Chapter 5
The Earth's dipole field and its temporal variations

Previously

- Basic assumption: the Earth's main field can be represented as a superposition of the magnetic fields created by several multipole magnets located at the center of the Earth.
- The simplest multipole magnet is the dipole, then quadrupole (four poles), octupole (eight poles), etc.
- The International Geomagnetic Reference Field (IGRF) is a series of mathematical models of the Earth's main field and its annual rate of change (secular variation). In source-free regions at the Earth's surface and above, the main field, with sources internal to the Earth, is the negative gradient of a scalar potential U_i which can be represented by a truncated series expansion:

$$U_i(r,\theta,\varphi,t) = R_E \sum_{n=1}^{n_{max}} \left[\left(\frac{R_E}{r} \right)^{n+1} \sum_{m=0}^{n} \left(g_n^m(t) \cos m\varphi + h_n^m(t) \sin m\varphi \right) SP_n^m(\cos\theta) \right]$$

- The most recent 12th Generation IGRF coefficients g_n^m and h_n^m can be found here: http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html

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- The Earth's magnetic poles
- Geomagnetic reversals
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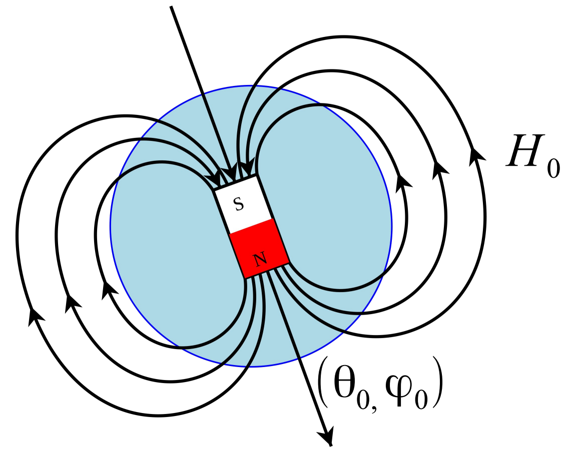
- Multipole expansion of the external sources of the Earth's magnetic field

Dipole component of the multipole expansion

Let us examine the simples multipole of the multipole expansion, the dipole $(n=1, m=0,1)$.
The components of the magnetic field are then:



$$X_i = -B_{\theta_i} = \left(\frac{R_E}{r}\right)^3 \left[-g_1^0 \sin\theta + (g_1^1 \cos\varphi + h_1^1 \sin\varphi)\cos\theta\right]$$

$$Y_i = B_{\varphi_i} = \left(\frac{R_E}{r}\right)^3 (g_1^1 \sin\varphi - h_1^1 \cos\varphi)$$

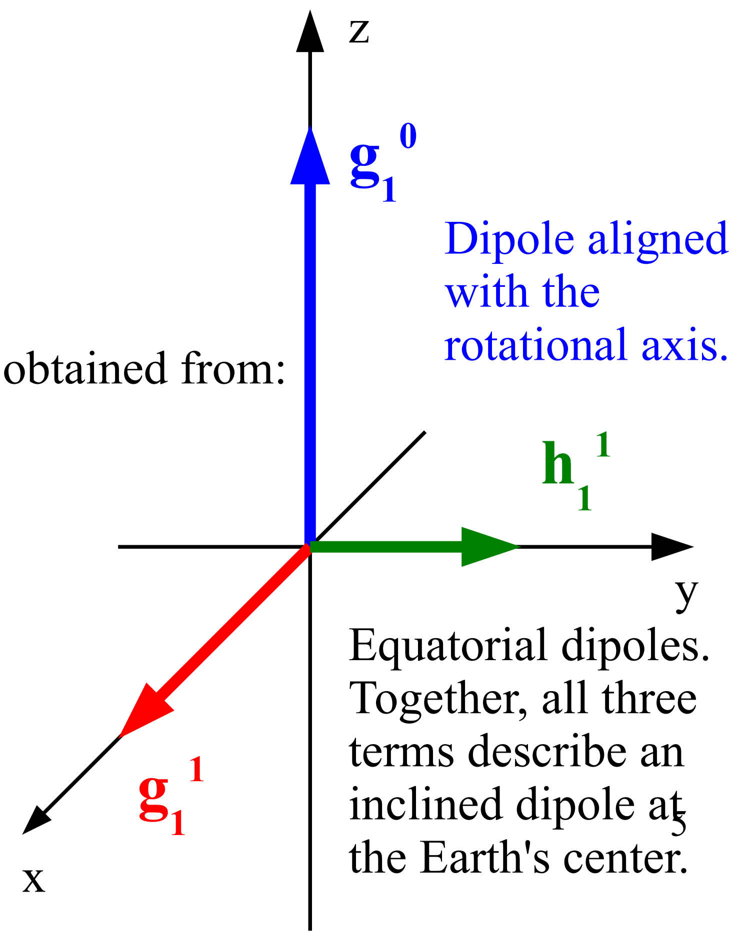
$$Z_i = -B_{r_i} = -2\left(\frac{R_E}{r}\right)^3 \left[g_1^0 \cos\theta + (g_1^1 \cos\varphi + h_1^1 \sin\varphi)\sin\theta\right]$$

Magnetic field strength at the equator

$$H_0 = \sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}$$

can be used to obtain the dipole moment m:

$$H_0 = \frac{\mu_0}{4\pi} \frac{m}{R_E^3}$$



The locations of the dipole (geomagnetic) poles $(\theta_{0,}\varphi_0)$ can be obtained from:

$$\theta_0 = \arctan\left(\frac{\sqrt{(g_1^1)^2 + (h_1^1)^2}}{g_1^0}\right)$$

$$\varphi_0 = \arctan\left(\frac{h_1^1}{g_1^1}\right)$$

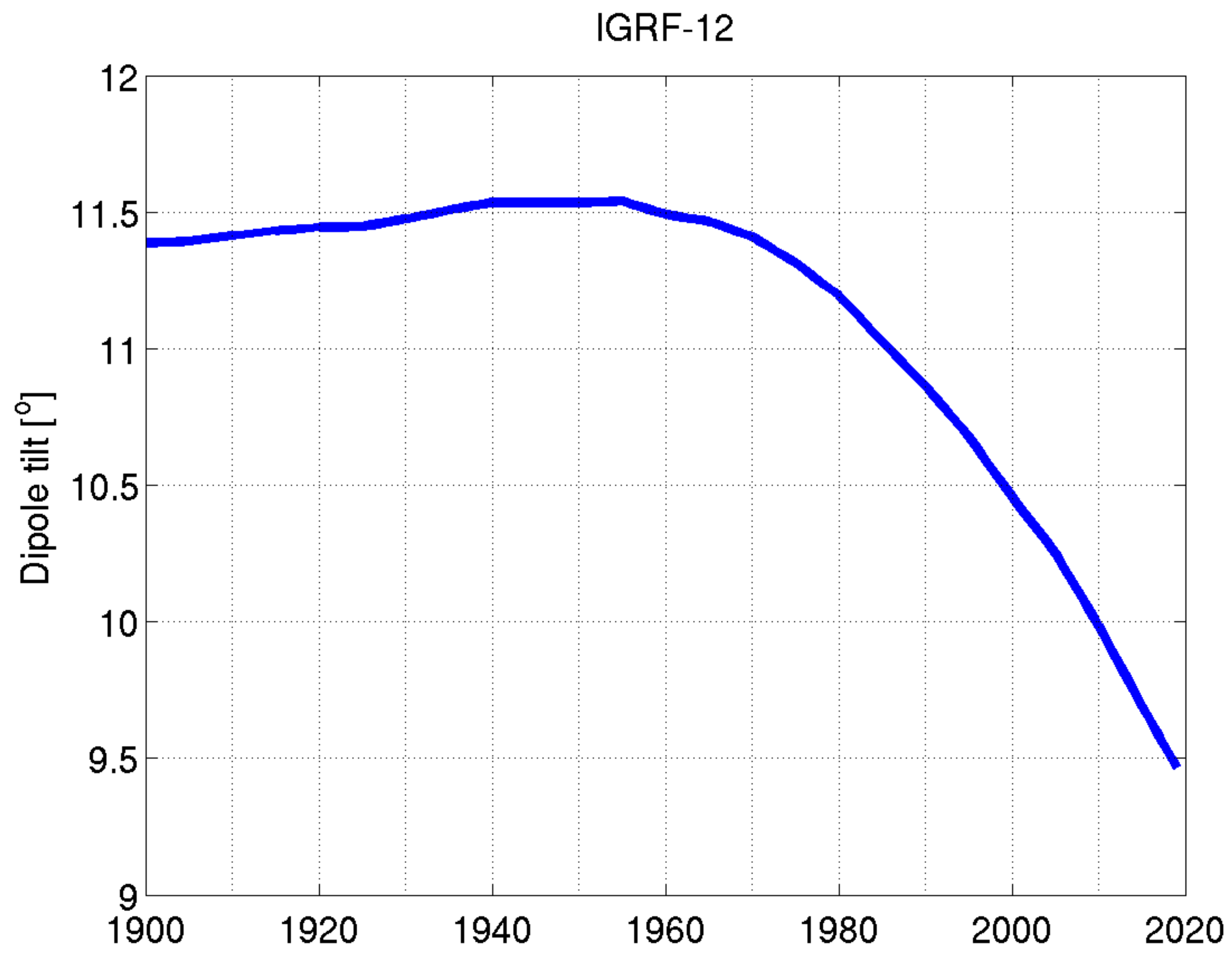
There are two poles, one in each hemisphere, where a line aligned with the dipole moment vector intersects the Earth's surface.

Example

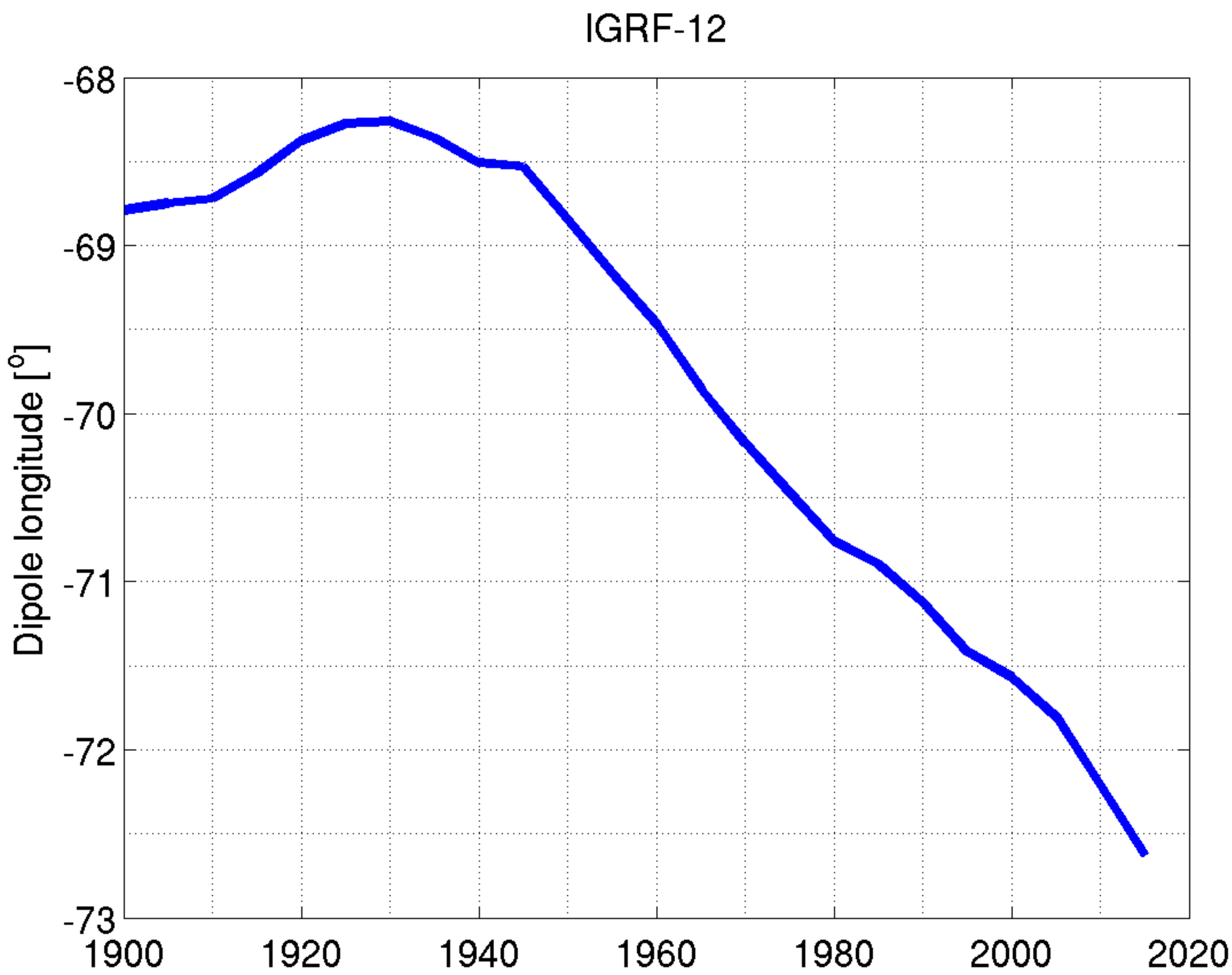
Matlab:

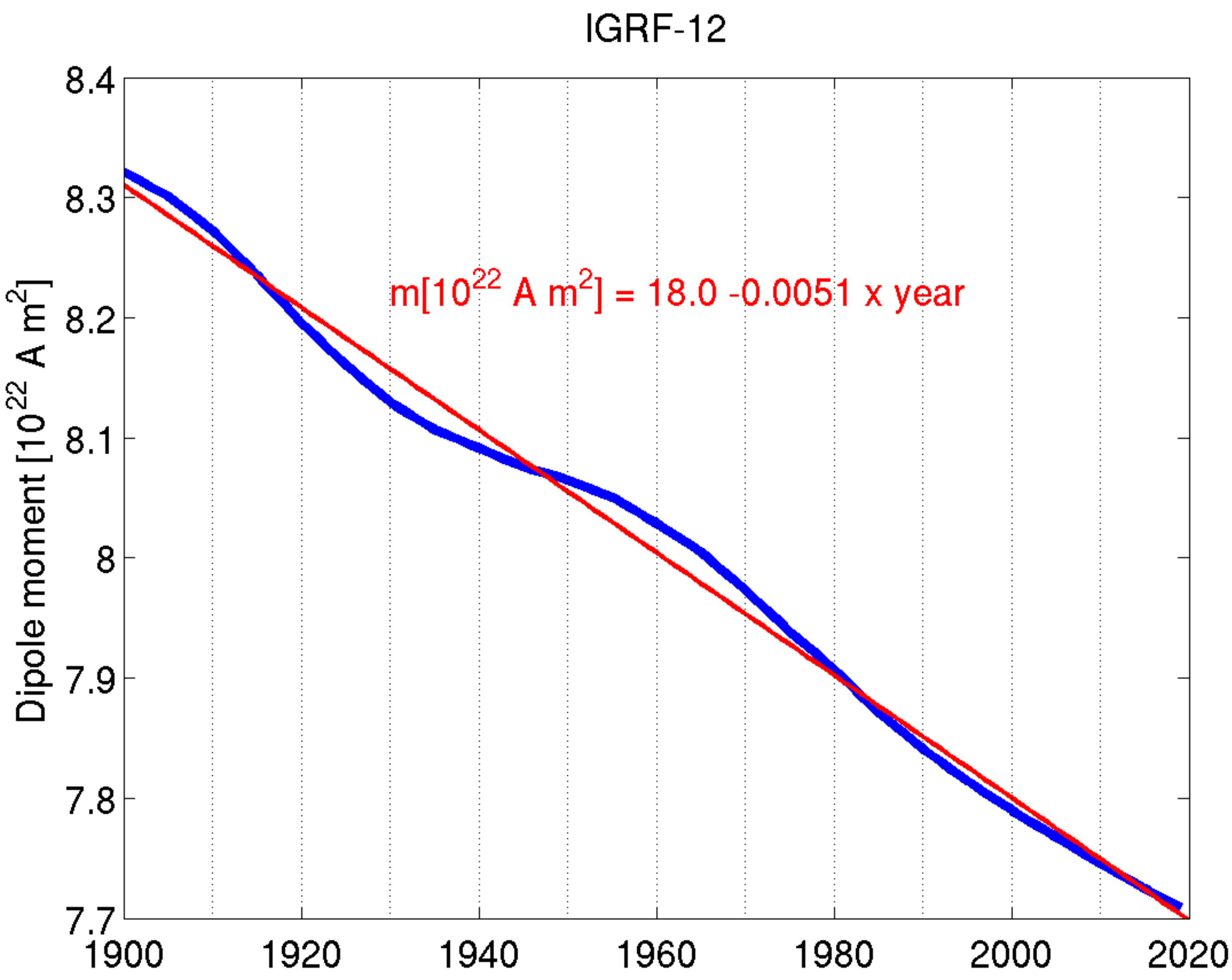
```
>> g10=-29422.0; % IGRF-12 2015.0
>> g11=-1501.0;
>> h11=4797.1;
>> lat = 90 - atan2(sqrt((g11)^2+(h11)^2),g10)/pi*180

lat =

  -80.3052

>> lon = atan2(h11,g11)/pi*180

lon =

  107.3748
```

IGRF-12 Epoch	North geomagnetic pole		South geomagnetic pole		Dipole moment [10^{22} A m^2]
	Latitude [º]	Longitude [º]	Latitude [º]	Longitude [º]	
1900.0	78.6	-68.8	-78.6	111.2	8.3
1905.0	78.6	-68.7	-78.6	111.3	8.3
1910.0	78.6	-68.7	-78.6	111.3	8.3
1915.0	78.6	-68.6	-78.6	111.4	8.2
1920.0	78.6	-68.4	-78.6	111.6	8.2
1925.0	78.6	-68.3	-78.6	111.7	8.2
1930.0	78.5	-68.3	-78.5	111.7	8.1
1935.0	78.5	-68.4	-78.5	111.6	8.1
1940.0	78.5	-68.5	-78.5	111.5	8.1
1945.0	78.5	-68.5	-78.5	111.5	8.1
1950.0	78.5	-68.8	-78.5	111.2	8.1
1955.0	78.5	-69.2	-78.5	110.8	8.1
1960.0	78.5	-69.5	-78.5	110.5	8.0
1965.0	78.5	-69.9	-78.5	110.1	8.0
1970.0	78.6	-70.2	-78.6	109.8	8.0
1975.0	78.7	-70.5	-78.7	109.5	7.9
1980.0	78.8	-70.8	-78.8	109.2	7.9
1985.0	79.0	-70.9	-79.0	109.1	7.9
1990.0	79.1	-71.1	-79.1	108.9	7.8
1995.0	79.3	-71.4	-79.3	108.6	7.8
2000.0	79.5	-71.6	-79.5	108.4	7.8
2005.0	79.7	-71.8	-79.7	108.2	7.8
2010.0	80.0	-72.2	-80.0	107.8	7.7
2015.0	80.3	-72.6	-80.3	107.4	7.7



IGRF-12
12
11.5
11
10.5
10
9.5
9
Dipole tilt [°]
1900
1920
1940
1960
1980
2000
2020


IGRF-12
Dipole longitude [°]
-68
-69
-70
-71
-72
-73
1900
1920
1940
1960
1980
2000
2020



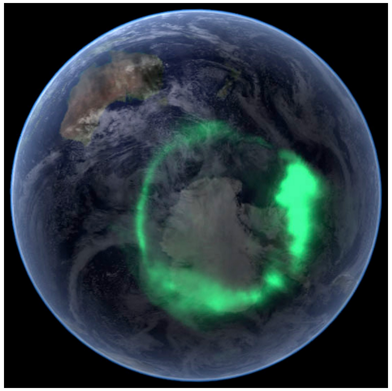
IGRF-12
m[10^22 A m^2] = 18.0 -0.0051 x year
Dipole moment [10^22 A m^2]
8.4
8.3
8.2
8.1
8
7.9
7.8
7.7
1900
1920
1940
1960
1980
2000
2020

The Earth's magnetic poles

The experimental determination of the locations of the dip (magnetic) poles is difficult:

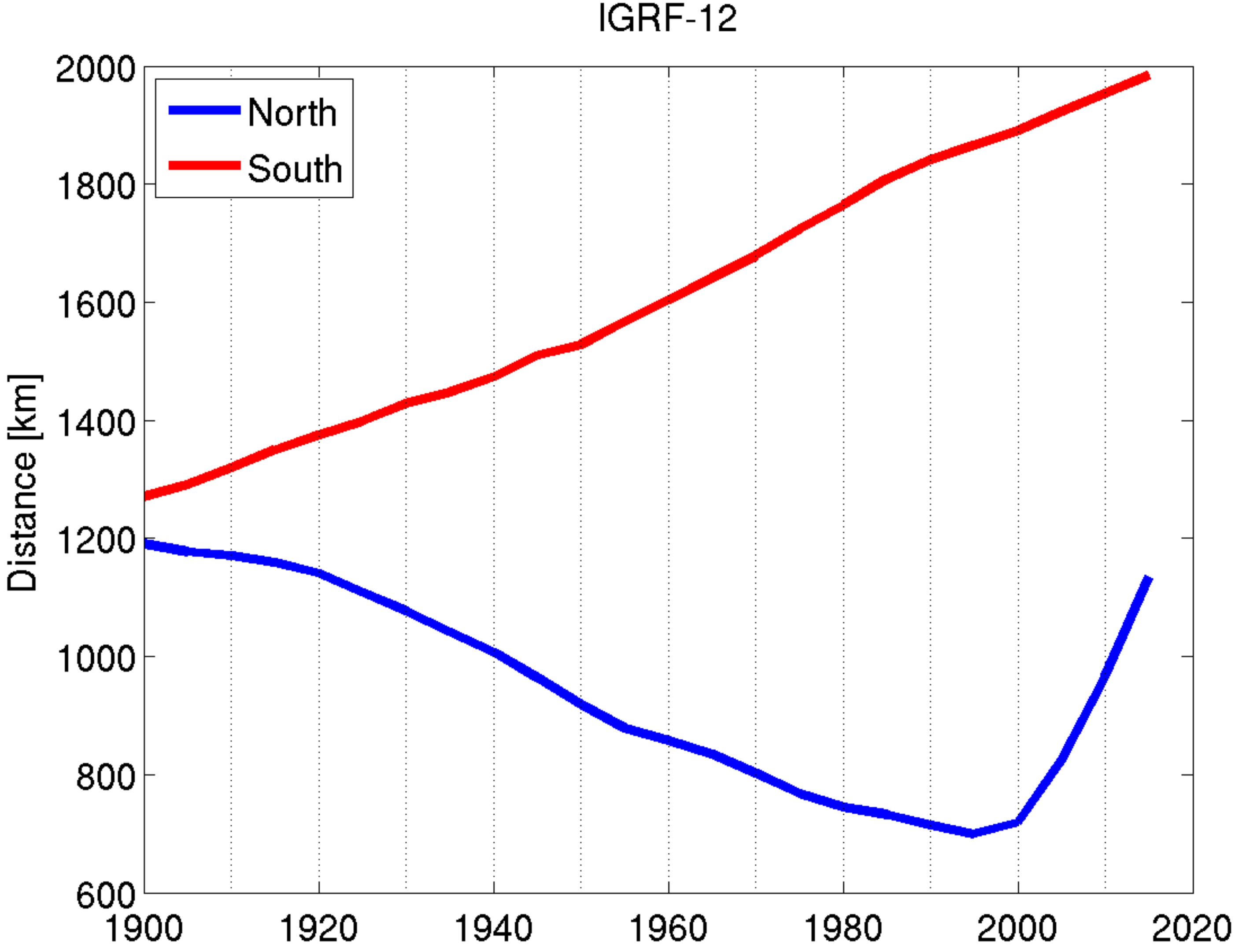
- Remoteness and harsh climatic conditions
- Rapidly varying magnetic fields which originate in a region of near-Earth space called the magnetosphere
  - Many dynamic electrical current systems exist on the surface of, and inside the magnetosphere and are connected to the ionized upper atmosphere at high latitudes.
  - As a result, the dip poles move considerable distances over one day, tracing out approximately oval-shaped loci (longer axis varies from 10-50 km depending on the level of geomagnetic activity) on a daily basis. The geomagnetic pole is located at the center of the ellipse. Thus, finding the pole requires measurements from several locations around the assumed pole, to determine the shape of the ellipse.
- The presence of magnetic material in the underlying rocks, i.e., the crustal magnetic field
  - Not included in models such as the IGRF but may be another reason for differences between the model dip poles and measured dip poles.

- Although one cannot make any observations in the region of the geomagnetic poles that might indicate their positions, these poles are often considered to be of greater significance than the dip poles:
  - The auroral ovals, which are approximately 5° latitude bands where the aurora are likely to be seen, are centered on the geomagnetic poles. In relation to this, many coordinate systems used in studies of the Earth's magnetosphere have the dipole axis as one of their defining axes.
  - Magnetic field reversals are defined by the flipping of the geomagnetic poles. These ancient poles are defined by the direction of the ancient magnetic field frozen into certain kinds of rock, and in their derivation, make the assumption that the field is simply that of a tilted dipole located at the Earth's center.
- Unlike geomagnetic (dipole) poles, magnetic (dip) poles move independently from each other.
- The deviation from a symmetric location is thousands of km.

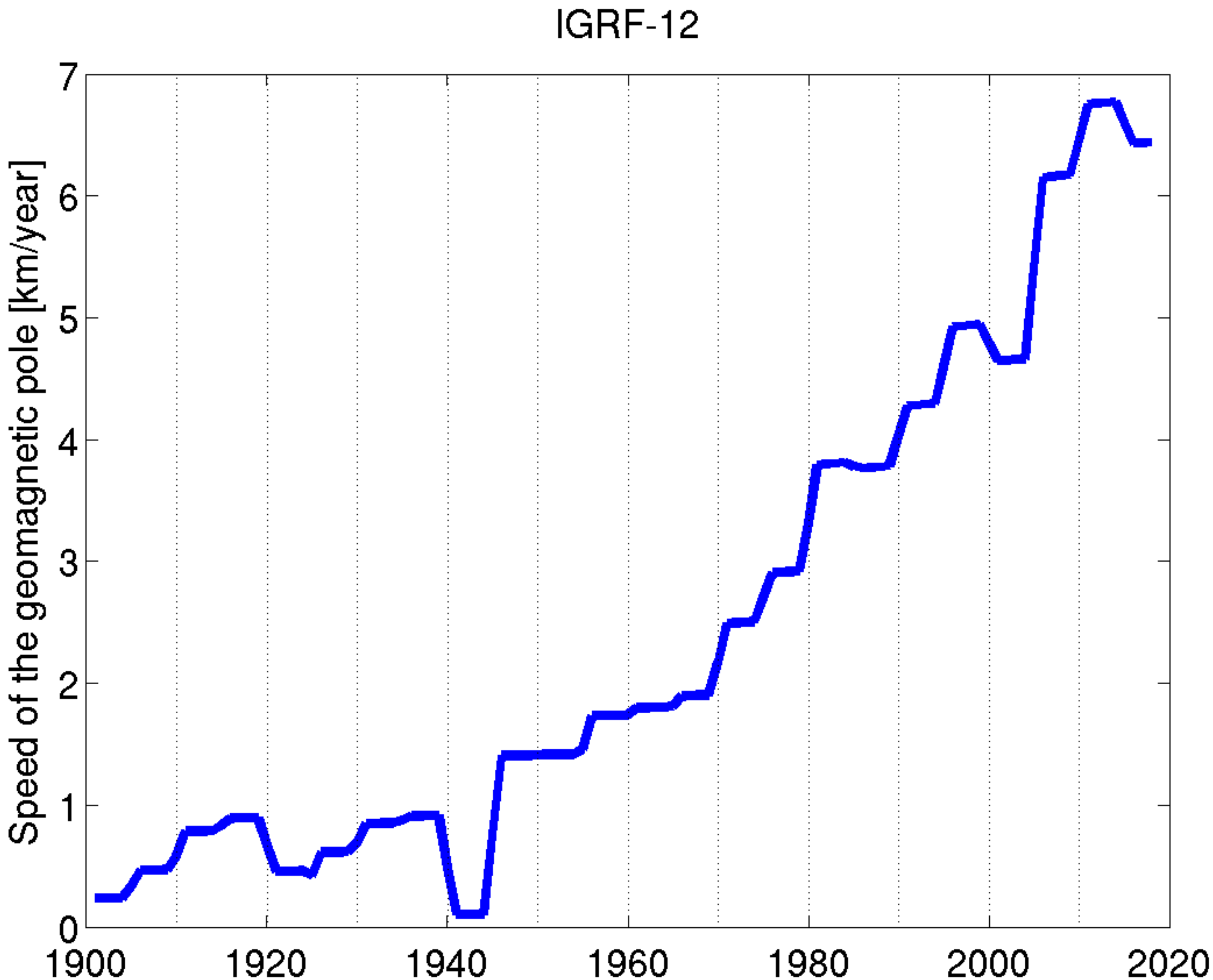


Aurora australis (11 September 2005) as captured by NASA's IMAGE satellite.

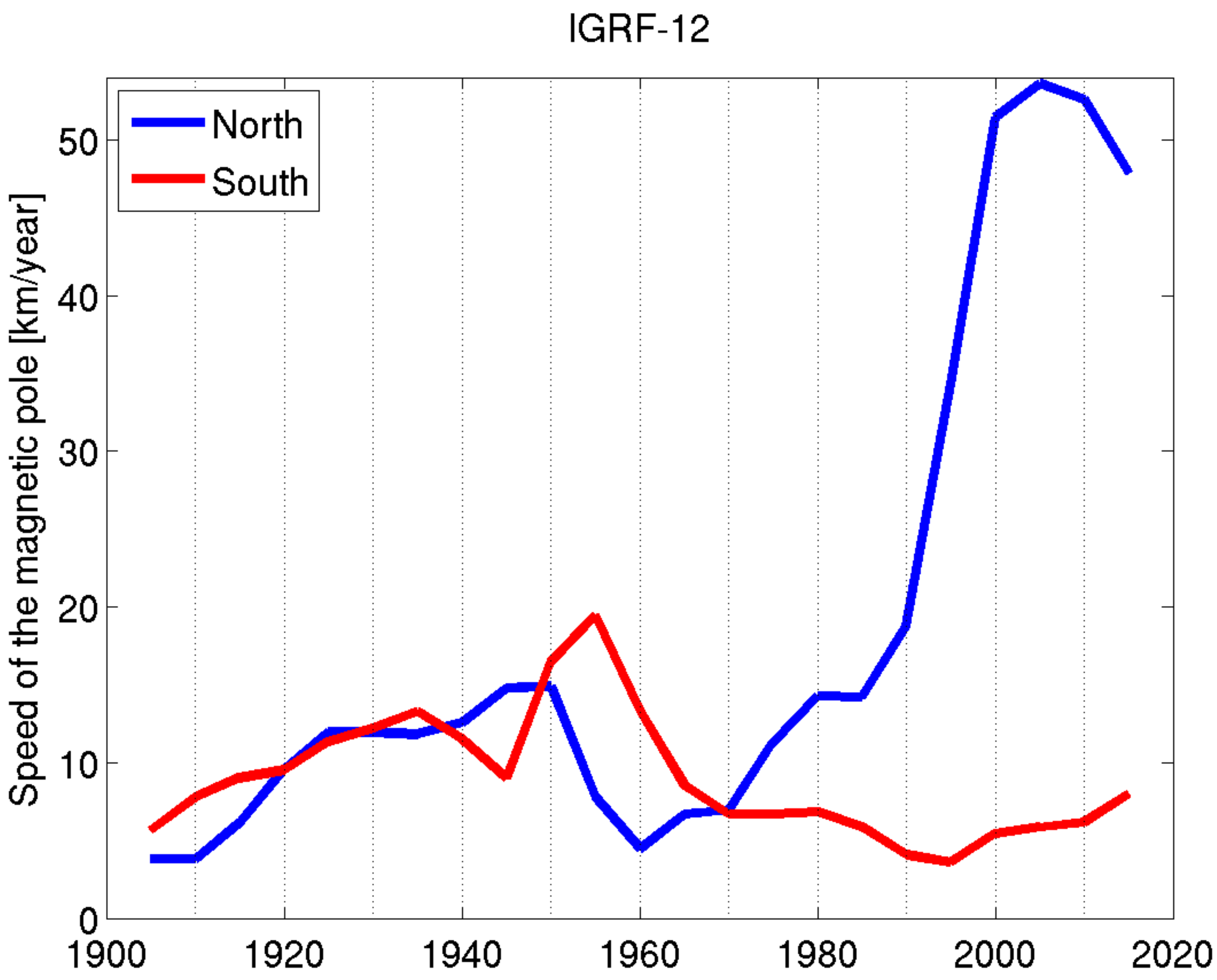
Distance between magnetic and geomagnetic pole



Speed of the geomagnetic poles

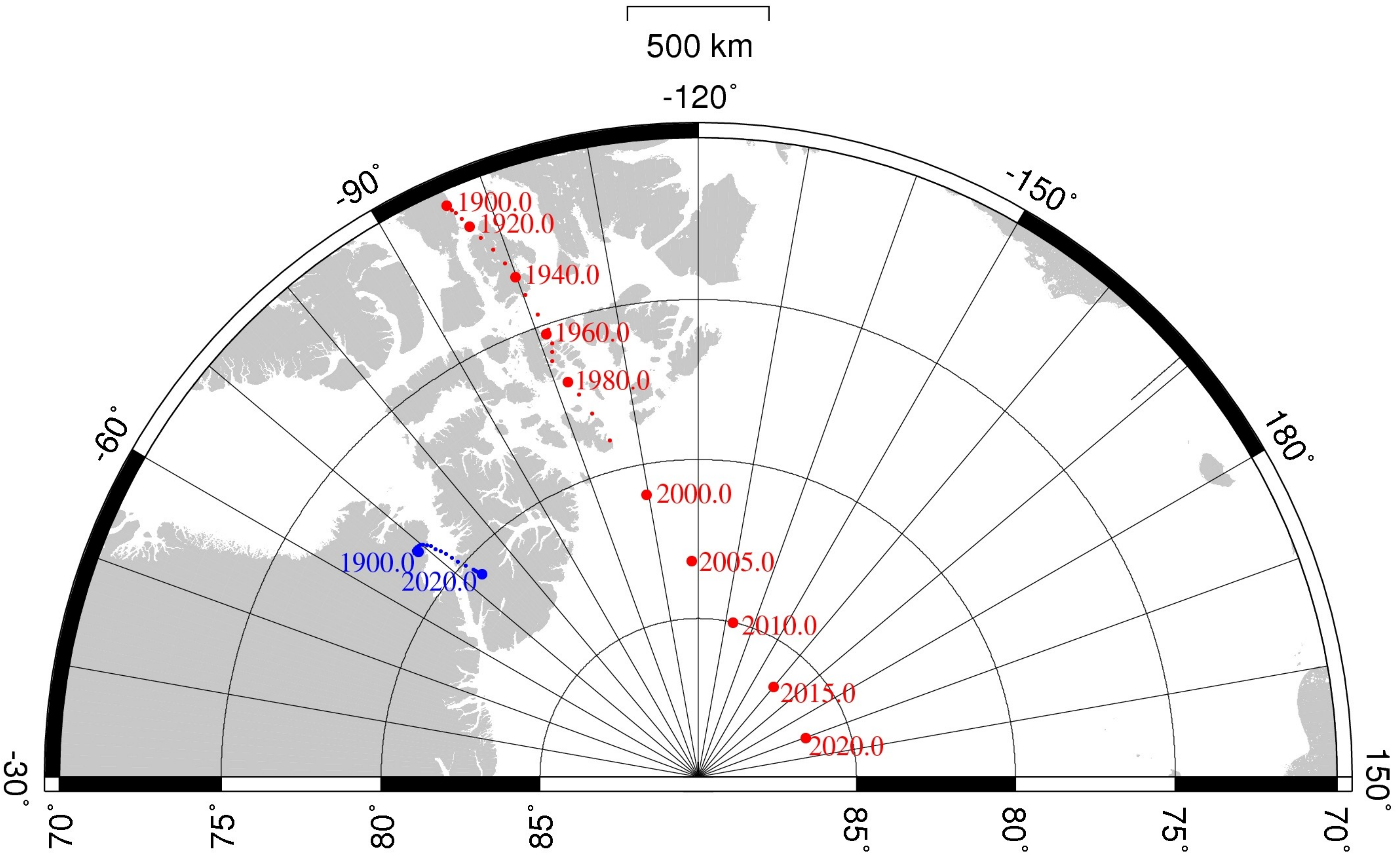


Speed of the magnetic poles

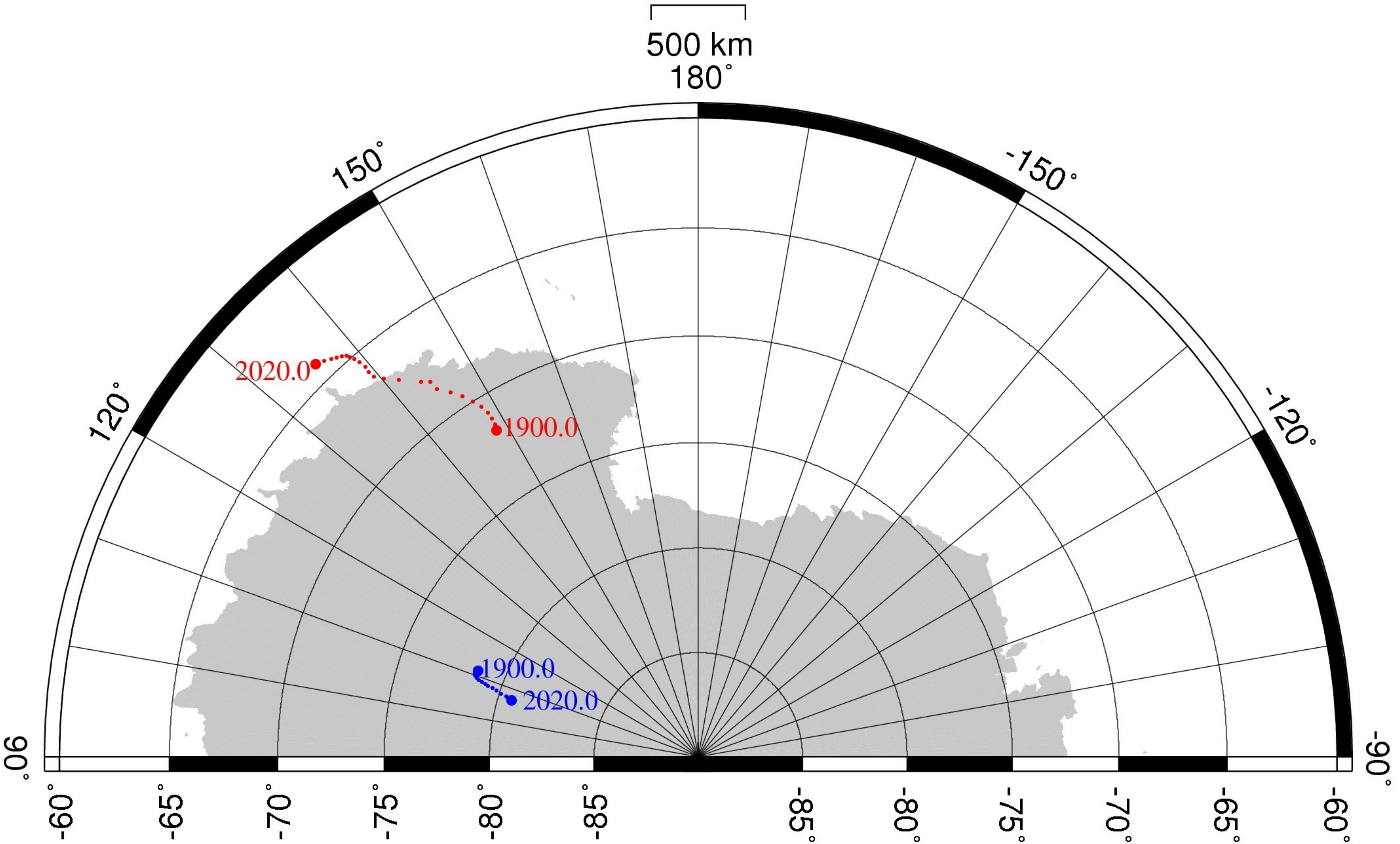


http://www.geomag.bgs.ac.uk/education/poles.html

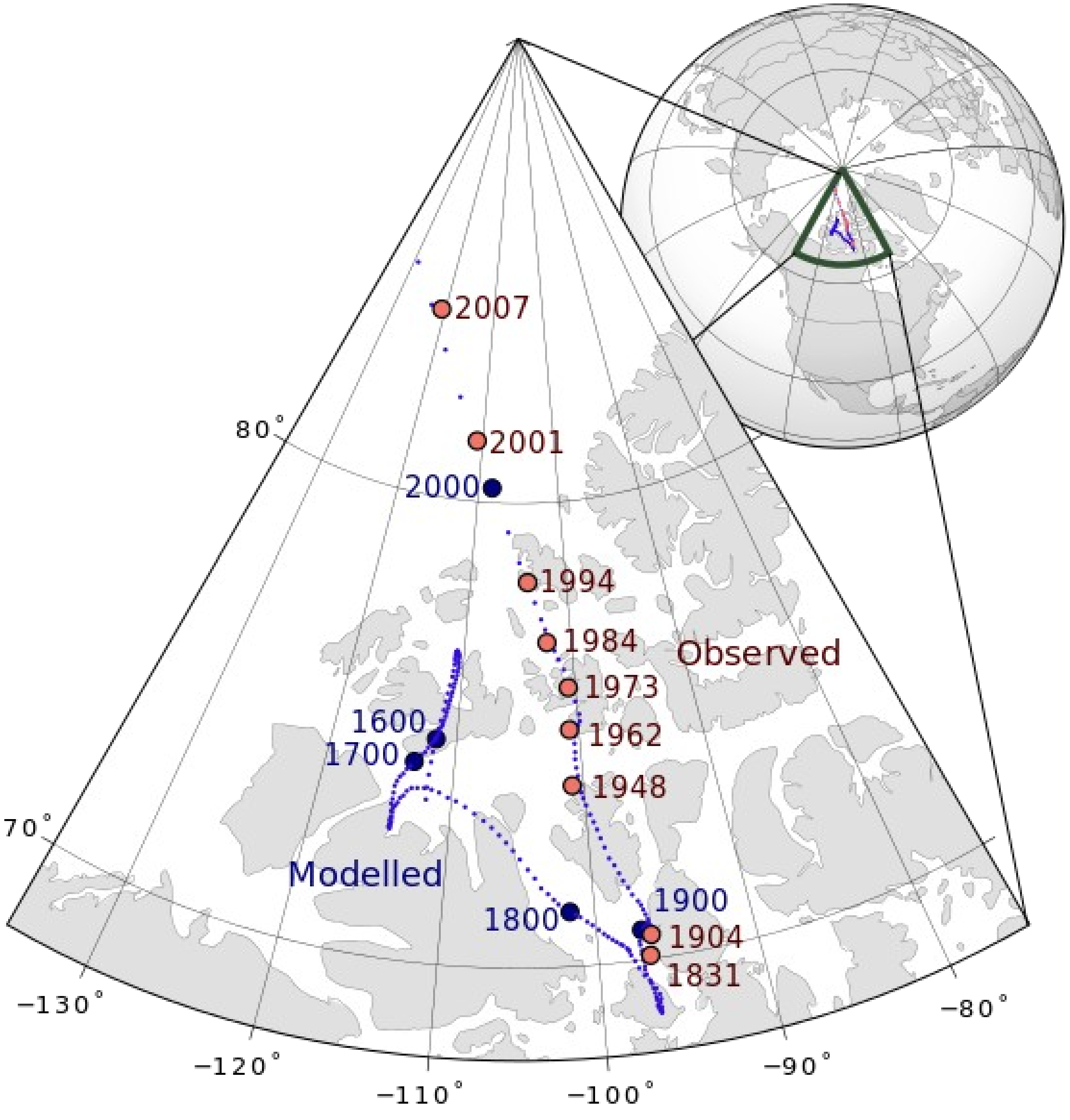
Positions of the north magnetic or dip pole (red) and the geomagnetic pole (blue) 1900.0-2020.0 estimated from IGRF-12



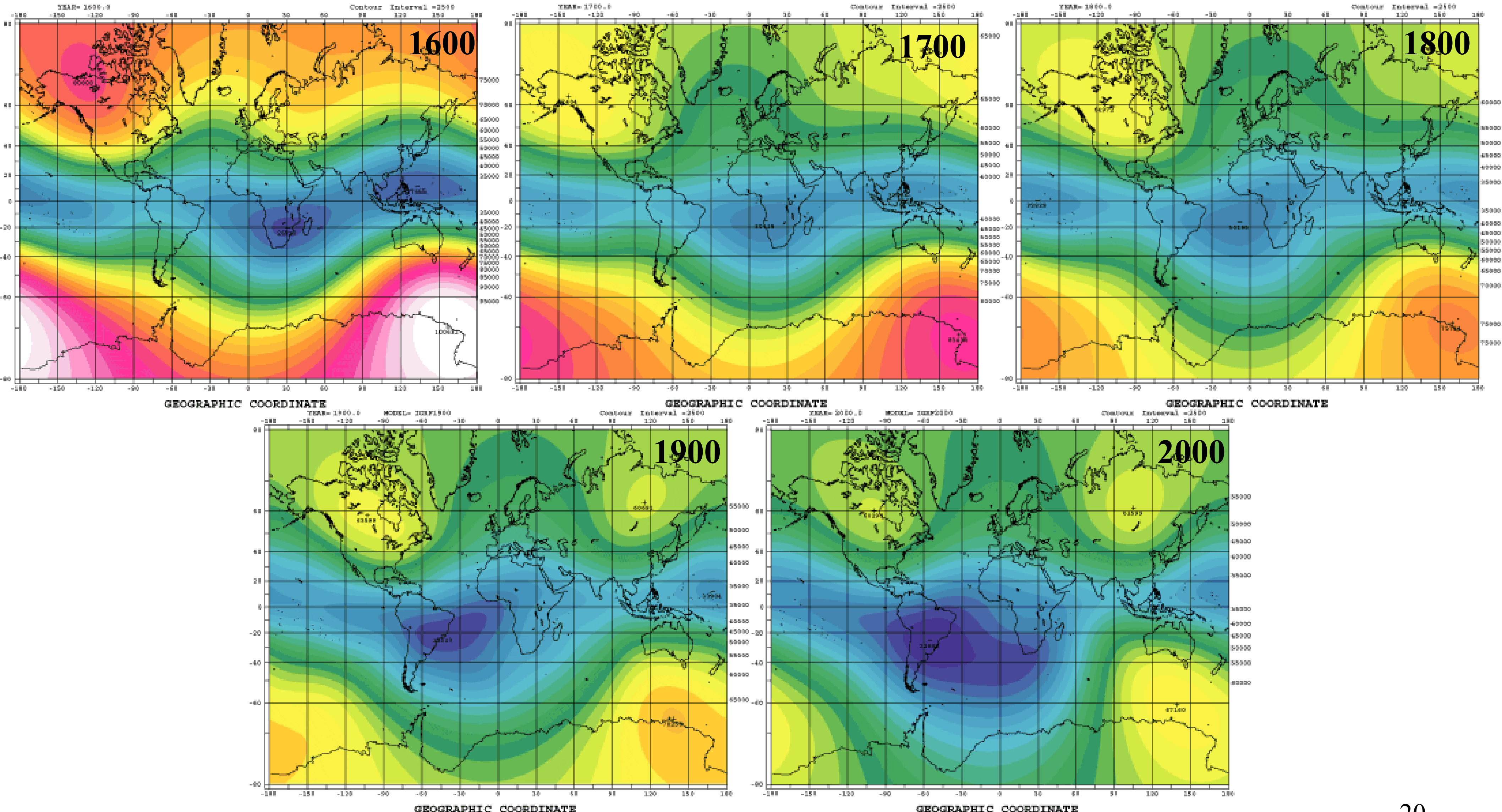
Positions of the south magnetic or dip pole (red) and the geomagnetic pole (blue) 1900.0-2020.0
estimated from IGRF-12



Motion of the Earth's magnetic north pole from 1600 to 2000

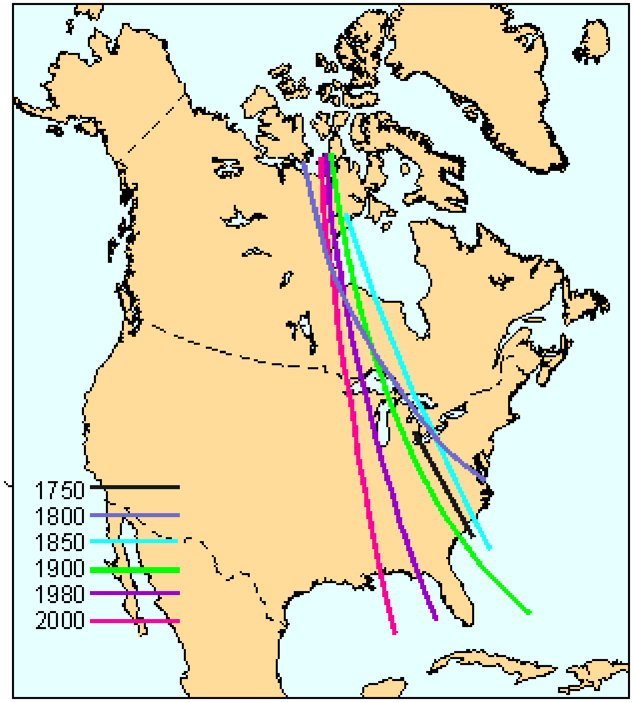


Secular variation in geomagnetic total intensity for the last 400 years



http://wdc.kugi.kyoto-u.ac.jp/igrf/anime/index.html

- Analysis of the secular variation show that most of it can be described in terms of three processes:
  - A decrease in the strength of the dipole part of the magnetic field.
  - A westward drift in the non-dipole part of the magnetic field.
  - Changes in the non-drifting part of the non-dipole field.
- At the short end of the secular variation time scale is the geomagnetic jerk, i.e., a relatively sudden change in the second derivative of the Earth's magnetic field with respect to time.
  - Jerks seem to occur in irregular intervals, on average about once every 10 years.
  - The strength of each jerk varies from location to location, and some jerks are observed only in some regions.
  - Global jerks seem to occur at slightly different times in different regions.
  - Jerks are believed to originate in the interior of the Earth (rather than being due to external phenomena such as the solar wind) but their precise cause is still a matter of research.

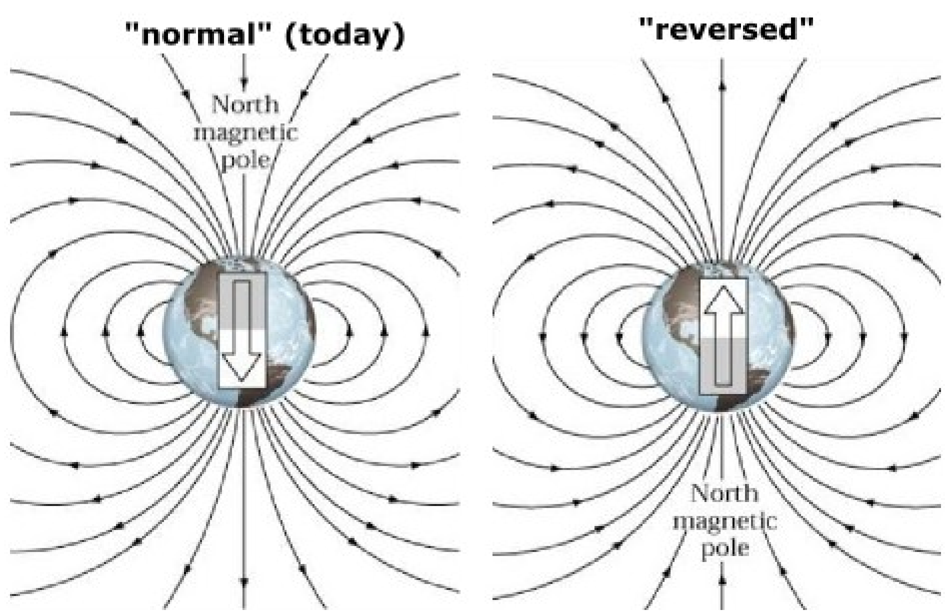


Drift of the agonic line (D=0°). From: http://geomag.nrcan.gc.ca/mag_fld/sec-eng.php

- The direction and speed of a magnetic pole depend on the distribution of the local anomalous (non-dipolar) field.
  - If the spatial gradients of the field are small, the pole can move long distances in a short time when the anomalous field changes.
  - If the spatial gradients are large, the pole may only move short distances even if the field changes significantly.
  - The different trajectories of the north and south magnetic pole (1600 → 2020) can be explained by the differences in the local anomalous fields.
- The sudden increase of the speed of the north magnetic pole is apparently associated with a global jerk of the anomalous field.

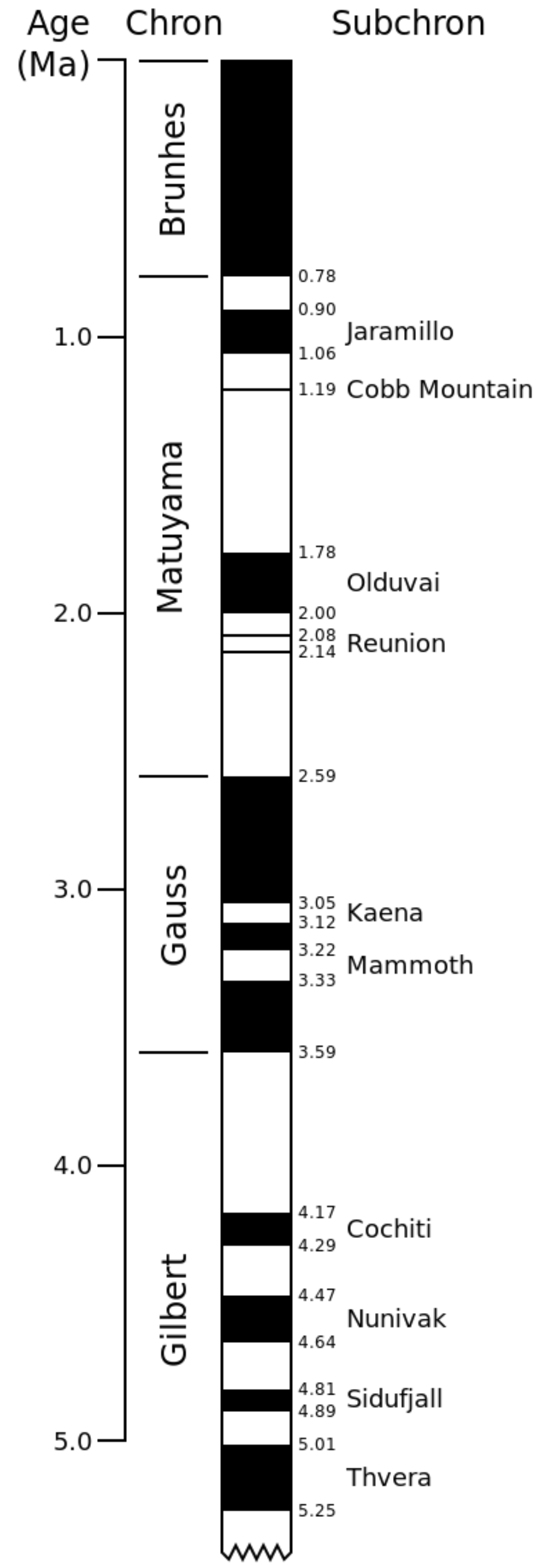
Geomagnetic reversals

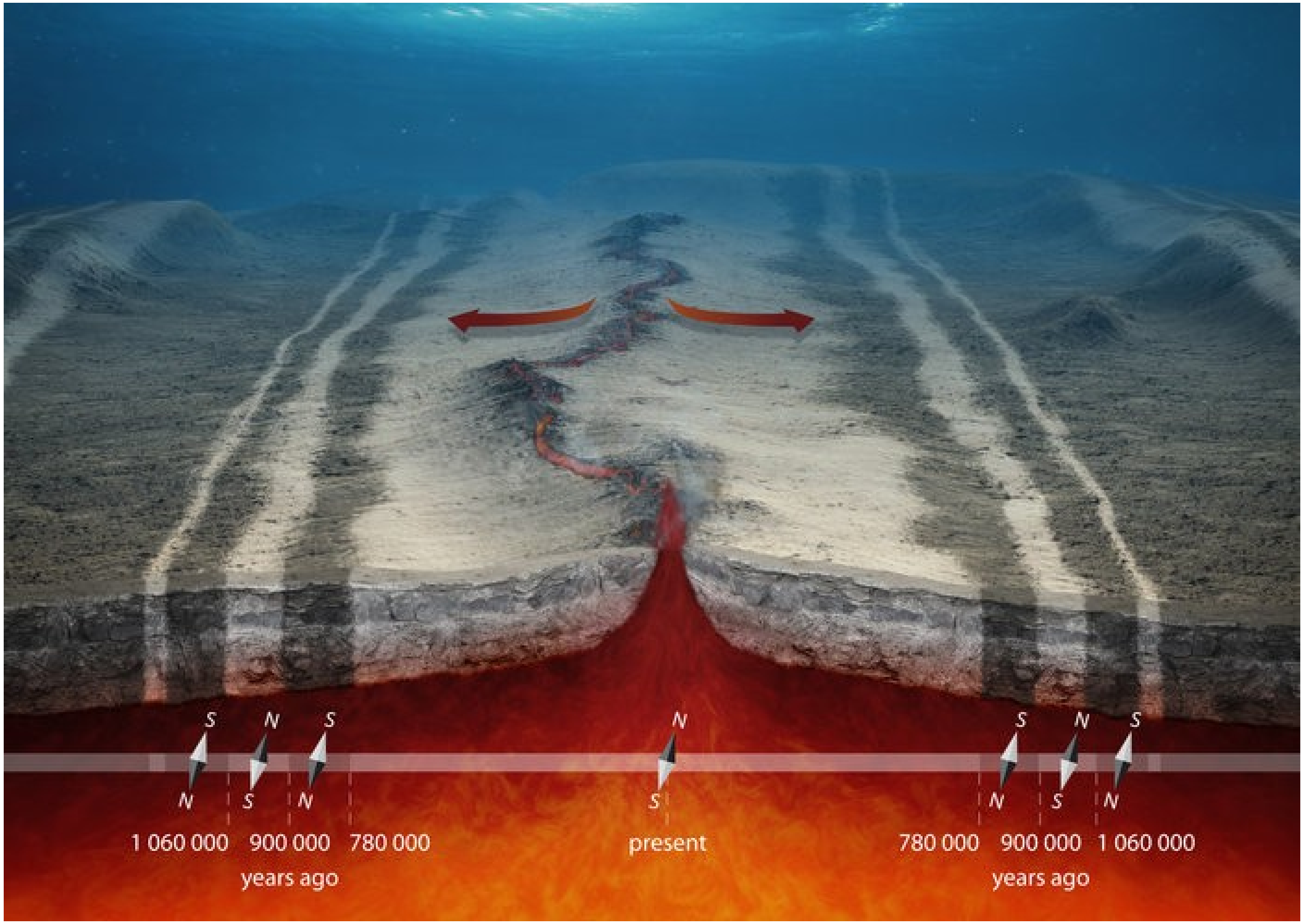
- A geomagnetic reversal is a change in the Earth's magnetic field such that the positions of magnetic north and magnetic south are interchanged.
- The Earth's field has alternated between periods of normal polarity, in which the direction of the field was the same as the present direction, and reverse polarity, in which the field was the opposite.
- These periods are called chrons.



Geomagnetic polarity during the last 5 million years. Dark areas denote periods where the polarity matches today's polarity, light areas denote periods where that polarity is reversed.

The polarity periods have been named after famous pioneers of geomagnetism. The current period of normal polarity is named after the French geophysicist B. Brunhes who discovered geomagnetic reversals in 1906.





Pole reversals are imprinted in the seafloor. As new oceanic crust is created through volcanic activity, iron-rich minerals in the upwelling magma are oriented to magnetic north at the time. These magnetic stripes are evidence of pole reversals.

They reveal that over the last 200 million years the poles have reversed, on average, about once every 200 000 – 300 000 years. Reversals are a slow process and do not happen with any regularity. Nevertheless, the last time this happened was about 780 000 years ago, so we are now overdue for a reversal.

- According to paleomagnetic observations, the Earth apparently has had a largely dipolar magnetic field throughout most of its lifetime.
  - Paleomagnetism is the study of the record of the Earth's magnetic field in rocks, sediment, or archeological materials.
- The oldest information (from rock samples) are from approximately $2.5 \cdot 10^9$ year ago.
- It appears that during the past $1.0 \cdot 10^9$ years, the magnetic field has on average ($1.0 \cdot 10^6$ year averages) been weaker than today. Before that, the magnetic field has been of the same strength as today.
- Typically, the Earth's magnetic field on average (e.g., 10 000 year averages) resembles the magnetic field of a dipole located at the center of the Earth and aligned with the Earth's rotational axis. However, the polarity of the field, i.e., whether the dipole moment vector points towards the geographic north of south pole, can vary 180^o.
- A polarity reversal typically takes 10 000 – 15 000 years.
- One polarity lasts for approximately 10^6 years.

A typical reversal of the Earth's magnetic field

Locally:

1. The strength of the magnetic field, B, weakens about 90%.

2. D and I change sign very “quickly”, even in about 1000 years. This phase is called the transition.

3. B increases back to its original value but $\boldsymbol{B}$ has changed direction by 180^{o}.

Globally:

1. The orientation of the dipole moment remains the same but its strength weakens.

2. The dipole component ($n = 1$) of the field disappears and only the non-dipole ($n > 1$) components remain. The strength of this remnant field is approximately 10% of the normal dipole field strength.

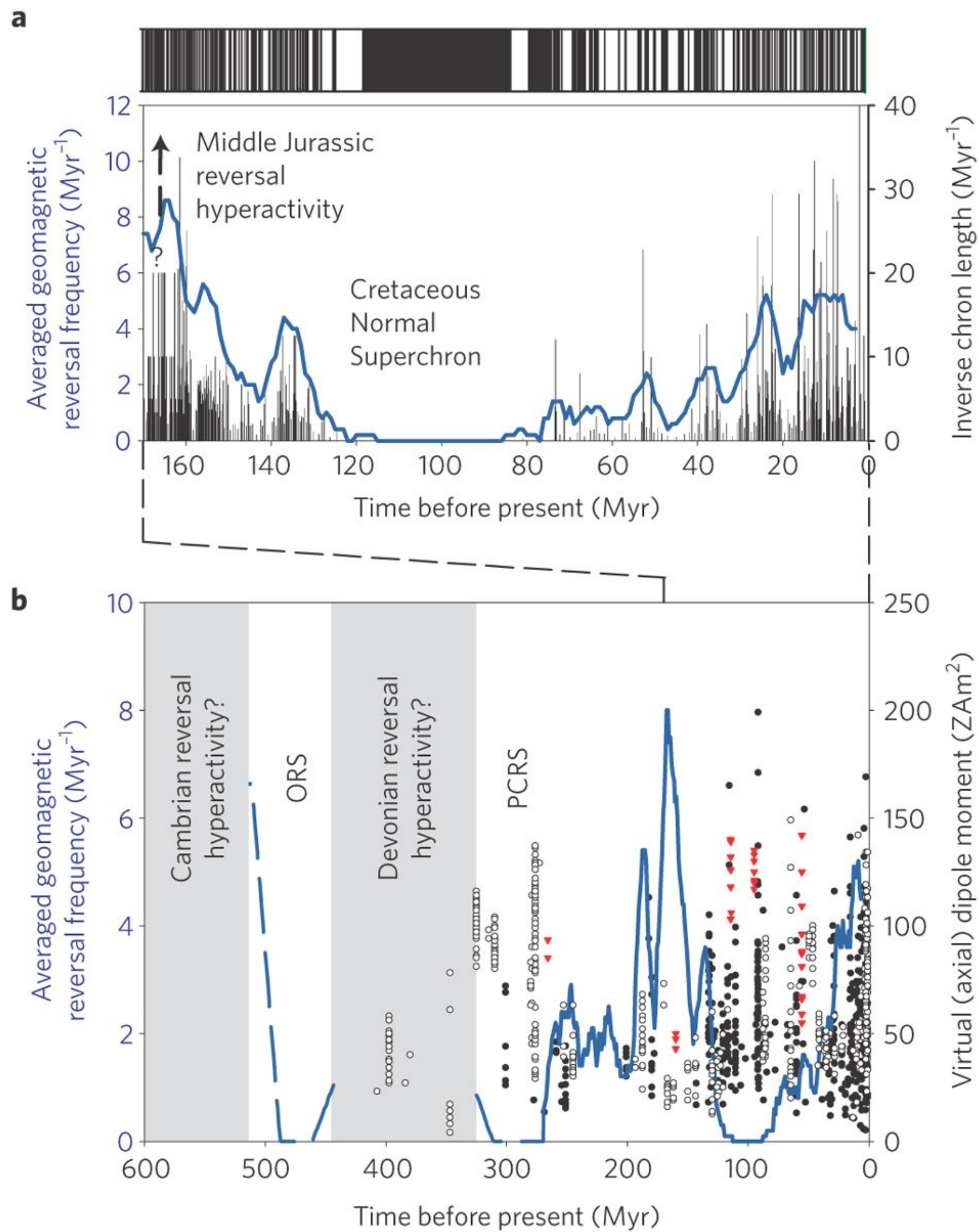
3. A new seed dipole, oriented opposite to the old global dipole, grows first in one hemisphere and then in the other. The two seed dipoles together produce a quadrupole field. As the two seed dipoles merge as one, a new global dipole emerges.

- During the last $50 \cdot 10^6$ years, the Earth's magnetic field has undergone a reversal every $0.33 \cdot 10^6$ years.
- The current “normal” polarity has lasted approximately $0.75 \cdot 10^6$ years ago, which is longer than on average. However, the reversal period has varied considerably in the past.
- The mechanism inside the Earth's that produces the polarity changes is currently not sufficiently well understood.
- Apparently, the physical mechanism inside the Earth's that causes the reversal of the Earth's magnetic field is similar to that inside the Sun that causes the reversal of the Sun's magnetic field approximately every 11 years: a magnetohydrodynamical instability.

(a) The marine magnetic anomaly record (MMA) and plots of inverse chron length (black bars) and reversal frequency (10 Myr running mean; blue line).

(b) Reversal frequency from the MMA and magnetostratigraphic studies (shaded area indicates insufficient data) alongside virtual (axial) dipole moment measurements (red triangles, open and filled circles for different methods).

http://www.nature.com/ngeo/journal/v5/n8/full/ngeo1521.html

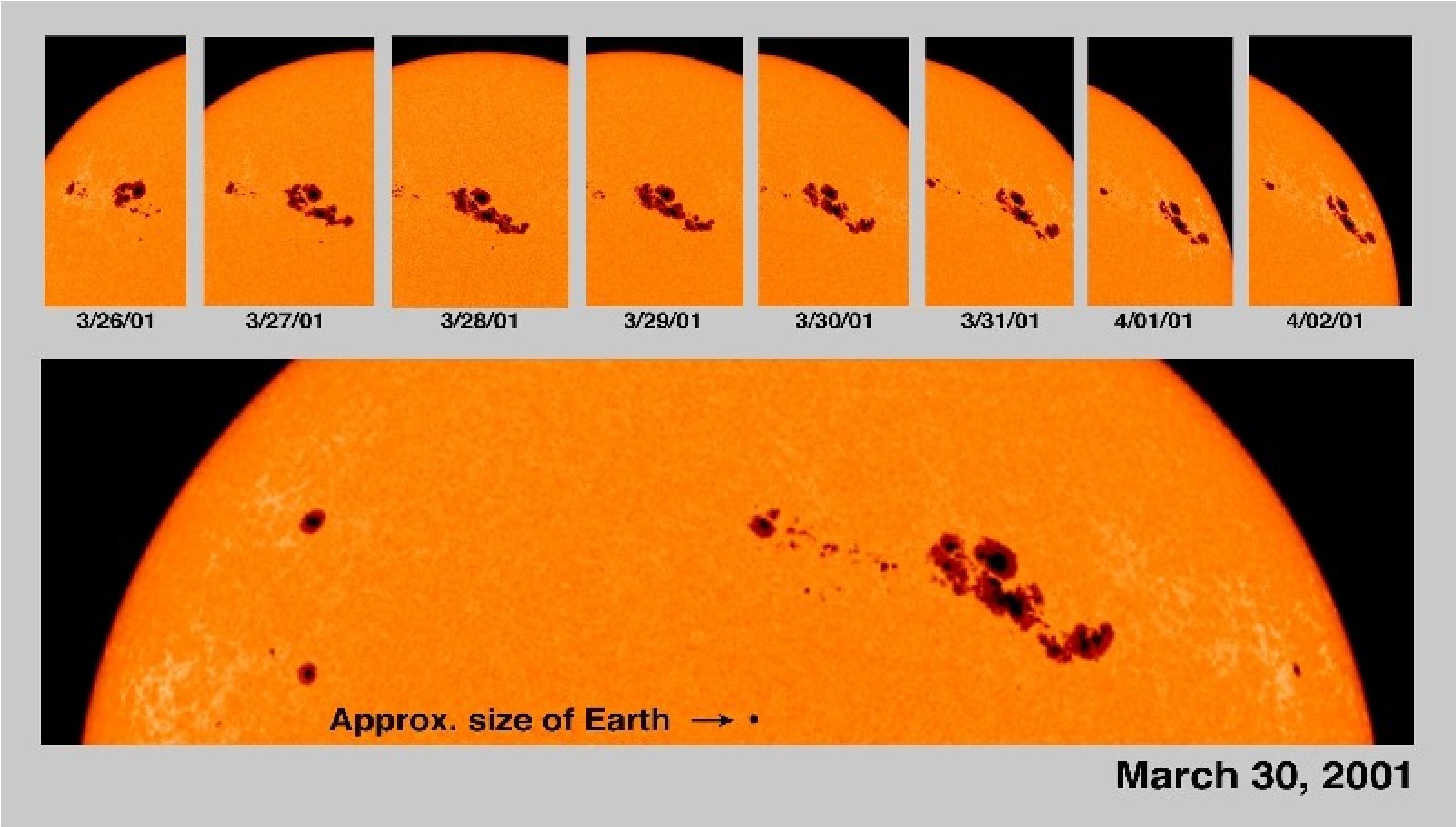


Is the Earth's magnetic field reversing now?

- The motion of the magnetic poles, the rapid weakening of the dipole component, and the increased asymmetry of the magnetic field between the hemispheres have been seen as indicators of an approaching magnetic field reversal.
  - Projecting the downward trend of the Earth's dipole moment forward in time would suggest zero dipole moment in some thousands of years.
- As it has been over 750 000 since the previous reversal, statistics support this interpretation.
- However, natural variation of the magnetic field may also explain the observations.
- Even if the Earth's magnetic field is reversing, it will take hundreds or thousands of years before this can be confirmed.

Reversals of the Sun's magnetic field

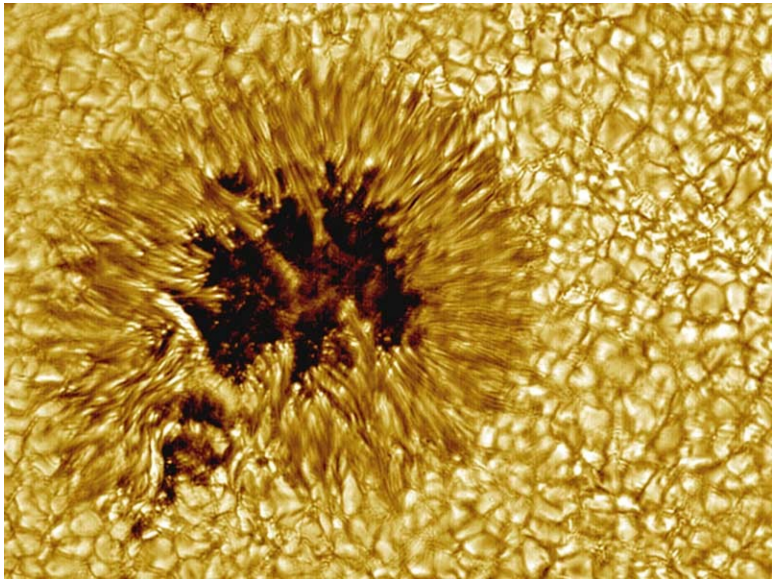
Sunspots



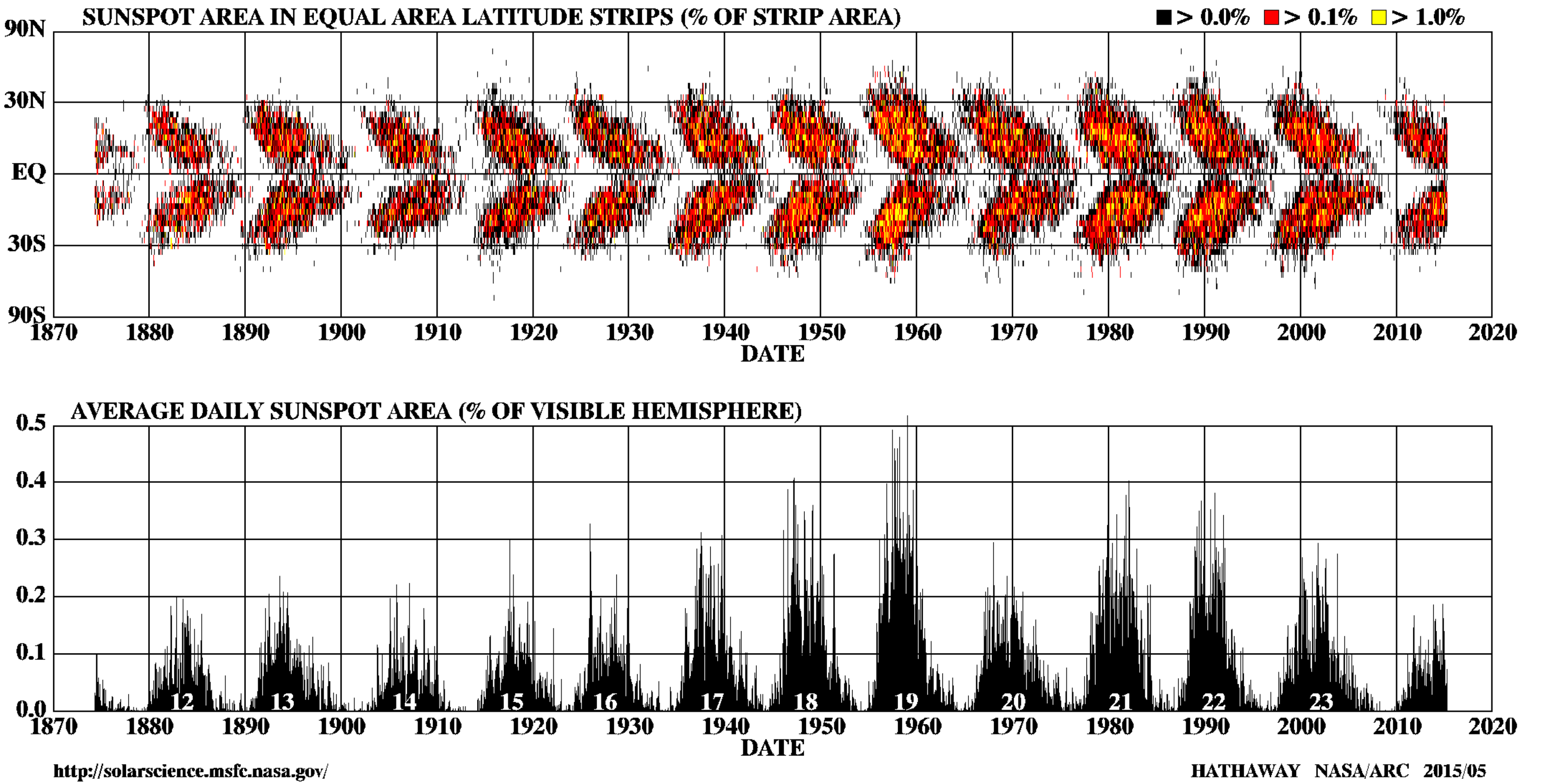
The largest sunspot group of solar cycle 23. The group moved across the visible solar disk with the Sun's rotation. Caused by intense magnetic fields emerging from the interior, a sunspot appears to be dark only when contrasted against the rest of the solar surface, because it is slightly cooler than the unmarked regions.

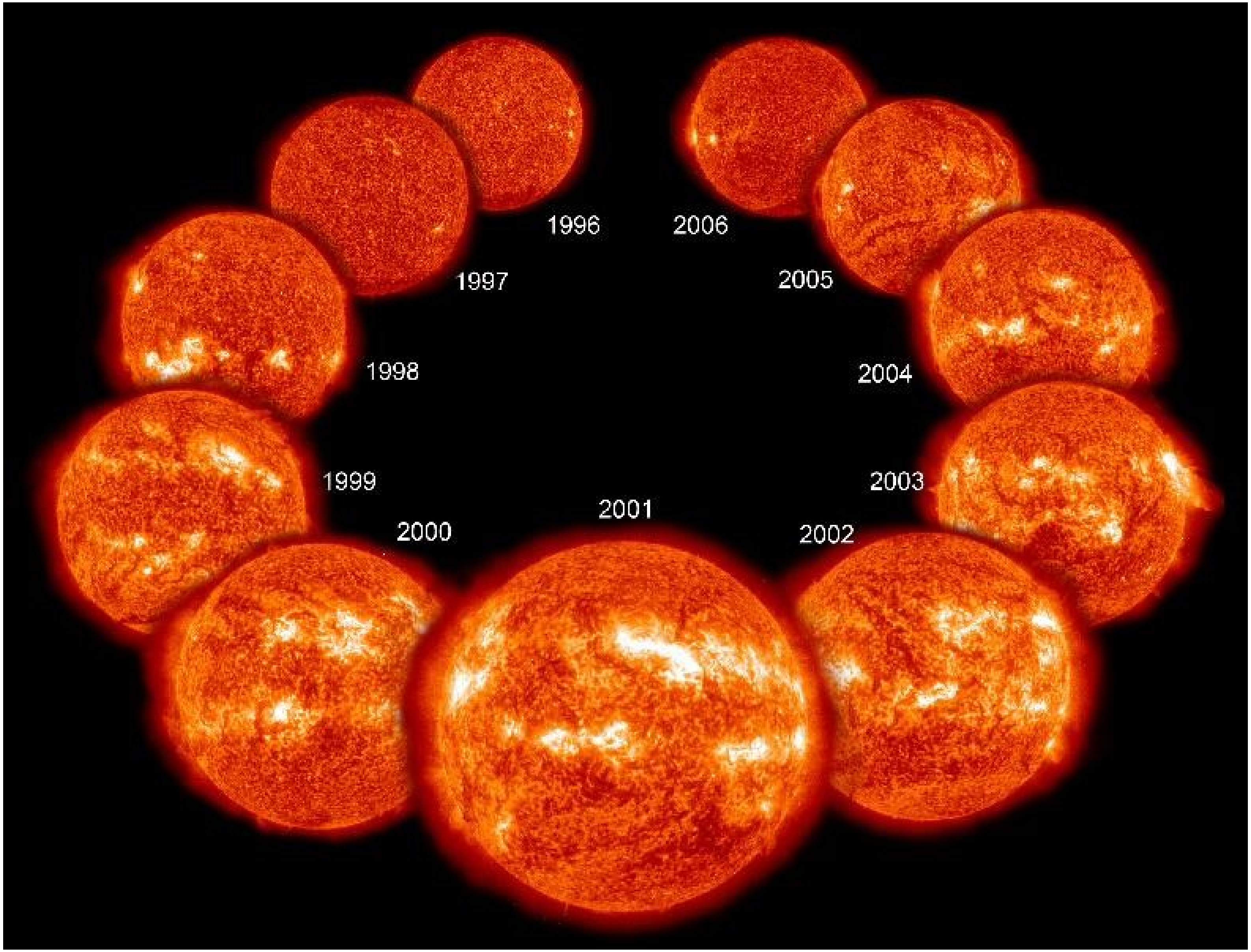
From: http://sohowww.nascom.nasa.gov/gallery

- Sunspots are temporary phenomena on the photosphere of the Sun that appear visibly as dark spots compared to surrounding regions.
- They correspond to concentrations of magnetic field that inhibit convection and result in reduced surface temperature compared to the surrounding photosphere.
- Sunspots usually appear as pairs, with each spot having the opposite magnetic polarity of the other.



DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS





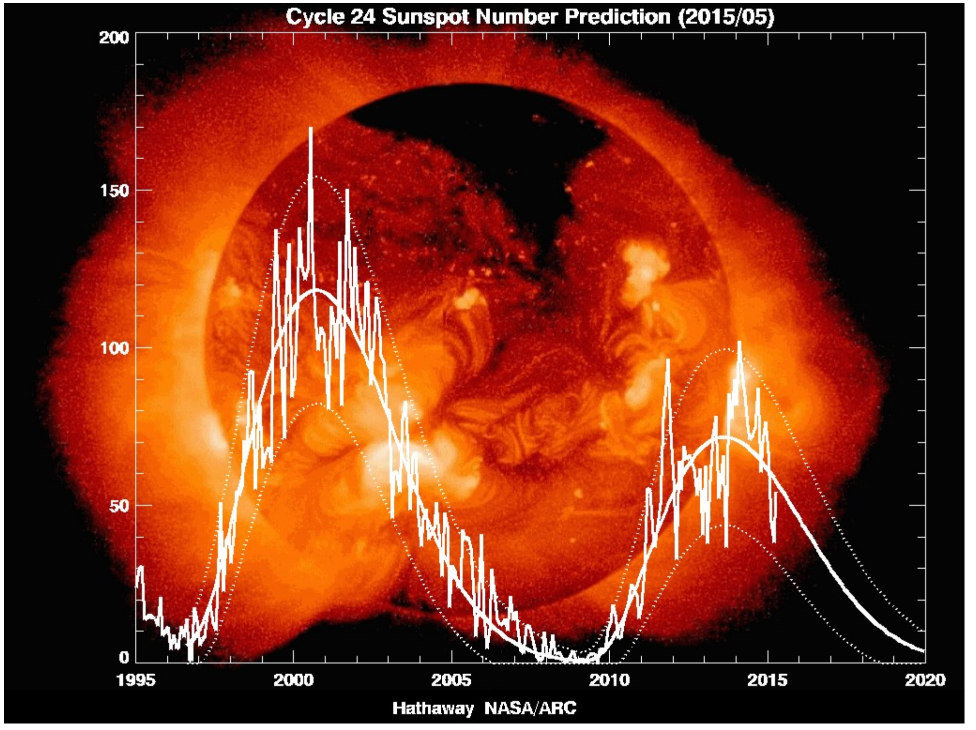
A SOHO Extreme ultraviolet Imaging Telescope (EIT) image in the 304 Angstrom wavelength of extreme UV light from each year of nearly an entire solar cycle. From: sohowww.nascom.nasa.gov/gallery.

11-year solar cycle

- The solar cycle is the periodic change in the Sun's activity (including changes in the levels of solar radiation and ejection of solar material) and appearance (visible in changes in the number of sunspots, flares, and other visible manifestations).
- Solar maximum and solar minimum refer respectively to epochs of maximum and minimum sunspot counts. Individual sunspot cycles are partitioned from one minimum to the next.
- Solar cycles have an average duration of about 11 years, but cycles as short as 9 years and as long as 14 years have been observed. Significant variations in the amplitude (maximum sunspot number) also occur.
- Sunspots do not appear at random over the surface of the sun but are concentrated in two latitude bands on either side of the equator.
- A butterfly diagram showing the positions of the spots for each rotation of the sun since May 1874 shows that these bands first form at mid-latitudes, widen, and then move toward the equator as each cycle progresses.

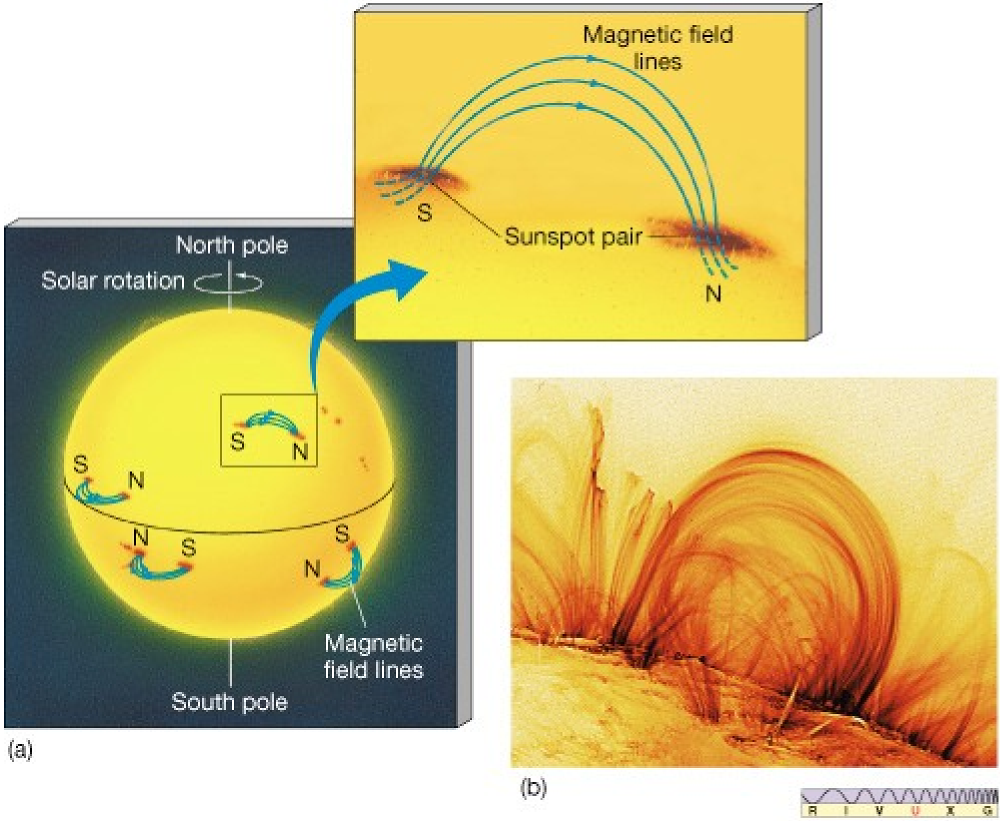
Current cycle

- We are currently over six years into Cycle 24.
- The smoothed sunspot number reached a peak of 81.9 in April 2014. This will probably become the official maximum.
- The current predicted and observed size makes this the smallest sunspot cycle since Cycle 14 which had a maximum of 64.2 in February of 1906.



22-year magnetic cycle

- Sunspots are strongly magnetized. The magnetic polarity of sunspot pairs:
  - Is always the same in a given solar hemisphere throughout a given sunspot cycle.
  - Is opposite across hemispheres throughout a cycle.
  - Reverses itself in both hemispheres from one sunspot cycle to the next.
- Thus, the solar cycle is actually a magnetic cycle with an average duration of 22 years. However, because very nearly all manifestations of the solar cycle are insensitive to magnetic polarity, it remains common usage to speak of the "11-year solar cycle".

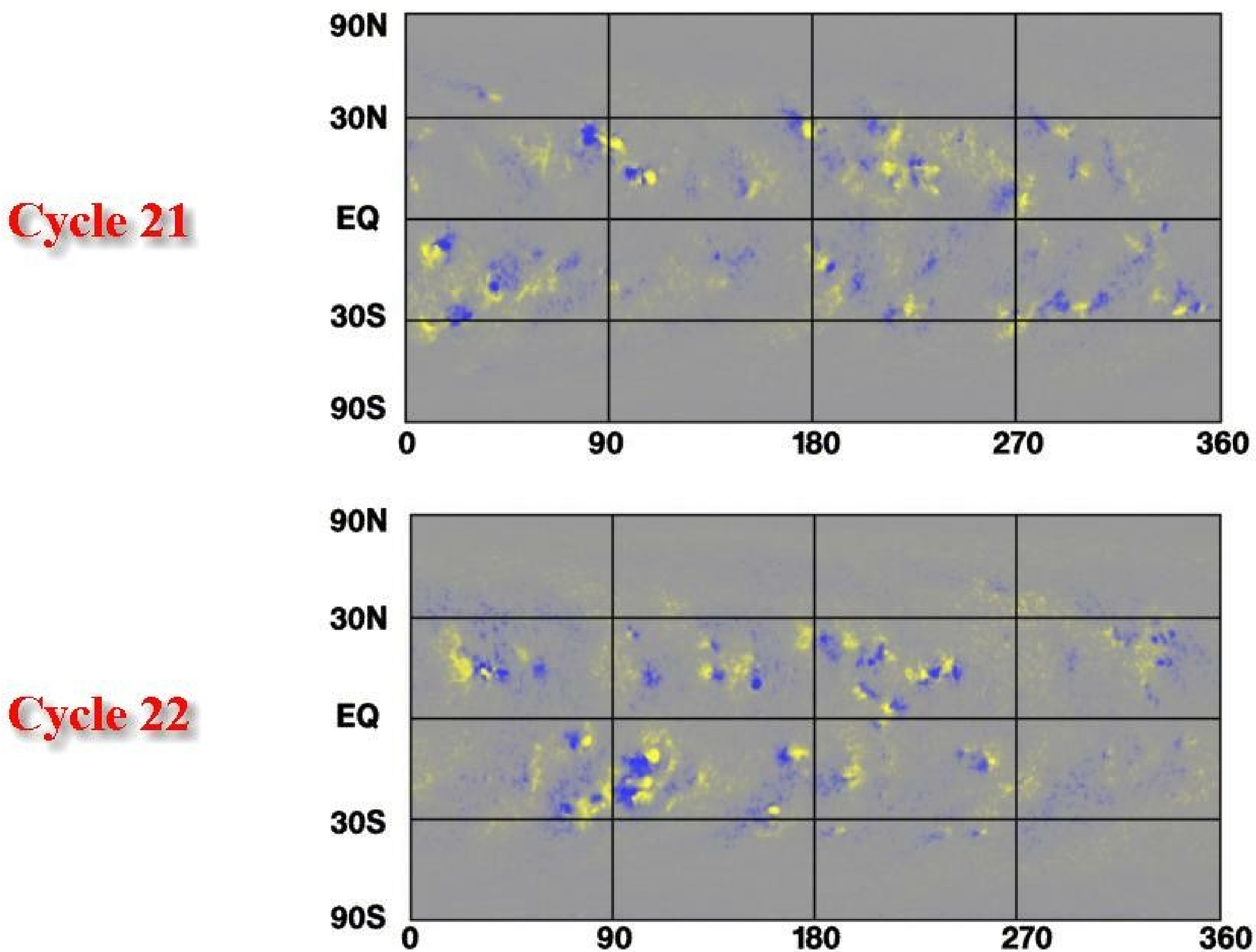


(a)

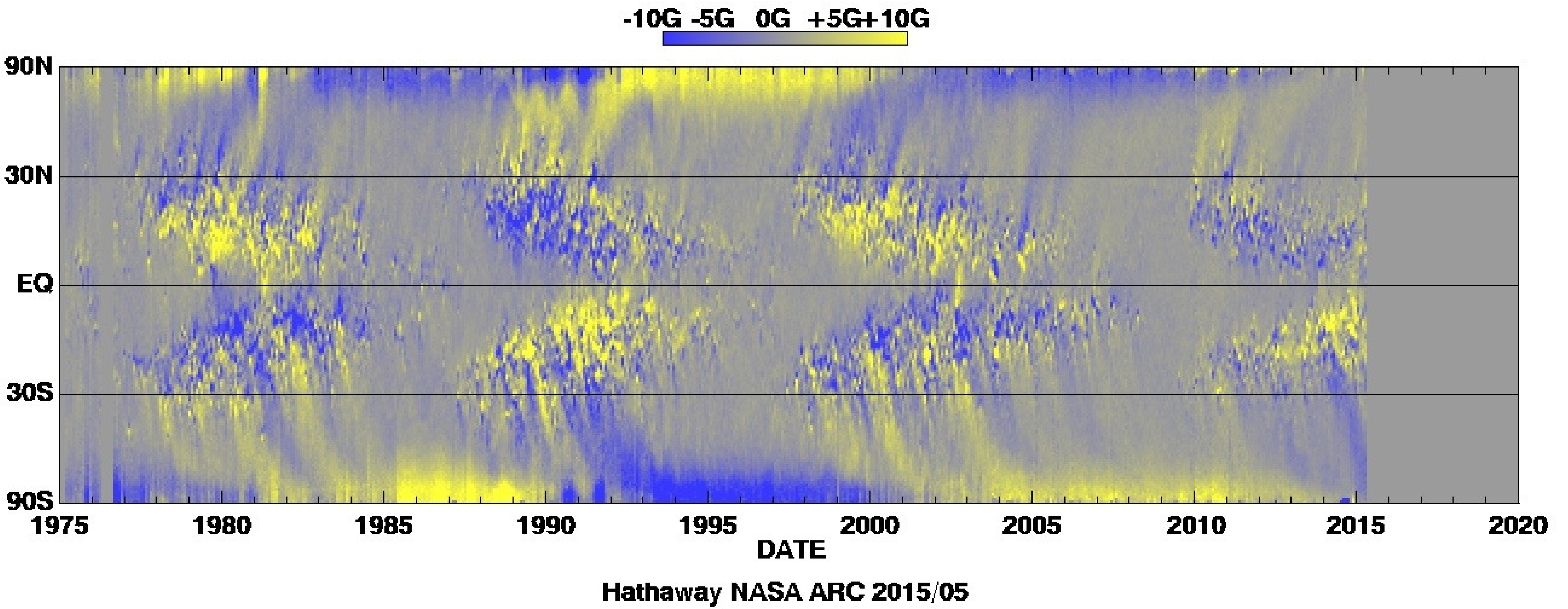
(b)

Hale's Polarity Law:

The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.



- The solar surface is magnetized even outside of sunspots. This weaker magnetic field is to first order a dipole which undergoes polarity reversals with the same period as the sunspot cycle.



Time vs. solar latitude diagram of the radial component of the solar magnetic field, averaged over successive solar rotation. The "butterfly" signature of sunspots is clearly visible at low latitudes.

The Solar Dynamo

- It is widely believed that the Sun's magnetic field is generated by a magnetic dynamo within the Sun.
- The fact that the Sun's magnetic field changes dramatically over the course of just a few years, and the fact that it changes in a cyclical manner indicates that the magnetic field continues to be generated within the Sun.
- A successful model for the solar dynamo must explain several observations:

  1) the 11-year period of the sunspot cycle,

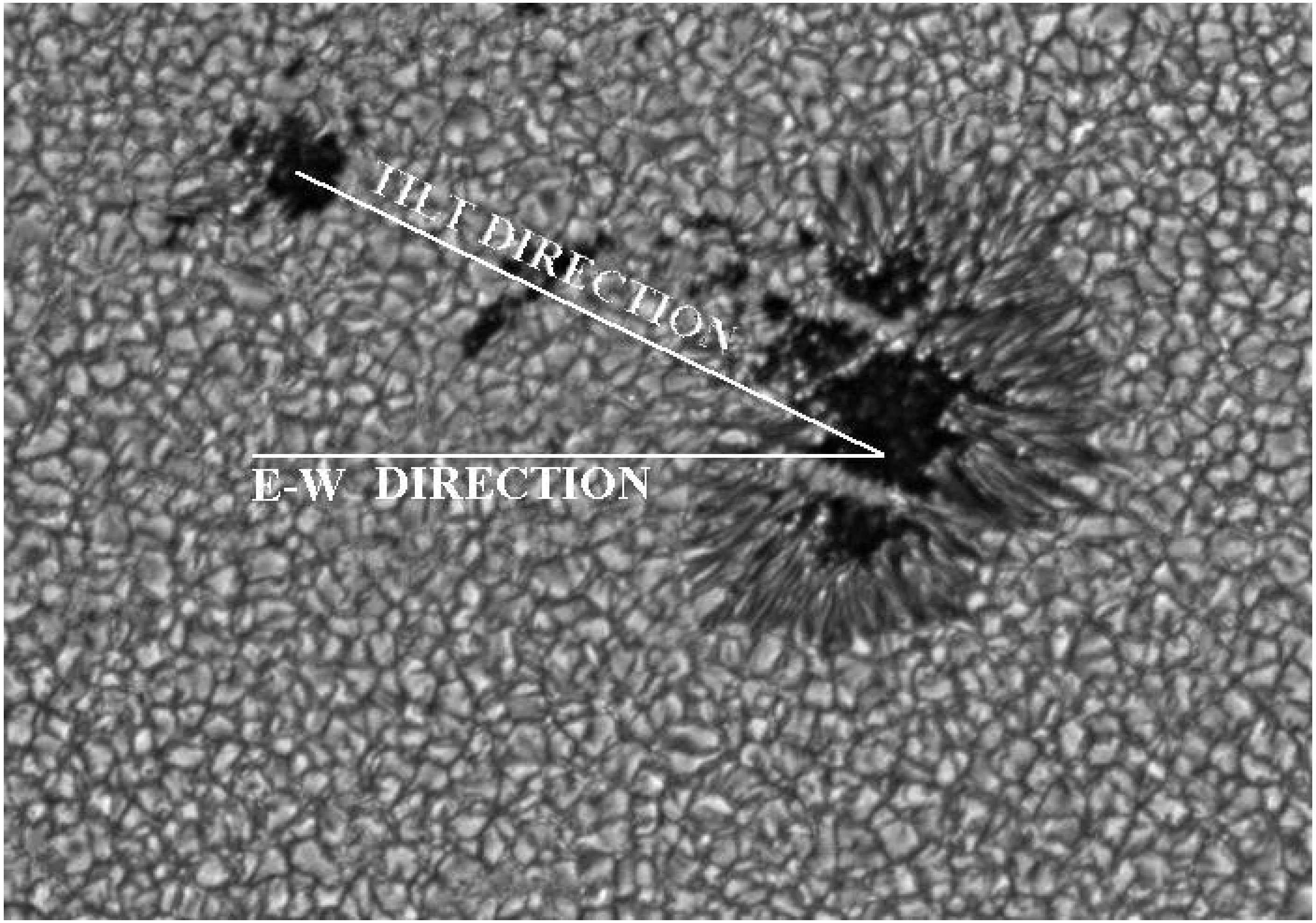
  2) the equator-ward drift of the active latitude as seen in the butterfly diagram,

  3) Hale's polarity law and the 22-year magnetic cycle,

  4) Joy's law for the observed tilt of sunspot groups and,

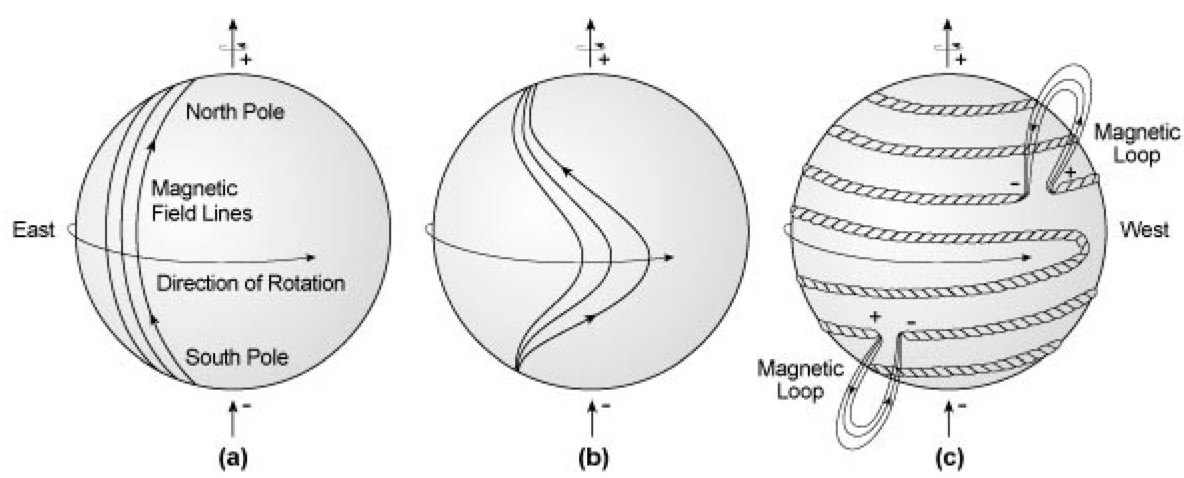
  5) the reversal of the polar magnetic fields near the time of cycle maximum as seen in the magnetic butterfly diagram.

Joy's law for the observed tilt of sunspot groups



A model for generating the orientation and polarity of sunspot magnetic fields

- At the beginning of the 11-year cycle of magnetic activity, when the number of sunspots is at a minimum, the magnetic field is dipolar (poloidal) (a).
- As time goes on, the highly-conductive, rotating material inside the Sun carries the magnetic field along and winds it up. Because the equatorial regions rotate at a faster rate than the polar ones (differential rotation), the internal magnetic fields become stretched out and wrapped round the Sun's center, becoming deformed into a partly toroidal field (b) and (c).
- At the time of activity maximum (c), active regions are formed in two belts, in the northern and southern hemispheres, and bipolar sunspot groups are created when magnetic loops break through the photosphere.



Multipole expansion of the external sources of the Earth's magnetic field

- In the spherical harmonic representation of the Earth's internal magnetic field, the magnetic field associated with multipole *n* decreases as $r^{-(n+2)}$
  - The first and dominant term in the expansion is the dipole (*n* = 1) located at the center of the Earth.
- In the spherical harmonic representation of the Earth's external magnetic field, the magnetic field associated with multipole *n* changes as r^{n-1}.
  - The first term (*n* = 1) is independent of *r*:

$$X_e = -q_1^0 \sin\theta + (q_1^1 \cos\varphi + s_1^1 \sin\varphi)\cos\theta$$
$$Y_e = q_1^1 \sin\varphi - s_1^1 \cos\varphi$$
$$Z_e = q_1^0 \cos\theta + (q_1^1 \cos\varphi + s_1^1 \sin\varphi)\sin\theta$$

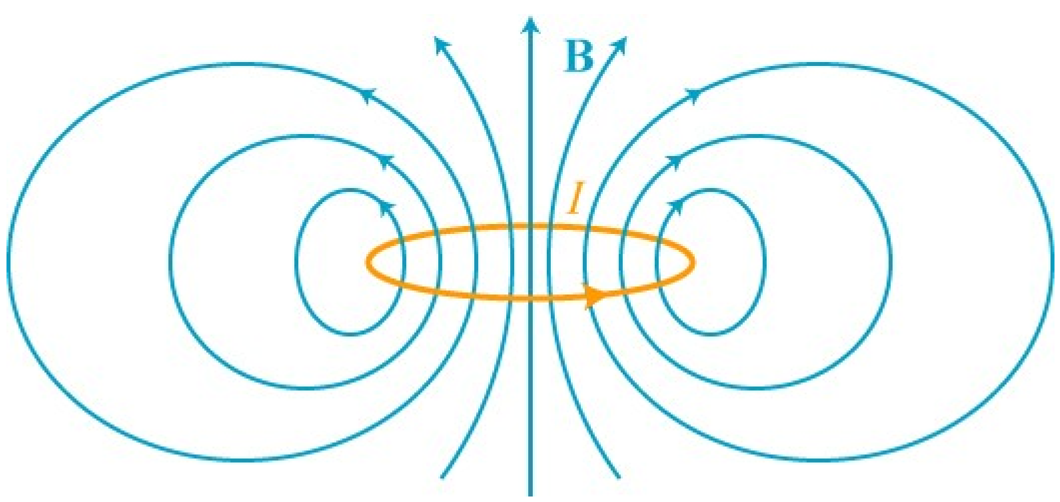
$$B_e = \sqrt{(q_1^0)^2 + (q_1^1)^2 + (s_1^1)^2}$$

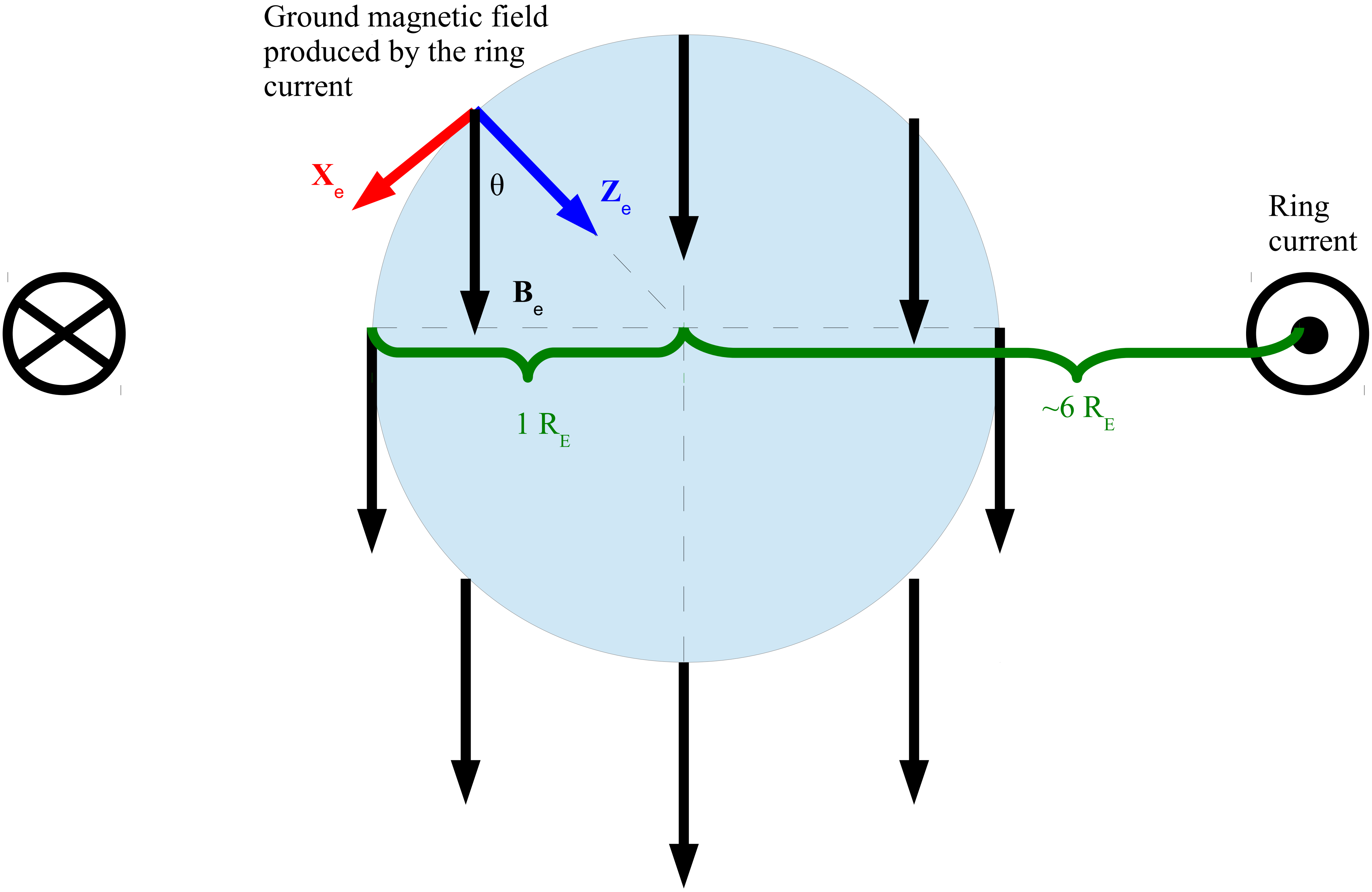
- The simplest case is the term q_1^0

- The corresponding magnetic field components are independent of longitude:

$$X_e = -q_1^0 \sin\theta$$
$$Y_e = 0$$
$$Z_e = q_1^0 \cos\theta$$

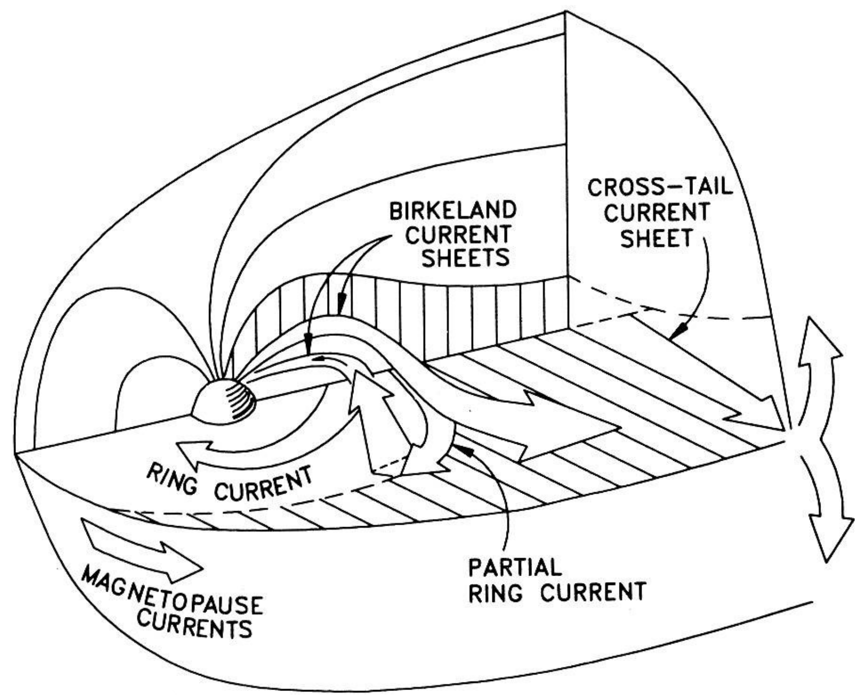
- A simple current system that could produce such a magnetic field on the ground, would be a circular current loop at the Earth's equatorial plane.

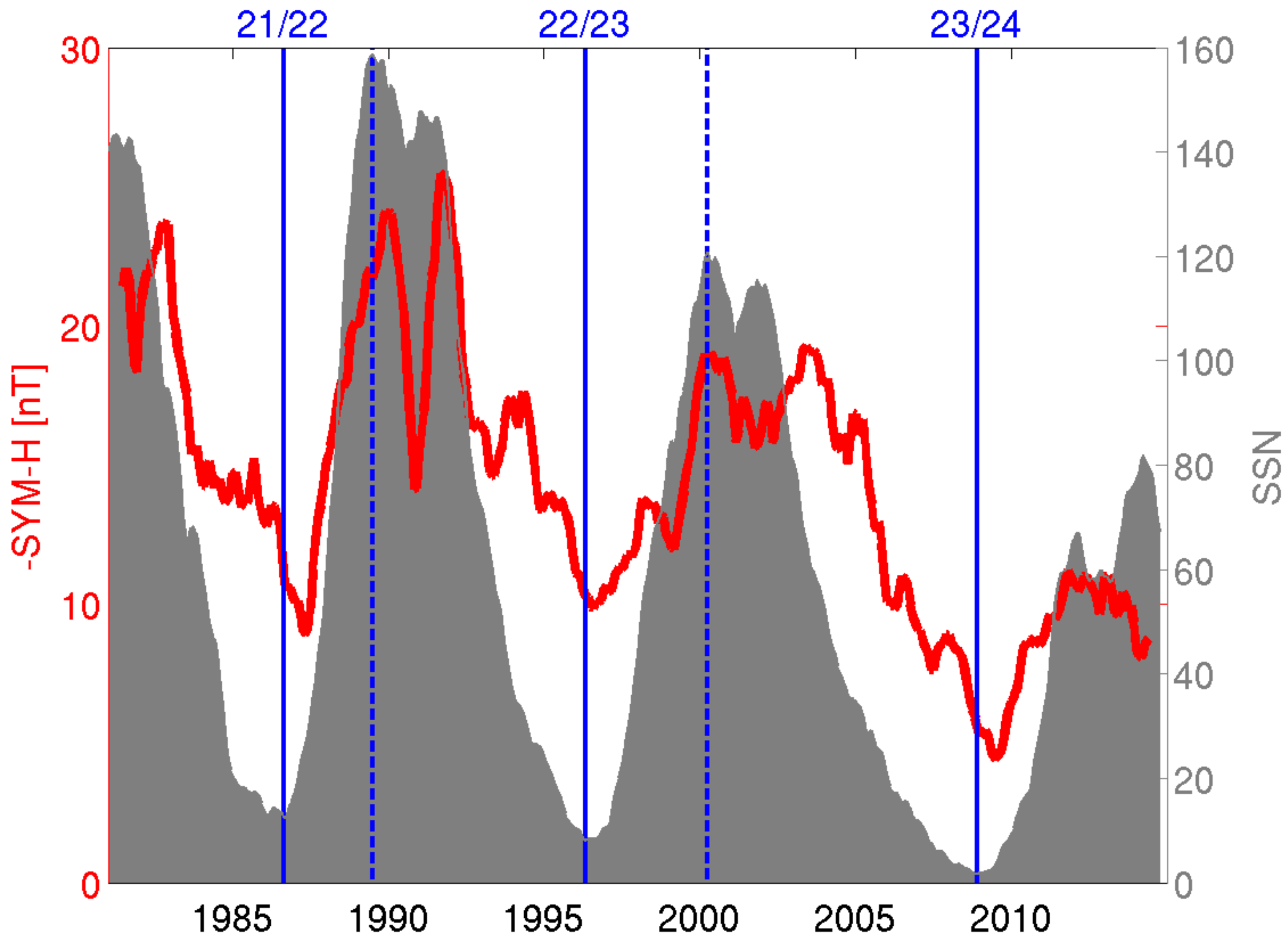



Ground magnetic field produced by the ring current
X_e
θ
Z_e
B_e
Ring current
1 R_E
~6 R_E

Ring current

- The Earth's ring current lies in the equatorial plane and circulates westward around the Earth at a distance of 3–5 R_E.
- The magnetic field produced by the ring current is oppositely directed to the Earth's internal dipole field on the ground near the equator: the ring current weakens the horizontal component of the magnetic field.
- The strength of the ring current varies with solar activity. A typical value for the strength of the ground magnetic field produced by the ring current is some tens of nT.





21/22
22/23
23/24
-SYM-H [nT]
SSN
30
20
10
0
160
140
120
100
80
60
40
20
0
1985
1990
1995
2000
2005
2010

Separating the internal and external contributions to the observed magnetic field

- The magnetic field ***B*** observed on the ground can be separated into an external and an internal part using the spherical harmonic expansions.
- As an example, let us examine a simple case: an axisymmetric field of the order $n = 1$

$$X = X_i + X_e = -\left(g_1^0 + q_1^0\right)\sin\theta$$
$$Y = Y_i + Y_e = 0$$
$$Z = Z_i + Z_e = \left(-2g_1^0 + q_1^0\right)\cos\theta$$

$$\rightarrow g_1^0 = -\frac{1}{3}\left(\frac{X}{\sin\theta} + \frac{Z}{\cos\theta}\right)$$
$$q_1^0 = \frac{1}{3}\left(-\frac{2X}{\sin\theta} + \frac{Z}{\cos\theta}\right)$$

$$\rightarrow X_i = -g_1^0 \sin\theta$$
$$Z_i = -2g_1^0 \cos\theta$$
$$X_e = -q_1^0 \sin\theta$$
$$Z_e = q_1^0 \cos\theta$$