that the level of magnetic activity is proportional to the inverse Rossby number of the star—a result that is consistent with the emission data. Clearly, as there is a small sample of stars for which we have a detailed record of magnetic activity and this record is comparatively short, there is a need to continue these observations as they give us great understanding of the magnetic properties of our nearest star—the Sun.

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Bibliography

Beer, J., 2000. Long-term indirect indices of solar variability. *Space Science Reviews*, **94**: 53–66.

Brandenburg, A., Saar, S.H., and Turpin, C.R., 1998. Time evolution of the magnetic activity cycle period. *The Astrophysical Journal*, **498**: L51–L54.

Eddy, J.A., 1976. The Maunder minimum. *Science*, **192**: 1189–1202.

Fröhlich, C., 2000. Observations of irradiance variations. *Space Science Reviews*, **94**: 15–24.

Hale, G.E., 1908. On the probable existence of a magnetic field in sunspots. *Astrophysics Journal*, **28**: 315–343.

Hoyt, D.V., and Schatten, K.H., 1998. *The Role of the Sun in Climate Change.* New York: Oxford University Press.

Maunder, E.W., 1913. Note on the distribution of sunspots in heliographic latitude. *Monthly Notices of the Royal Astronomical Society*, **64**: 747–761.

Mestel, L., 1999. *Stellar Magnetism.* Oxford: Clarendon Press.

Ribes, J.C., and Nesme-Ribes, E., 1993. The solar sunspot cycle in the Maunder minimum AD 1645–AD 1715. *Astronomy and Astrophysics*, **276**: 549–563.

Rosner, R., 2000. Magnetic fields of stars: using stars as tools for understanding the origins of cosmic magnetic fields. *Philosophical Transactions of the Royal Society of London, Series. A*, **358**: 689–708.

Stix, M., 1976. Differential rotation and the solar dynamo. *Astronomy and Astrophysics*, **47**: 243–254.

Wagner, G. *et al*., 2001. Presence of the solar de vres cycle (205 years) during the last ice age. *Geophysical Research Letters*, **28**: 303.

Vorontsov, S.V., Christensen-Dalsgaard, J., Schou, J., Strakhov, V.N., and Thompson, M.J., 2002. Helioseismic measurement of solar torsional oscillations. *Science*, **296**: 101–103.

Cross-references

Dynamo, Solar

MAGNETIC INDICES

Magnetic indices are simple measures of magnetic activity that occurs, typically, over periods of time of less than a few hours and which is recorded by magnetometers at ground-based observatories (Mayaud, 1980; Rangarajan, 1989; McPherron, 1995). The variations that indices measure have their origin in the Earth's ionosphere and magnetosphere. Some indices having been designed specifically to quantify idealized physical processes, while others function as more generic measures of magnetic activity. Indices are routinely used across the many subdisciplines in geomagnetism, including direct studies of the physics of the upper atmosphere and space, for induction studies of the Earth's crust and mantle, and for removal of disturbed-time magnetic data in studies of the Earth's deep interior and core. Here we summarize the most commonly used magnetic indices, using data from a worldwide distribution of observatories, those shown in Figure M31 and whose sponsoring agencies are given in Table M1.

Range indices *K* and K_p

The 3-h *K* integer index was introduced by Bartels (1938) as a measure of the range of irregular and rapid, storm-time magnetic activity. It is designed to be insensitive to the longer term components of magnetic variation, including those associated with the overall evolution of a magnetic storm, the normal quiet-time diurnal variation, and the very much longer term geomagnetic secular variation arising from core convection. The *K* index is calculated separately for each observatory, and, therefore, with an ensemble of *K* indices from different observatory sites, the geography of rapid, ground level magnetic activity can be quantified.

When it was first implemented, the calculation of *K* relied on the direct measurement of an analog trace on a photographic record. Today, in order to preserve continuity with historical records, computer programs using digital data mimic the original procedure. First, the diurnal and secular variations are removed by fitting a smooth curve to 1-min horizontal component (H) observatory data. The range of the remaining data occurring over a 3-h period is measured. This is then converted to a quasilogarithmic *K* integer, $0, 1, 2, \ldots, 9$, according to a scale that is specific to each observatory and which is designed to normalize the occurrence frequency of individual *K* values among the many observatories and over many years.

A qualitative understanding of the *K* index and its calculation can be obtained from Figure M32. There we show a trace, Figure M32a, of the horizontal intensity at the Fredericksburg observatory recording magnetically quiet conditions during days 299–301 of 2003, followed by the sudden commencement in day 302 and the subsequent development of the main and recovery phases of the so-called great Halloween Storm. In Figure M32b we show, on a logarithmic scale, the range of the Fredericksburg data over discrete 3-h intervals, and in Figure M32c we show the *K* index values themselves. Note the close correspondence between the magnetogram, the log of the range and the *K* index. This storm is one of the 10 largest in the past 70 years since continuous measurements of storm size have been routinely undertaken. For more information on this particular storm, see the special issue of the *Journal of Geophysical Research*, A9, **110**, 2005.

Planetary-scale magnetic activity is measured by the K_p index (Menvielle and Berthelier, 1991). This is derived from the average of fractional *K* indices at 13 subauroral observatories (Table M1) in such a way as to compensate for diurnal and seasonal differences between the individual observatory *K* values. The final K_p index has values $0, 0.3, 0.7, 1.0, 1.3, \ldots$ etc. For illustration, in Figure M33 we show magnetograms from the 13 observatories contributing to K_p, recording the Halloween Storm of 2003, along with the K_p index itself. The distribution of observatories is far from uniform, with a predominant representation from North America and Europe, and very little representation from the southern hemisphere. In fact, in Figure M33, it is easy to see differences during the storm in the magnetograms among the different regional groupings of observatories. Although geographic bias is an obvious concern for any index intended as a measure of planetary-scale magnetic activity, K_p has proven to be very useful for scientific study (e.g., Thomsen, 2004). And, since it has been continuously calculated since 1932, K_p lends itself to studies of magnetic disturbances occurring over many solar cycles.

There are several other indices related to the *K* and K_p. A_k and A_p are linear versions of *K* and K_p. K_n, A_n, K_s, and A_s are similar to K_p and A_p except that they use, respectively, northern and southern hemisphere observatories; their global averages are K_m and A_m. The *aa* index is like the K_p except that it utilizes only two, roughly antipodal, observatories, one in the northern hemisphere and one in the southern hemisphere. *aa* has been continuously calculated since 1868, making it one of the longest historical time series in geophysics.

Auroral electrojet indices AU, AL, AE, AO

During magnetic storms, particularly during substorms, magnetospheric electric currents are often diverted along field lines, with

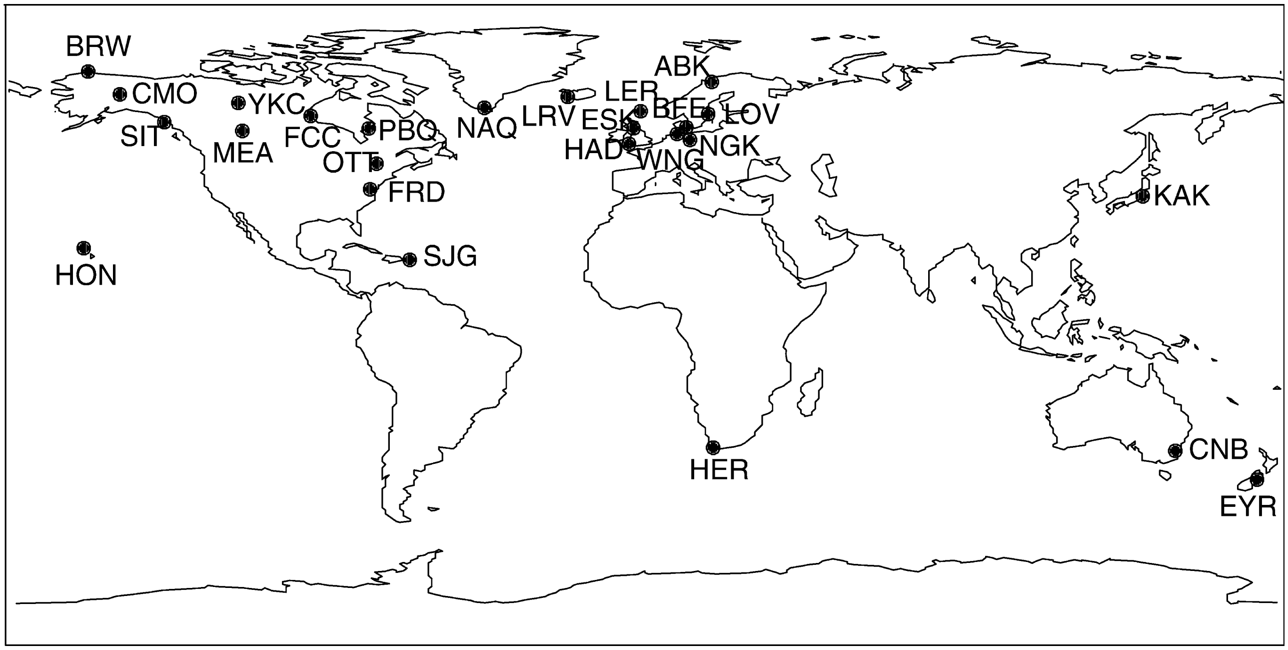

Figure M31 Map showing geographic distribution of magnetic index observatories.

Table M1 Summary of index observatories used here

Agency	Country	Observatory	Observatory	Index
Geoscience Australia	Australia	Canberra	CNB	K_p
Geological Survey of Canada	Canada	Fort Churchill	FCC	AE
Geological Survey of Canada	Canada	Meanook	MEA	K_p
Geological Survey of Canada	Canada	Ottawa	OTT	K_p
Geological Survey of Canada	Canada	Poste-de-la-Baleine	PBQ	AE
Geological Survey of Canada	Canada	Yellowknife	YKC	AE
Danish Meteorological Institute	Denmark	Brorfelde	BFE	K_p
Danish Meteorological Institute	Denmark	Narsarsuaq	NAQ	AE
GeoForschungsZentrum Potsdam	Germany	Niemegk	NGK	K_p
GeoForschungsZentrum Potsdam	Germany	Wingst	WNG	K_p
University of Iceland	Iceland	Leirvogur	LRV	AE
Japan Meteorological Agency	Japan	Kakioka	KAK	D_{st}
Geological and Nuclear Science	New Zealand	Eyerewell	EYR	K_p
National Research Foundation	South Africa	Hermanus	HER	D_{st}
Swedish Geological Survey	Sweden	Abisko	ABK	AE
Swedish Geological Survey	Sweden	Lovoe	LOV	K_p
British Geological Survey	United Kingdom	Eskdalemuir	ESK	K_p
British Geological Survey	United Kingdom	Hartland	HAD	K_p
British Geological Survey	United Kingdom	Lerwick	LER	K_p
US Geological Survey	United States	Barrow	BRW	AE
US Geological Survey	United States	College	CMO	AE
US Geological Survey	United States	Fredericksburg	FRD	K_p
US Geological Survey	United States	Honolulu	HON	D_{st}
US Geological Survey	United States	San Juan	SJG	D_{st}
US Geological Survey	United States	Sitka	SIT	K_p

current closure through the ionosphere. To measure the auroral zone component of this circuit, Davis and Sugiura (1966) defined the auroral electrojet index AE. Ideally, the index would be derived from data collected from an equally spaced set of observatories forming a necklace situated underneath the northern and southern auroral ovals. Unfortunately, the southern hemispheric distribution of observatories is far too sparse for reasonable utility in calculating AE, and the northern hemispheric observatories only form a partial necklace, due to the present shortage of reliable observatory operations in northern Russia. Progress is continuing, of course, to remedy this shortcoming, but for

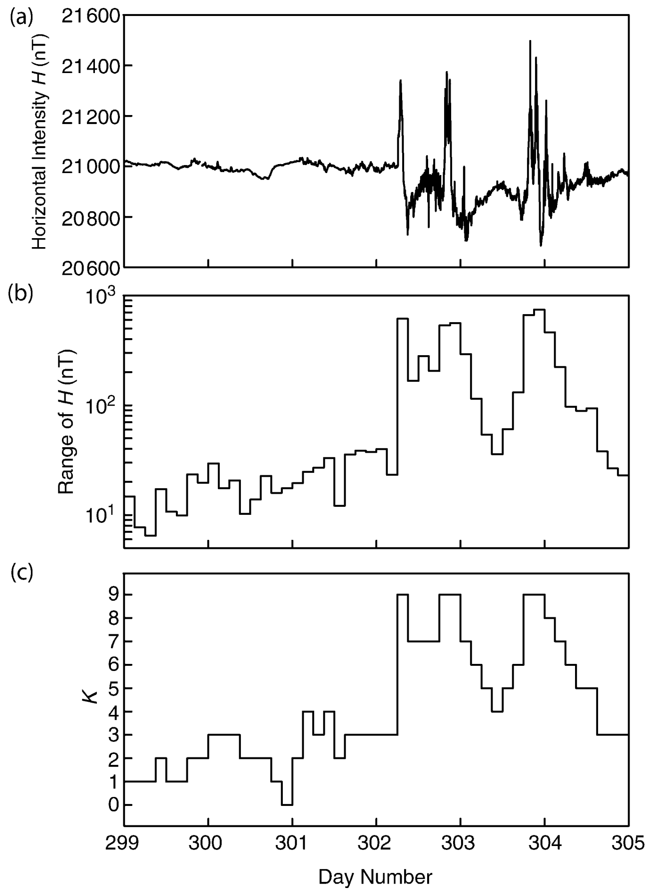

Figure M32 Example of (a) magnetometer data, horizontal intensity (H) from the Fredericksburg observatory recording the Halloween Storm of 2003, (b) the maximum range of H during discrete 3 h intervals, and (c) the K index for Fredericksburg.

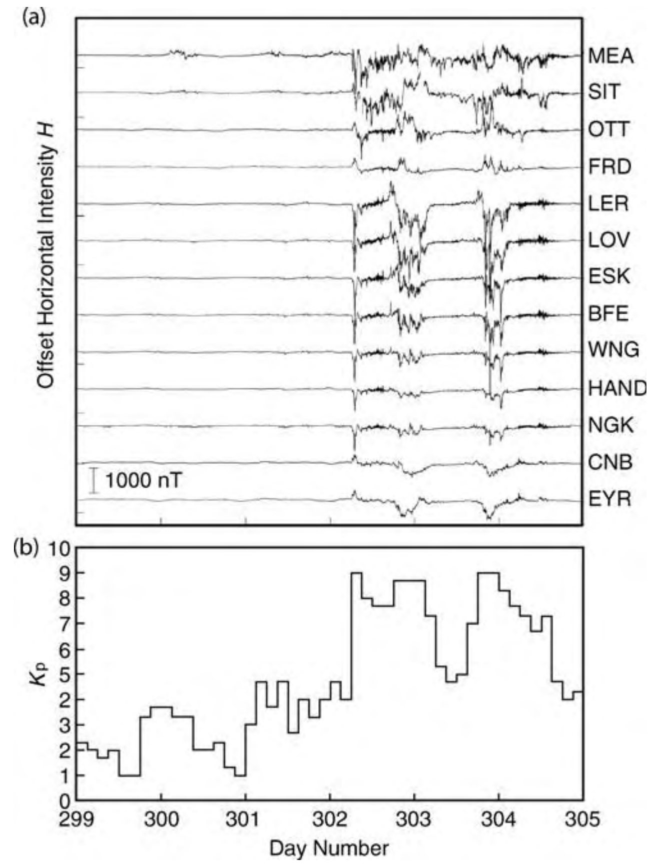

Figure M33 Example of (a) magnetometer data, horizontal intensity (H), from the observatories used in the calculation of the K_p index, together with (b) the corresponding K_p index. The observatories have been grouped into North American, European, and southern hemisphere regions in order to highlight similarities of the data within each region and differences in the data across the globe.

now the partial necklace of northern hemisphere observatories is used to calculate an approximate AE.

The calculation of AE is relatively straightforward. One-min resolution data from auroral observatories are used, and the average horizontal intensity during the five magnetically quietest days is subtracted. The total range of the data from among the various AE observatories for each minute is measured, with AU being the highest value and AL being the lowest value. The difference is defined as $AE = AU - AL$, and for completeness the average is also defined as $AO = 1/2(AU - AL)$. For illustration, in Figure M34, we show magnetograms from the eight auroral observatories contributing to AE, during the Halloween Storm of 2003, along with the AE and its attendant relatives.

Equatorial storm indices D_{st} and A_{sym}

One of the most systematic effects seen in ground-based magnetometer data is a general depression of the horizontal magnetic field as recorded at near-equatorial observatories (Moos, 1910). This is often interpreted as an enhancement of a westward magnetospheric equatorial ring current, whose magnetic field at the Earth's surface partially cancels the predominantly northerly component of the main field. The storm-time disturbance index D_{st} (Sugiura, 1964) is designed to measure this phenomenon. D_{st} is one of the most widely used indices in academic research on the magnetosphere, in part because it is well motivated by a specific physical theory.

The calculation of D_{st} is generally similar to that of AE, but it is more refined, since the magnetic signal of interest is quite a bit smaller. One-min resolution horizontal intensity data from low-latitude observatories are used, and diurnal and secular variation baselines are subtracted. A geometric adjustment is made to the resulting data from each observatory so that they are all normalized to the magnetic equator. The average, then, is the D_{st} index. It is worth noting that, unlike the other indices summarized here, D_{st} is not a range index. Its relative A_{sym} is a range index, however, determined by the difference between the largest and smallest disturbance field among the four contributing observatories.

In Figure M35 we show magnetograms from the four observatories contributing to D_{st} and A_{sym}, for the Halloween storm of 2003, along with the indices themselves. The commencement of the storm is easily identified, and although the magnetic field is very disturbed during the first hour or so of the storm, the disturbance shows pronounced longitudinal difference, and hence a dramatically enhanced A_{sym}. With the subsequent worldwide depression of H through to the beginning of day 303 the storm is at its main phase of development. During this time D_{st} becomes increasingly negative. It is of interest to note that it is during this main phase that AE is also rapidly variable, signally the occurrence of substorms with the closure of magnetospheric electric currents through the ionosphere. AE diminishes during the recovery period of the storm as D_{st} also pulls back for its most negative values and A_{sym} is diminished. Toward the end of day 303 the second act of this complicated storm begins, with a repeat of the observed relationships of the various indices.

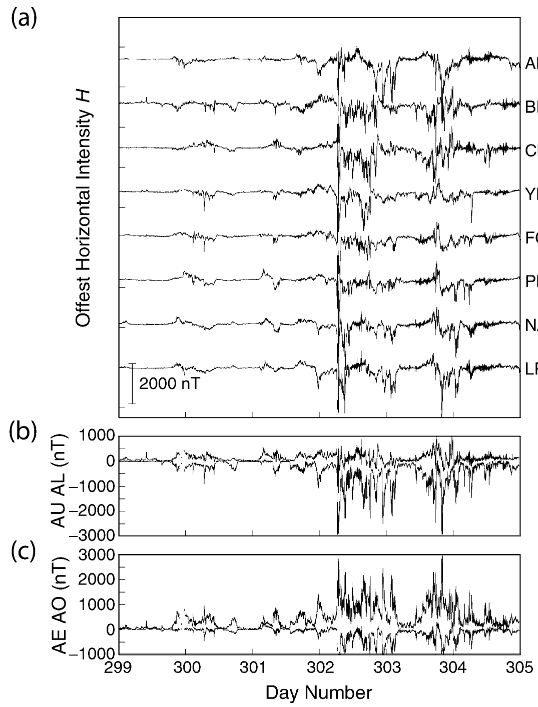

Figure M34 Example of (a) magnetometer data, horizontal intensity (H), from the observatories used in the calculation of the AE indices, together with (b) the corresponding AU and AL indices and the (c) AE and AO indices.

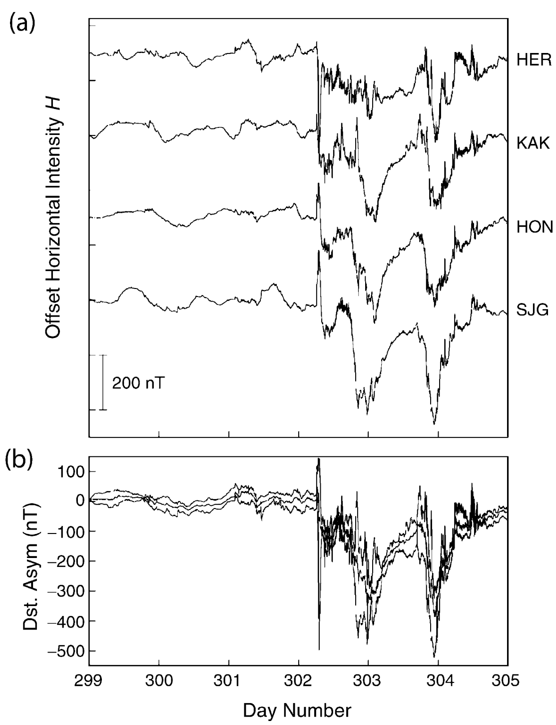

Figure M35 Example of (a) magnetometer data, horizontal intensity (H), from the observatories used in the calculation of the D_{st} indices, together with (b) the corresponding D_{st} plotted as the center trace and the maximum and minimum disturbance values, the difference of which is A_{sym}.

Availability

Magnetic indices are routinely calculated by a number of different agencies. Intermagnet agencies routinely calculate K indices for their observatories (www.intermagnet.org). The GeoForschungsZentrum in Potsdam calculates K_p (www.gfz-potsdam.de). The Kyoto World Data Center calculates AE and D_{st} (swdcwww.kugi.kyoto-u.ac.jp). Other agencies supporting the archiving and distribution of the indices include the World Data Centers in Copenhagen (web.dmi.dk/fsweb/projects/wdcc1) and Boulder (www.ngdc.noaa.gov), as well as the International Service of Geomagnetic Indices in Paris (www.cetp.ipsl.fr).

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Bibliography

Bartels, J., 1938. Potsdamer erdmagnetische Kennziffern, 1 Mitteilung. *Zeitschrift für Geophysik*, **14**: 68–78, 699–718.
Davis, T.N., and Sugiura, M., 1966. Auroral electrojet activity index AE and its universal time variations. *Journal of Geophysical Research*, **71**: 785–801.
Mayaud, P.N., 1980. *Derivation, Meaning, and Use of Geomagnetic Indices, Geophysical Monograph 22.* Washington, DC: American Geophysical Union.
McPherron, R.L., 1995. Standard indices of geomagnetic activity. In Kivelson, M.G., and Russell, C.T. (eds.), *Introduction to Space Physics.* Cambridge, UK: Cambridge University Press, pp. 451–458.
Menvielle, M., and Berthelier, A., 1991. The K-derived planetary indices—description and availability. *Reviews of Geophysics*, **29**: 415–432.
Moos, N.A.F., 1910. *Colaba Magnetic Data, 1846 to 1905. 2. The Phenomenon and its Discussion.* Bombay, India: Central Government Press.
Rangarajan, G.K., 1989. Indices of geomagnetic activity. In Jacobs, J.A. (ed.), *Geomagnetism* , Vol. 2. London, UK: Academic Press, pp. 323–384.
Sugiura, M., 1964. Hourly values of equatorial D_{st} for the IGY. *Annals of the International Geophysical Year*, **35**: 945–948.
Thomsen, M.F., 2004. Why K_p is such a good measure of magnetospheric convection. *Space Weather*, **2**: S11004, doi:10.1029/2004SW000089.

Cross-references

IAGA, International Association of Geomagnetism and Aeronomy
Ionosphere
Magnetosphere of the Earth

MAGNETIC MINERALOGY, CHANGES DUE TO HEATING

Mineralogical alterations occur very often in rocks subjected to thermal treatment. Laboratory heating may cause, in many cases, not only magnetic phase transformations, but also changes in the effective magnetic grain sizes, the internal stress, and the oxidation state. The presence or absence of such alterations is crucial to the validity and success of numerous magnetic studies.

The basic assumption in paleointensity determinations in the measurement of anisotropy of thermoremanent magnetization is that the rock is not modified during the different successively applied heating treatments. For simple thermal demagnetization, the occurrence of mineralogical alteration can introduce errors in the determination of the magnetic carrier if the latter had undergone transformation a at lower