wind streams escape into the interplanetary space causing disturbances in the magnetosphere of the Earth (e.g., *Crooker and Cliver*, 1994).

A recurrent two-sector structure in the Sun is typically associated with an emerging spectral peak close to 27 d whereas the 14-d modulation becomes more important during intervals corresponding to four sectors per solar rotation.

4. Conclusions

Sodankylä is the oldest geomagnetic observatory inside the Arctic Circle. It has been in operation almost continuously for nearly 100 years. Observatory traditions at Sodankylä reach back in time to the first International Polar Year in 1882–1883. The magnetic recordings at Sodankylä, together with the data from the Helsinki and Nurmijärvi observatories, complete the Finnish geomagnetic observatory data series that has its origin in 1844.

Magnetic activity indices derived from observatory magnetic data are an important source of information in space weather studies. Long-term magnetic series are especially important because they give proxy data from the solar processes causing near-Earth space weather phenomena.

A comparison between manually derived magnetic indices (K) from Sodankylä (1996–2010) and computed ones by an automatic FMI-algorithm shows that there are no significant differences between the indices. There is a minor tendency that computer-derived indices are lower (usually no more than one K-index unit) than the manual numbers due to slightly different data sets used in the comparisons. Manually scaled K-values are produced from point values (15-s data) when computer produced values are derived from 10 s average data.

The manual process for producing the K-indices at Sodankylä can be replaced by the automatic calculations based on the FMI-algorithm without causing appreciable changes in the homogeneity of the K-index series.

During the last sunspot cycle (1996–2008) the solar activity, as measured by geomagnetic disturbances, was at the highest level in the autumn of 2003 since the start of the activity monitoring in 1844. On the other hand in the beginning of the new solar cycle in early 2009, magnetic activity was lowest for about 100 years predicting that the present sunspot cycle (24) will be much less intensive than its predecessors in the late 20th century. Space weather conditions are thus expected to be rather mild during the next ten years compared to what were observed in the previous decades.

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