Solar physics and Space Weather

Lecture 2a of 5: Sunspots

Jan Janssens

Contents

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  - How to observe
  - Properties
- Sunspot groups
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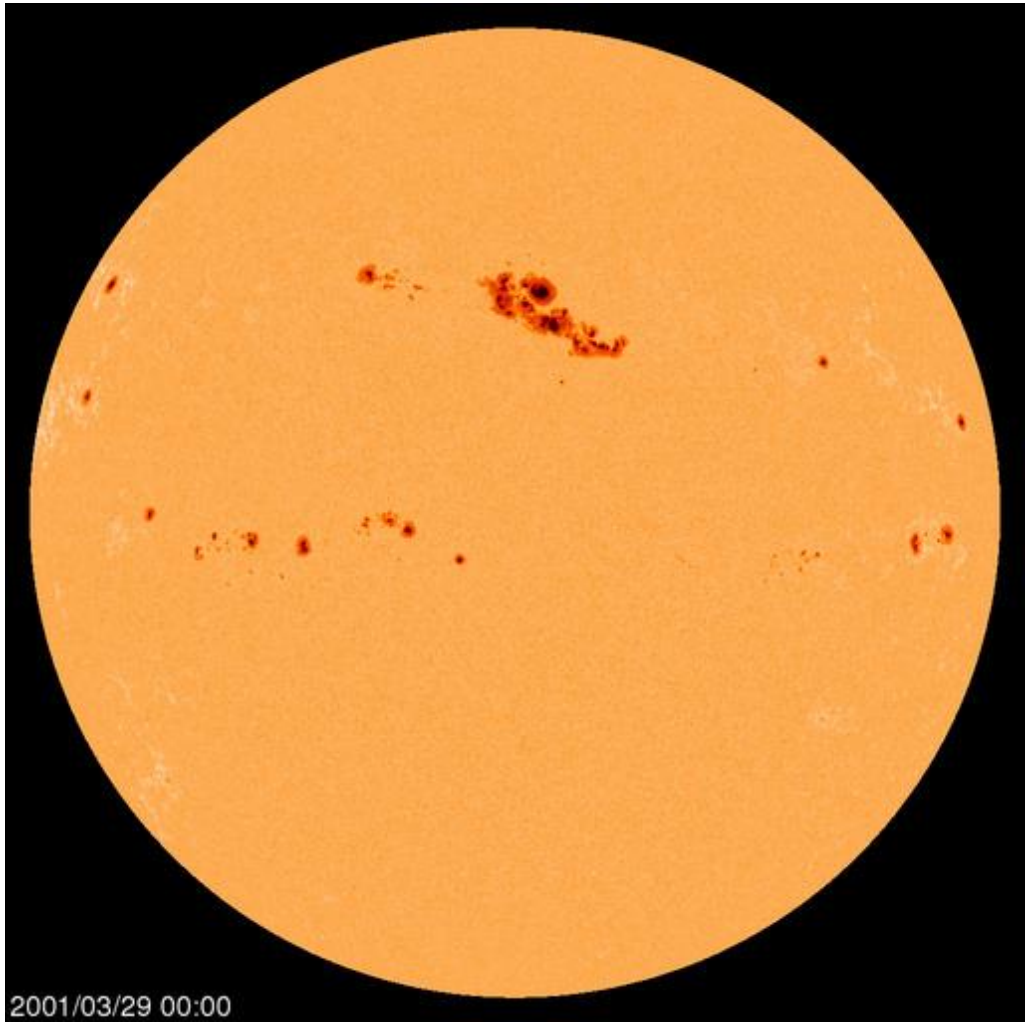
  - Properties
  - Classifications
    - Solar flares
- Sunspot number
  - What is it
  - Types
- Sunspot cycle
  - History
  - Properties



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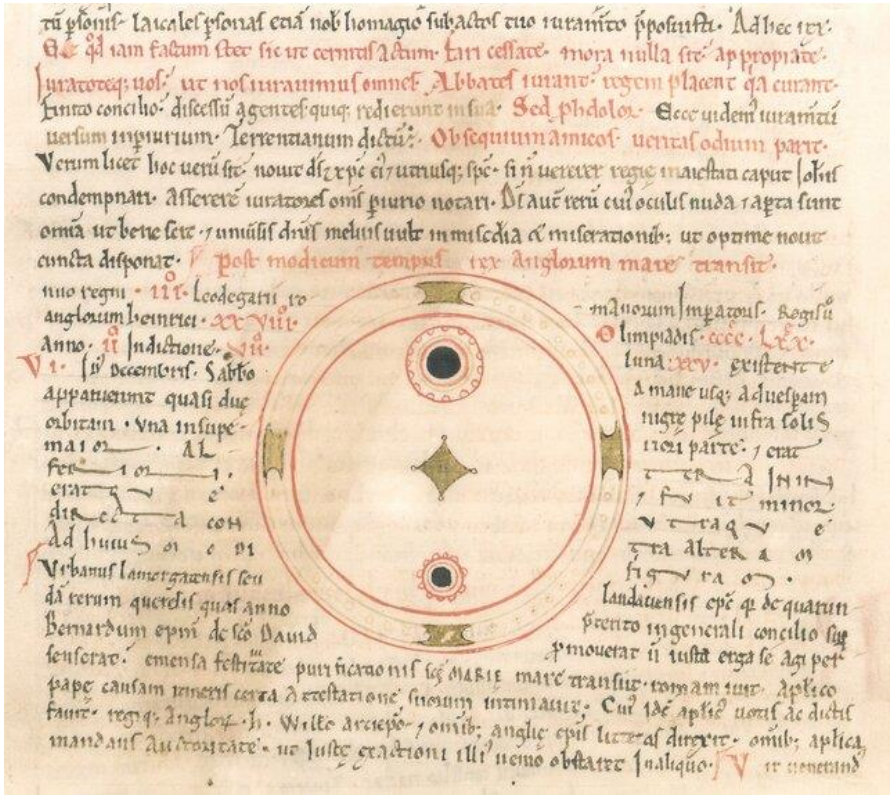
Sunspots – First observations

- China
  - Book of Changes (“I Ching”)
  - 800 BC
- First drawing
  - John of Worcester
  - 8 Dec 1128

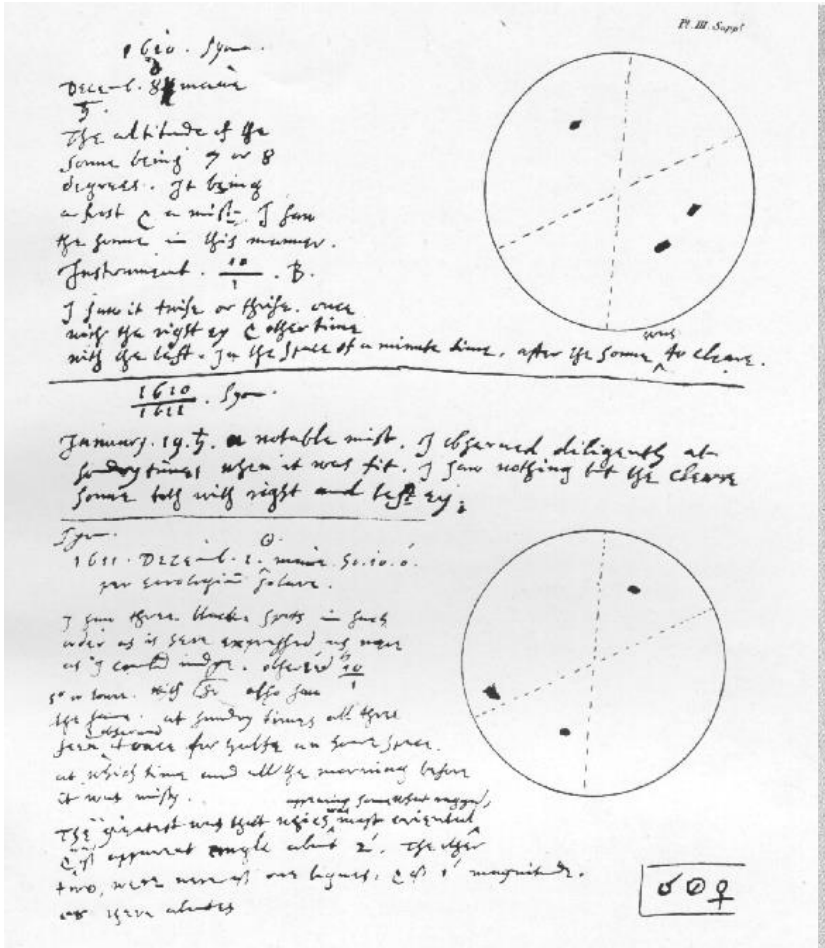
The Recording of Sunspot Phenomena Originated In Astrology

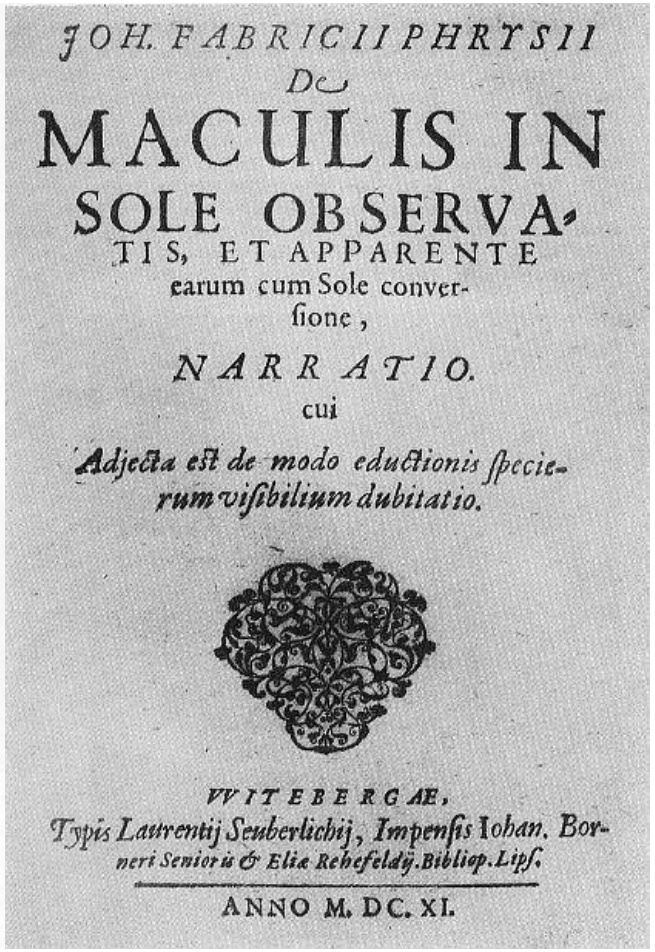
We do not know when sunspot phenomena were first recorded in China. By 800 B.C. such records were reflected in “*Feng* 丰 ,” hexagram 55 of the Book of Changes (*Zhou yi* 周易). “Dipper seen in the sun” (lines 2 and 4) and “dark spots seen in the sun” (line 3) refer to sunspot phenomena. Since lines 2 and 4 end in “auspicious,” and line 3 in “no misfortune,” there is no doubt that the goal of this text is divinatory.[2]



Sunspots – First observations

- China
  - Book of Changes
  - 800 BC
- First drawing
  - John of Worcester
  - 8 Dec 1128
- First telescopic drawing
  - Thomas Harriot
  - 8 Dec 1610
- First publication
  - Johannes Fabricius
  - 13 June 1611





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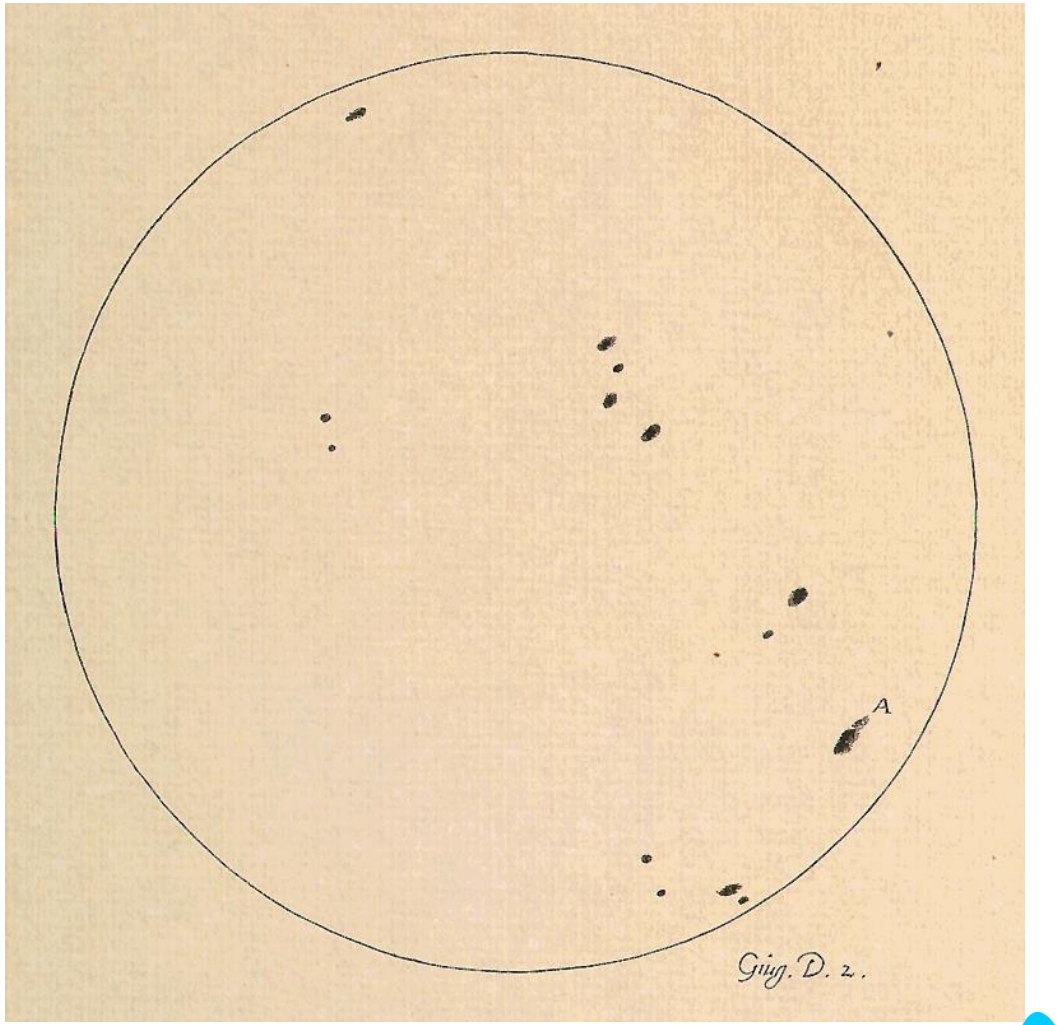
Sunspots – First observations

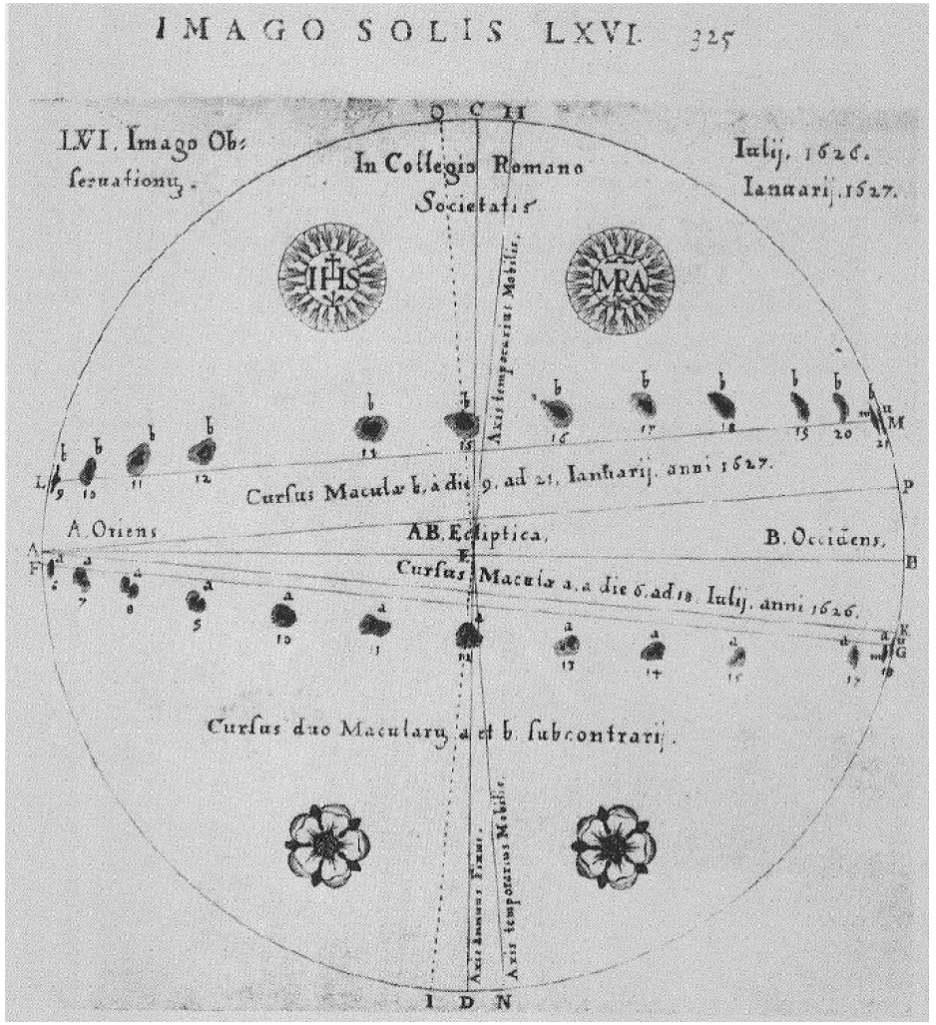
- Galileo Galilei
  - Oldest drawing: 12 Feb 1612
  - Main discoveries on sunspots:
    - On the Sun (not satellites)
      - The Sun is NOT perfect!
    - Rotate with the Sun (+/- 1 month)
      - Can reappear
    - Sunspots change shape



2 June – 8 July 1613

Sunspots – First observations

- Galileo Galilei
  - Oldest drawing: 12 Feb 1612
  - Main discoveries on sunspots:
    - On the Sun (not satellites)
      - The Sun is NOT perfect!
    - Rotate with the Sun (+/- 1 month)
      - Can reappear
    - Sunspots change shape
- Christoph Scheiner
  - Rosa Ursina sive sol
  - Main discoveries:
    - Solar axis is inclined
    - “Differential rotation”



Christoph Scheiner, Rosa Ursina (1630)

Sunspots – How to observe

Naked eye – Eclipse glasses,…

Telescope – Projection

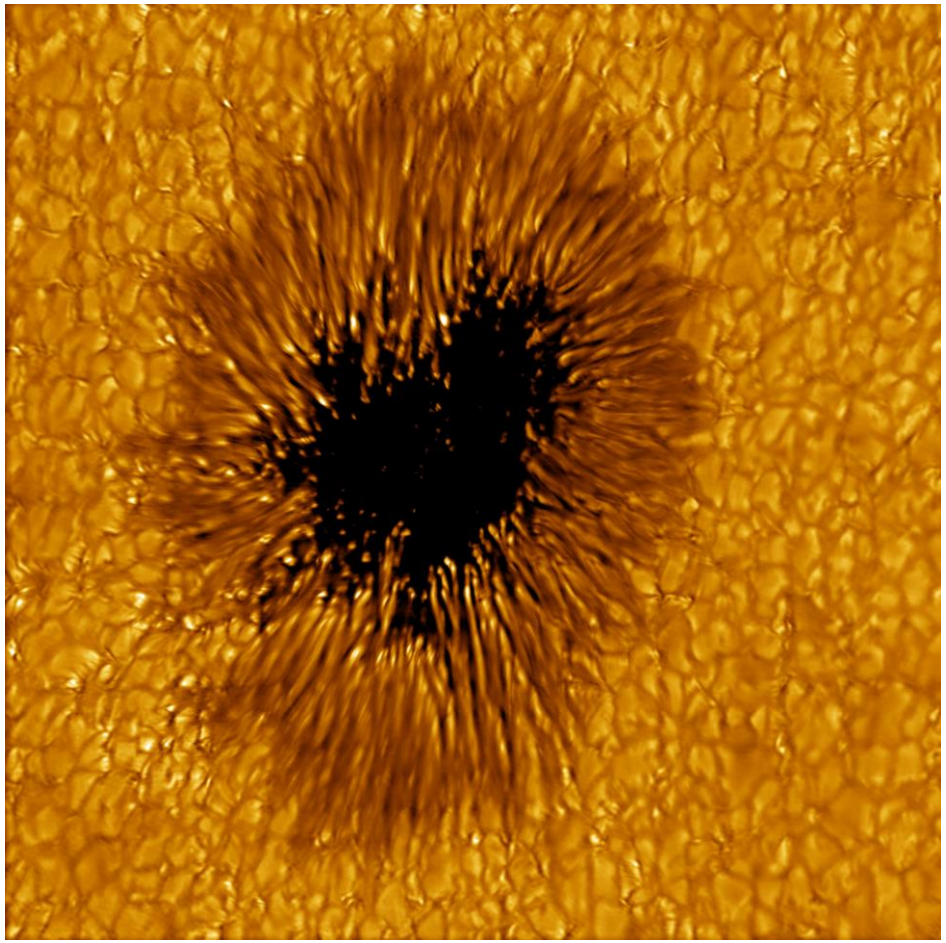
Royal Observatory of Belgium / SIDC / SILSO

Sunspots – How to observe

Largest solar telescope – DKIST (4m)

Daniel K. Inouye Solar Telescope (Hawaii)

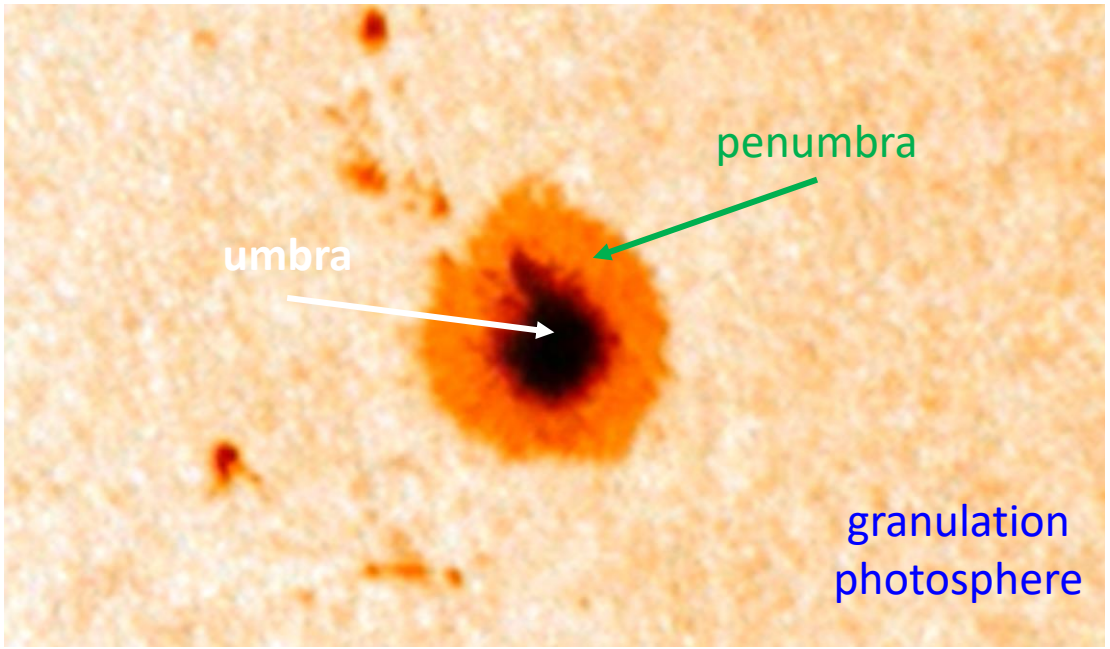
Largest resolution images (30 km)

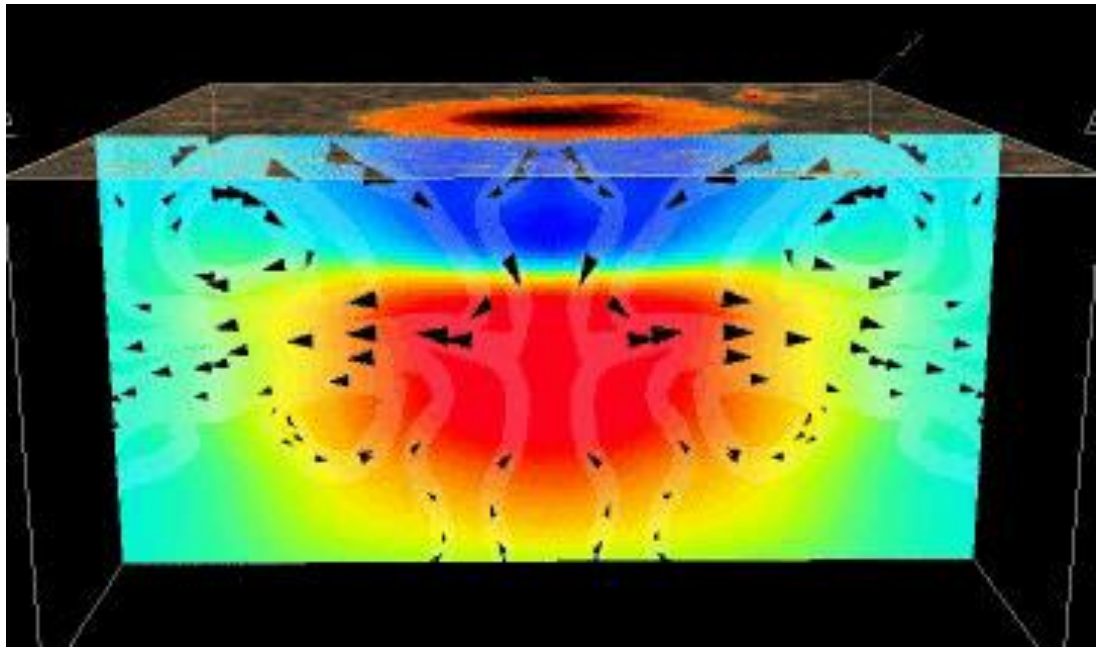


Sunspots – Structure and creation

Structure: *umbra and penumbra*

Creation: *magnetic disturbance at the surface of the Sun*

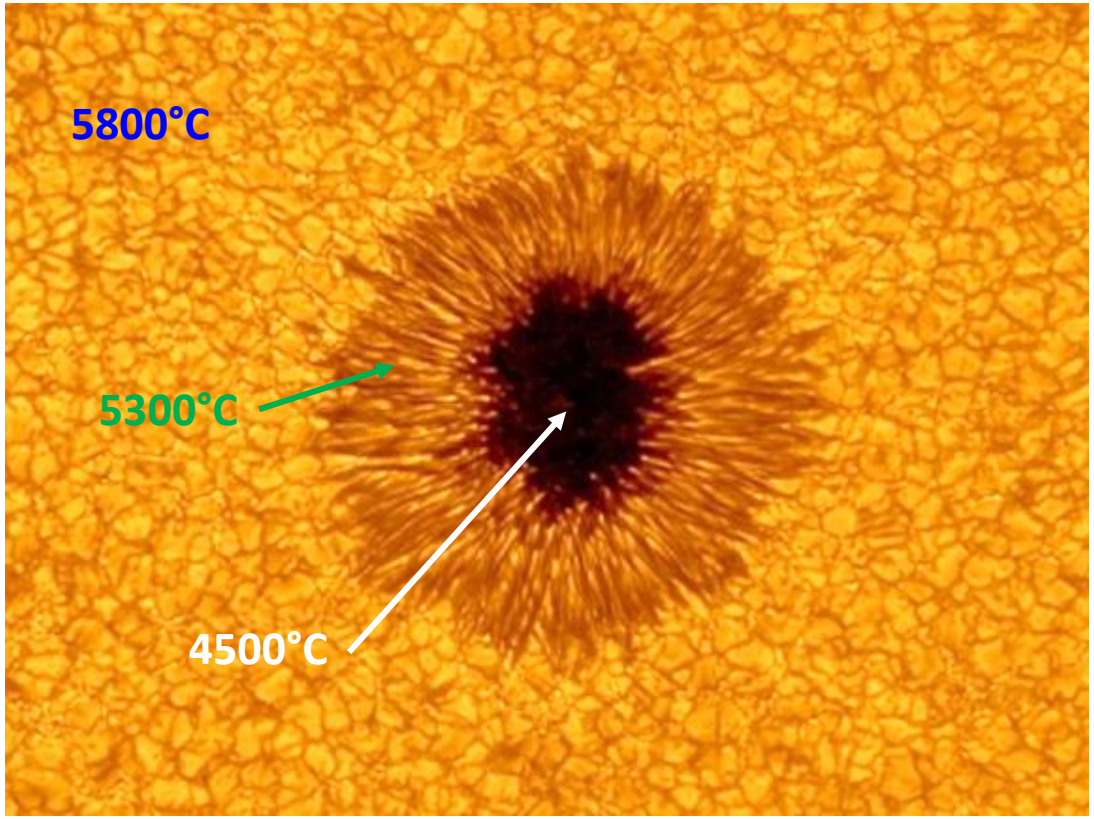




Credits: SOHO/MDI - https://soho.nascom.nasa.gov/gallery/images/sunspotmdib.html

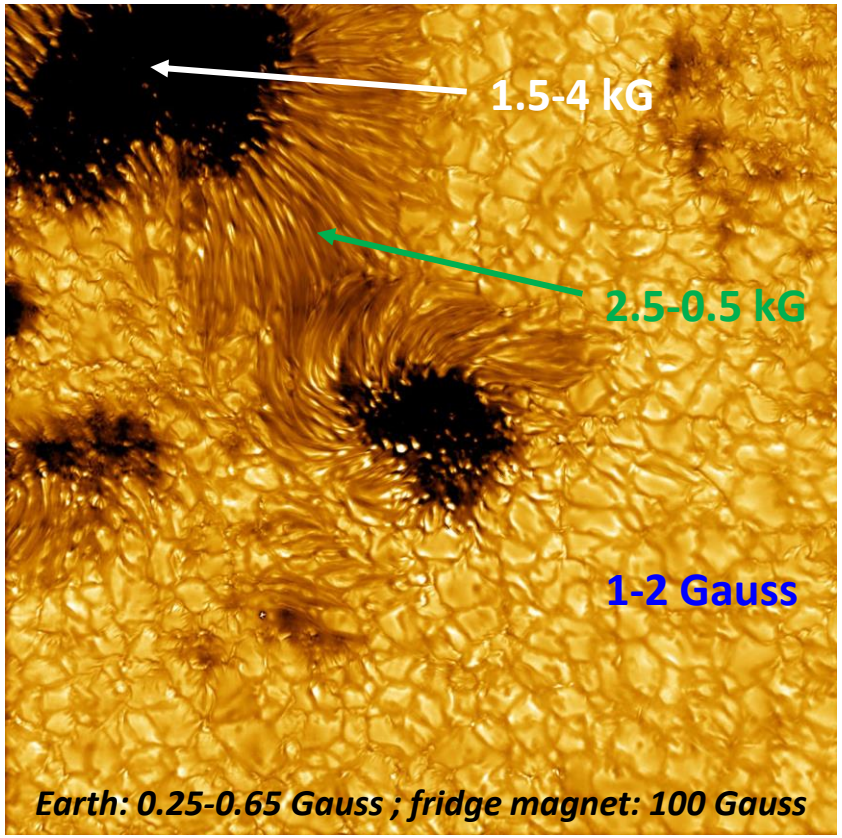
Sunspots – Properties

Temperature



Goode Solar Telescope (BBSO)

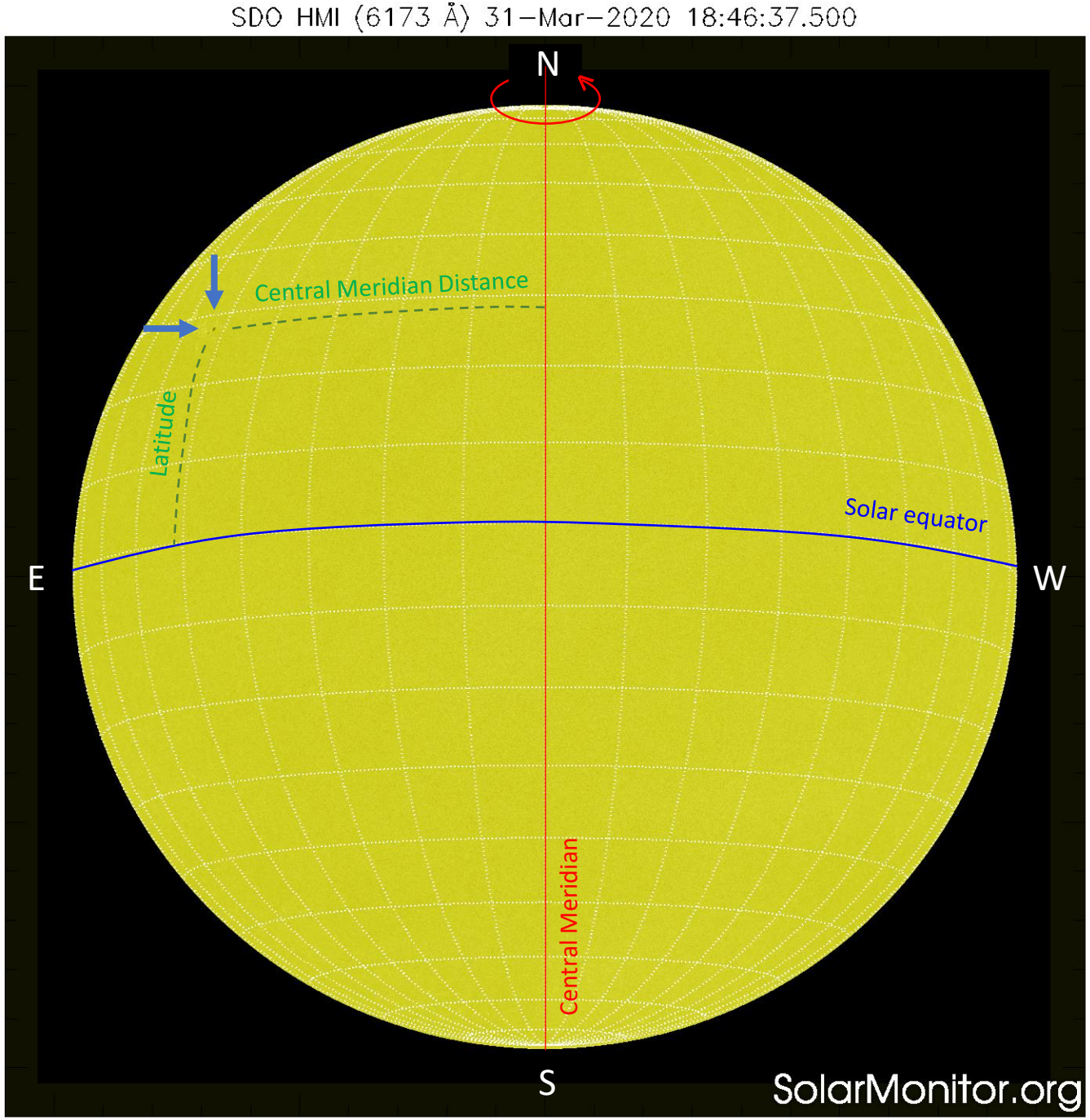
Magnetic field strength



DKIST

Sunspots - Location

- Quadrants
- Solar rotation
  - +/- 27 days (apparent)
    - Carrington rotation
    - +/-13° per day
  - Differential rotation
    - Poles rotate slower than equator
- Position
  - Latitude
  - Central Meridian Distance (CMD)
  - Example
    - N28E52
  - Within a group, sunspots can “wander”



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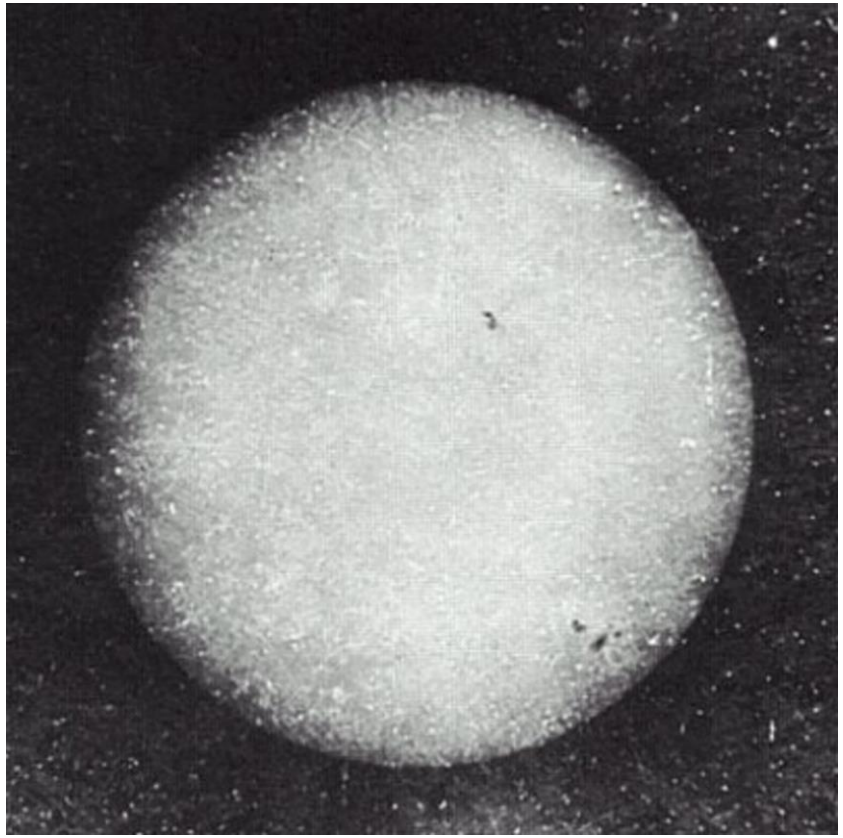
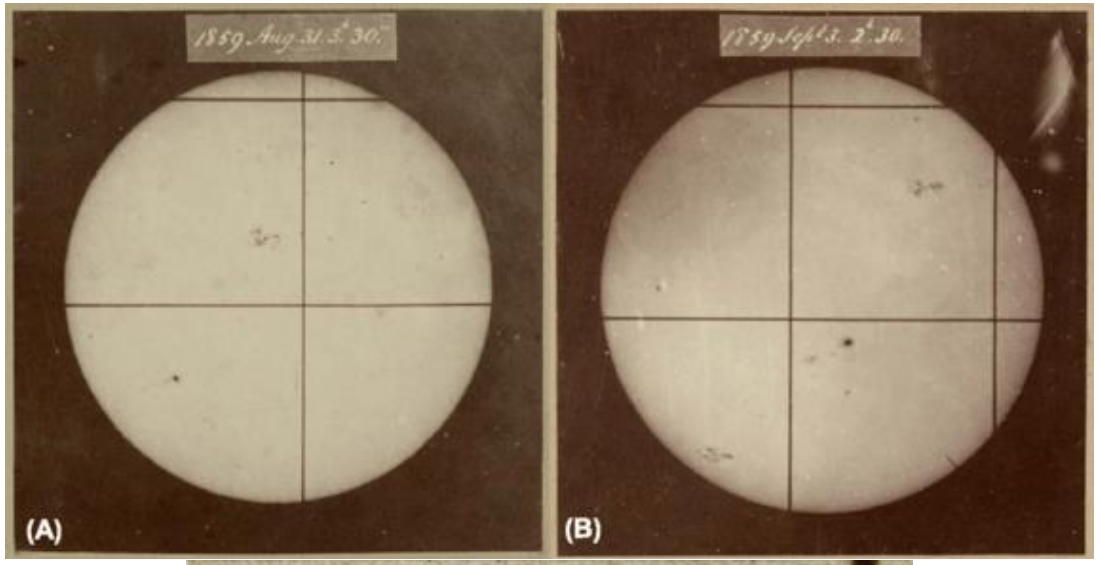
Sunspot groups

First photograph of the Sun – *Fizeau & Foucault (2 April 1845)*

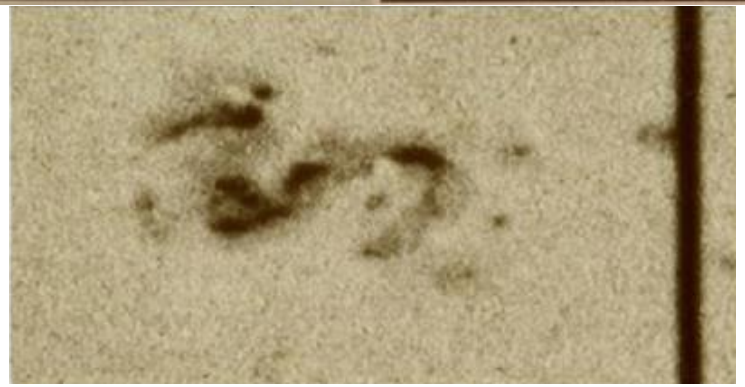


Credits: ESA

Photograph of the Carrington group – *Warren de la Rue on 31 August and 03 September 1859*



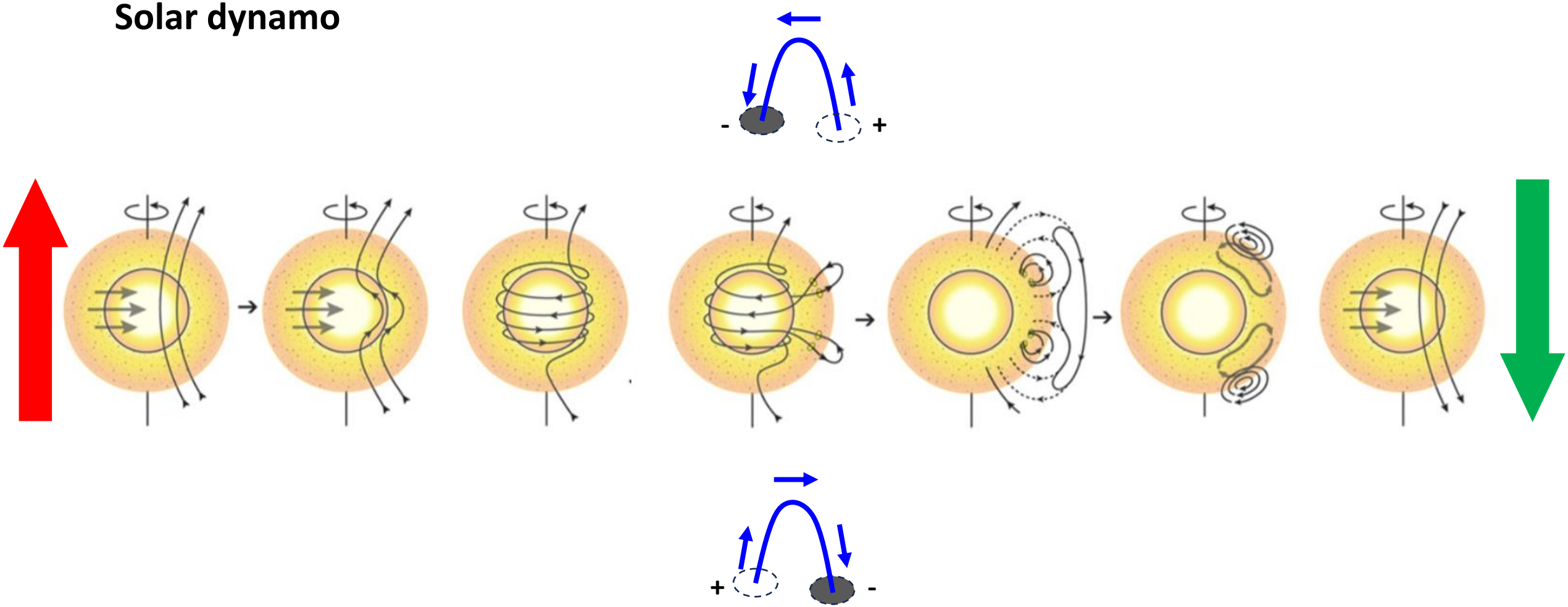
Cliver & Keer 2012



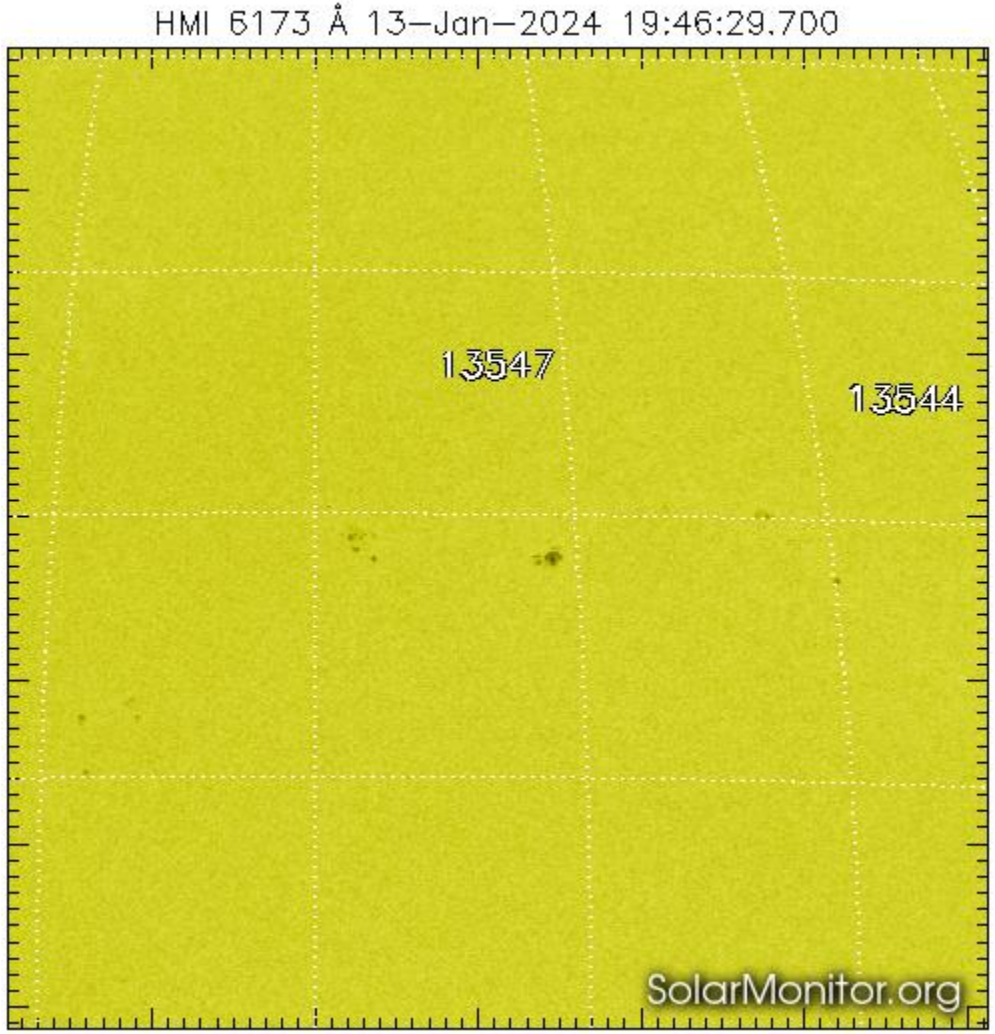
Usoskin et al. 2023

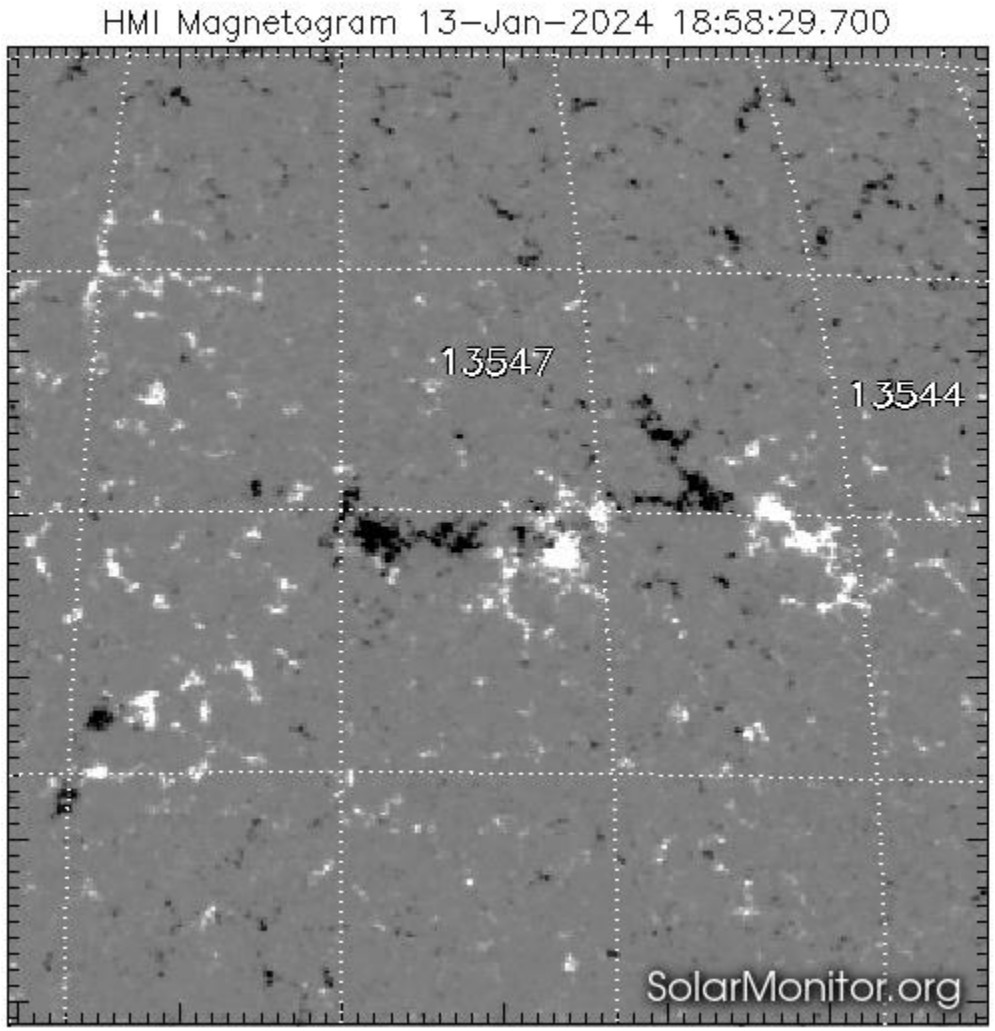
Sunspot groups – Solar dynamo

Solar dynamo



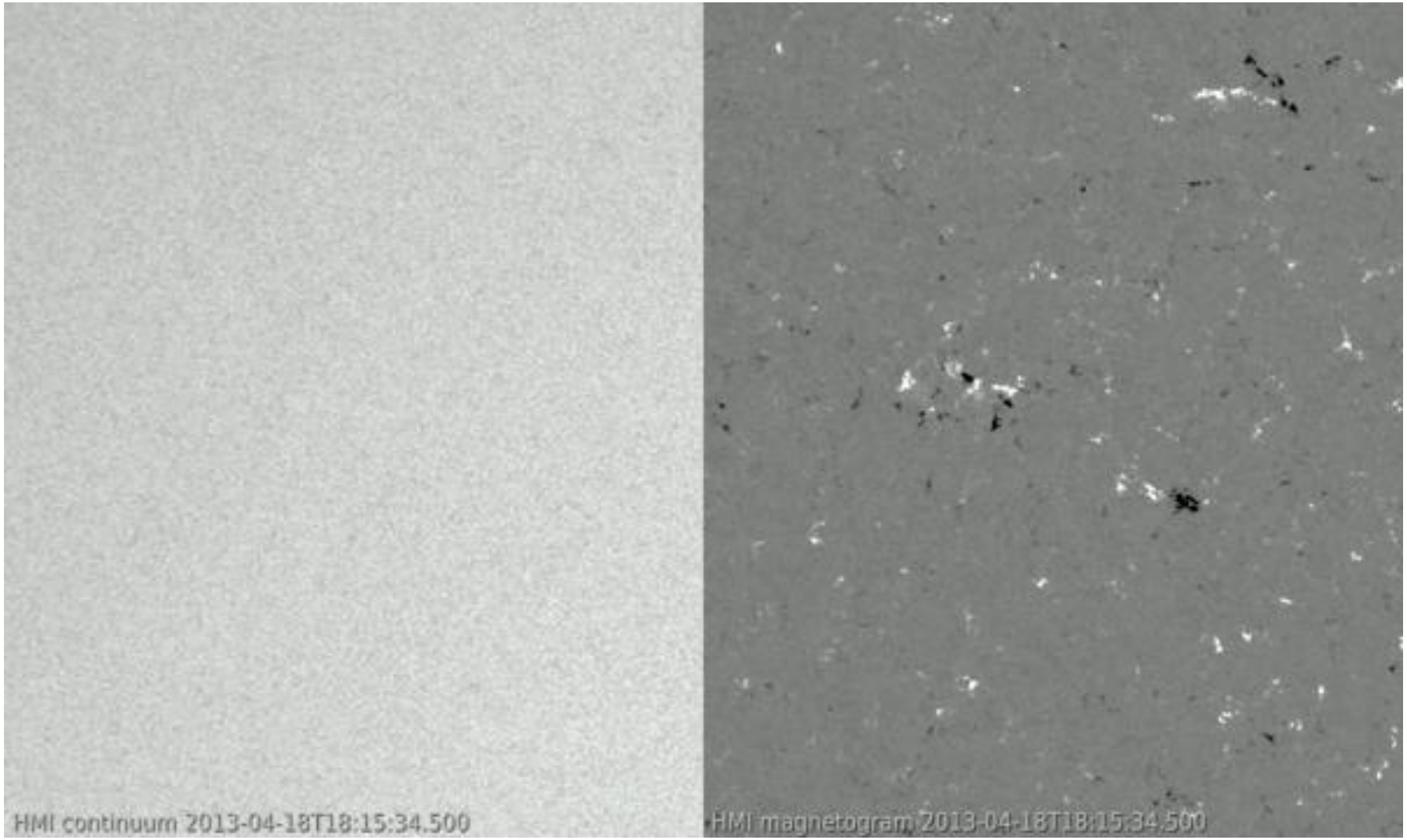
Sunspot groups - Bipolar



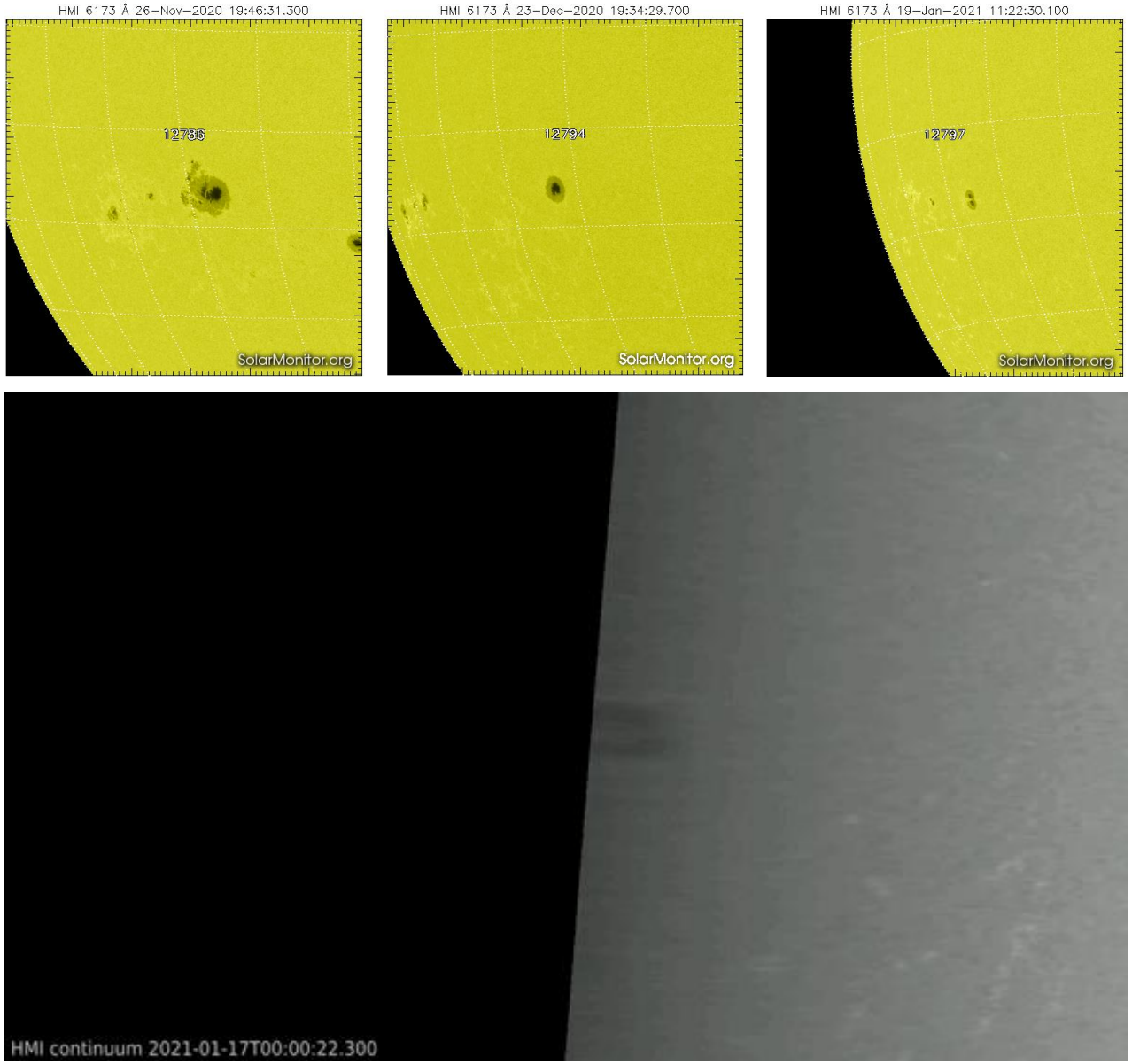


Most sunspot groups are bipolar. During SC24-25: 33% unipolar ; 67% bipolar

Sunspot groups – Evolution (birth)



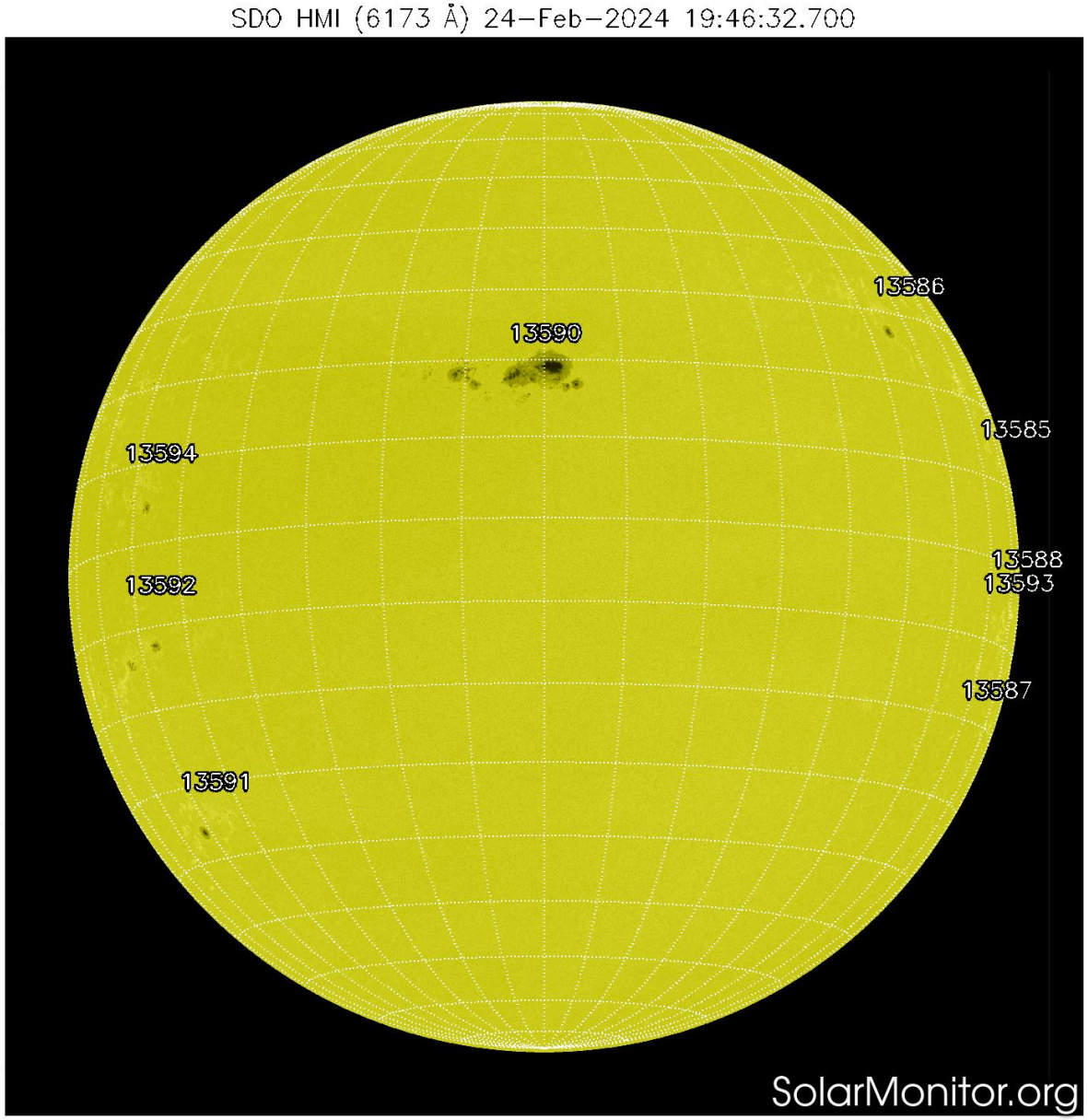
Sunspot groups – Evolution (decay)



Sunspot groups - Numbering

- Greenwich (RGO)
  - 1874-1976
- NOAA/USAF
  - 1972-present
  - Currently at 13615
    - Returning groups get new number
- Catania
  - 0 => 99
  - Start over

- All data (1874-present) at
  - Solar Cycle Science
  - http://solarcyclescience.com/activeregions.html



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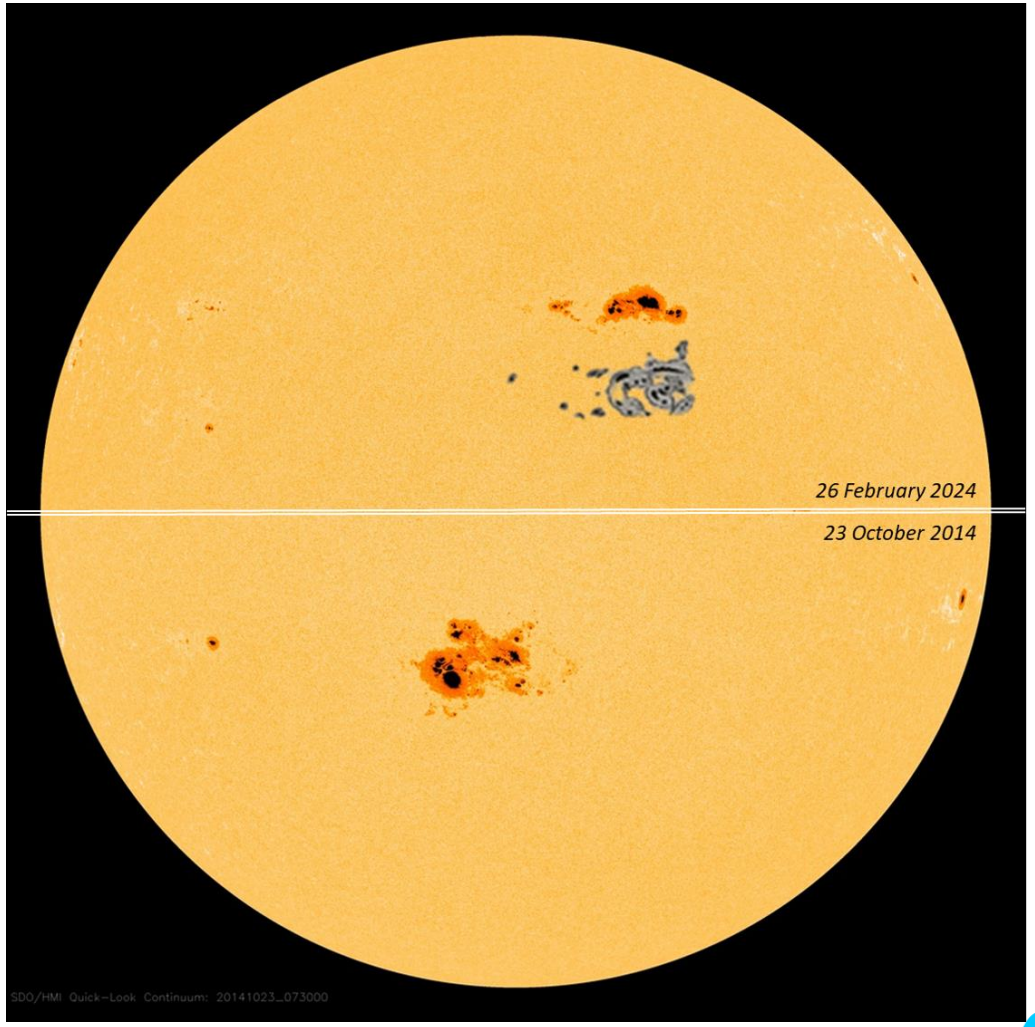
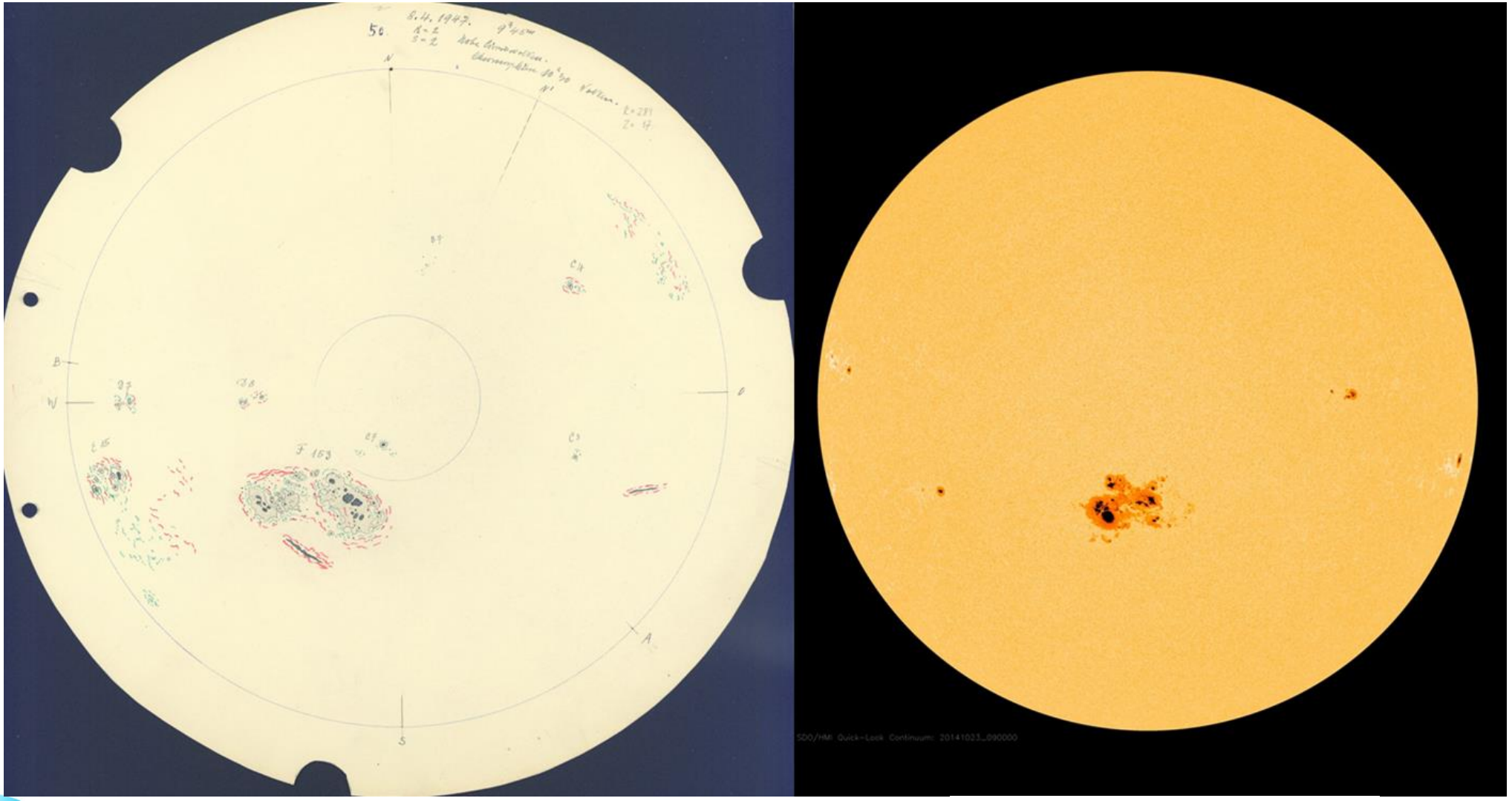
Sunspot groups – Sunspot area

- Expressed in “MH”
  - Millionths of a solar Hemisphere
  - Area $_{Earth}$ = 167 MH
- Several methodologies
  - Differences between Observatories
  - RGO = 1.4 x NOAA
- Sunspot groups:
  - Typical: ~ 170 MH
  - Largest on 8 April 1947
    - Greenwich 1488603
      - 6320 MH



Sunspot groups – Sunspot area

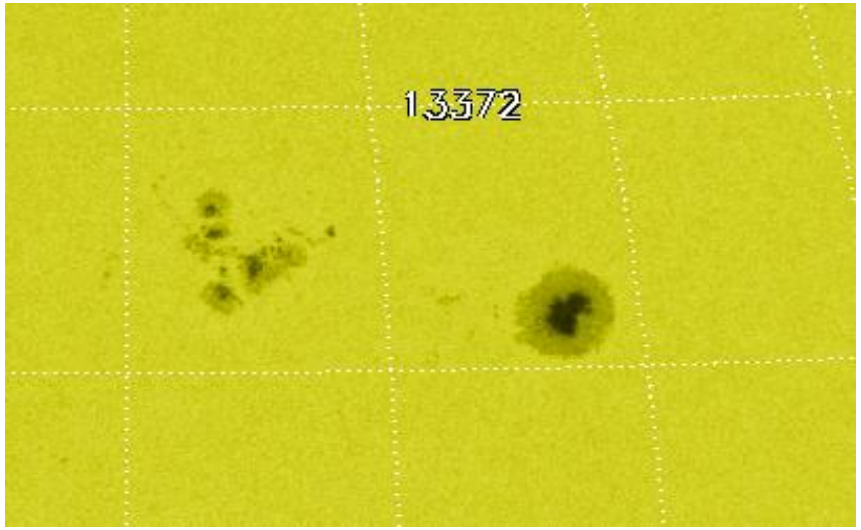


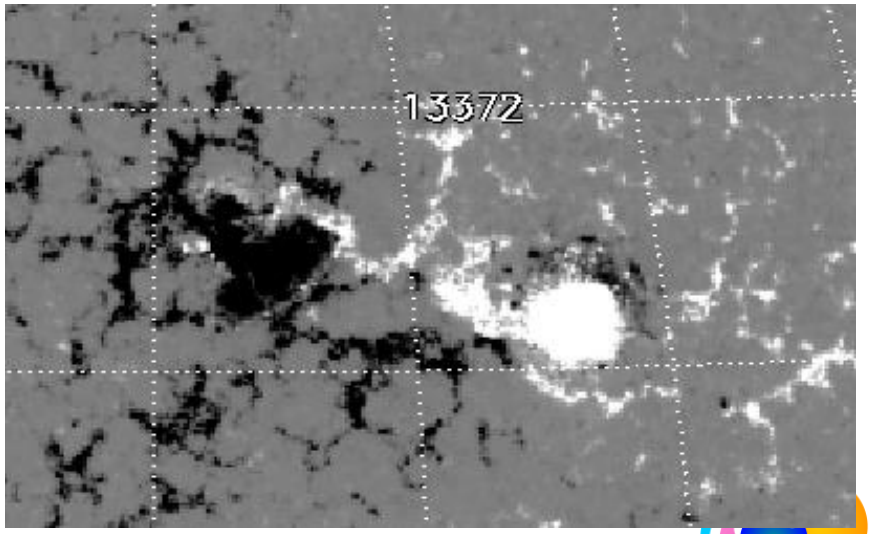
Kanzelhöhe, 8 April 1947

SDO/HMI, 23 October 2003

Sunspot groups – “The” laws (1/2)

- Leading spots tend to have larger MF than trailing spots
  - Form earlier, last longer
- The leading spot is usually more inclined towards the solar equator than the trailing one
  - Effect becomes more pronounced with increasing latitude (“Joy’s law”)
- Leading and trailing sunspots usually have opposite magnetic polarities
  - Opposite between solar hemispheres





Sunspot groups - Classifications

- Two classification schemes
  - White light
    - McIntosh classification
    - Based on the sunspot group morphology
  - Magnetogram
    - Mount Wilson classification
    - Based on the magnetic structure of a sunspot group

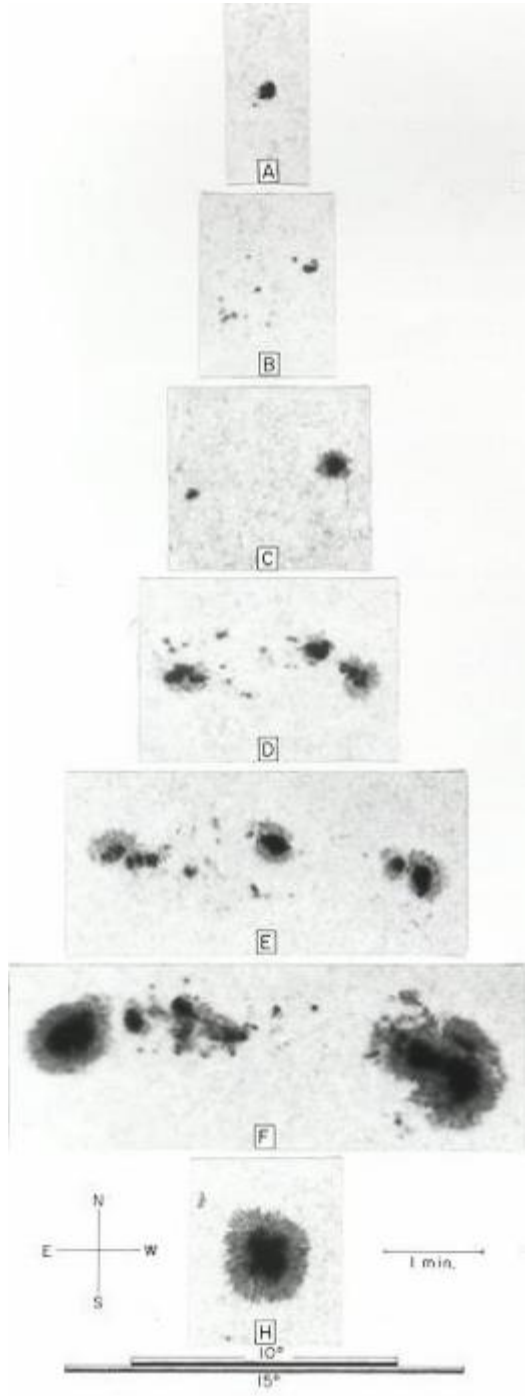
- Detailed discussion and examples at STCE's SWx classification page
  - https://www.stce.be/educational/classification

Sunspot groups - The McIntosh classification

- Developed by P. McIntosh in the late 1960s, published in 1990
- 3 components: Zpc
  - Z – Zürich modified : general outlook of the sunspot group
    - 7 possibilities
  - p – Penumbra: outlook and size of the penumbra of the main spot
    - 6 possibilities
  - c – Compactness: describes the sunspot distribution in the interior of the sunspot group
    - 4 possibilities
- In total not 168 classes, but “only” 60 classes
- Based on a full-disk view of the Sun

The McIntosh classification - Z

- General outlook of the group
  - Unipolar or bipolar group?
    - Unipolar: distance between spots < 3°
    - Bipolar: distance between main spots > 3°
      - If large spots: distance > 5°
  - Penumbra or no penumbra?
  - Penumbra on one or both sides of the sunspot group?
  - Length of the group (>10°? >15°?)
    - Between the outer extremities of the main spots



A

B

C

D

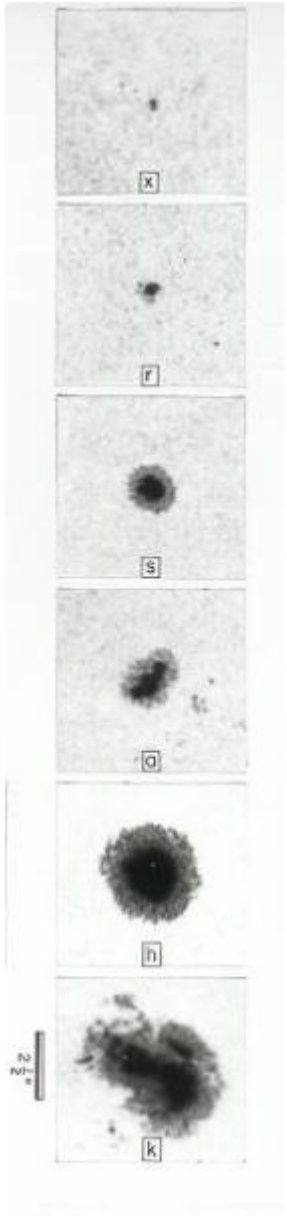
E

F

H

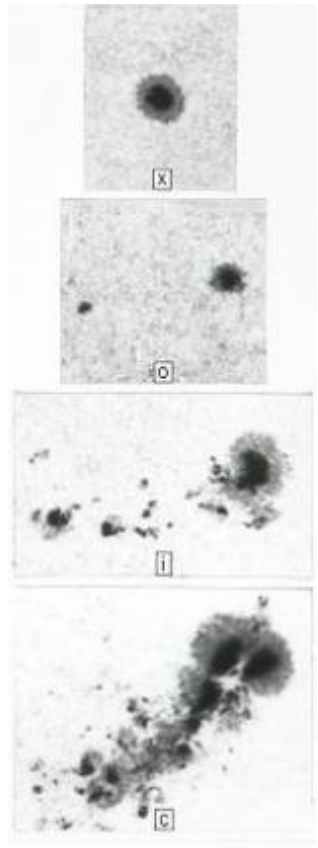
The McIntosh classification - p

- Penumbra and size of principal sunspot
  - Rudimentary or mature penumbra?
    - Rudimentary: incomplete and/or small penumbra
  - Symmetric or asymmetric main spot?
    - Symmetric means also: elliptical, multi umbrae, slight irregularity of the edge
  - North-South diameter of main spot >2,5°?
    - To avoid misleading effect from sunspot stretching by solar rotation
    - “h” and “k” are the big brothers/sisters of resp. “s” and “a”



The McIntosh classification - c

- Internal sunspot distribution
  - Sunspots between leading and trailing main spots?
    - Open: No or a few small spots
    - Intermediate: Numerous small spots, but no mature
  - Is there internally at least 1 spot with a mature penumbra?
    - Compact: many strong spots with at least 1 containing a mature penumbra
    - Extreme case: entire sunspot group enveloped by a continuous penumbra



Sunspot groups - The McI classification - Example

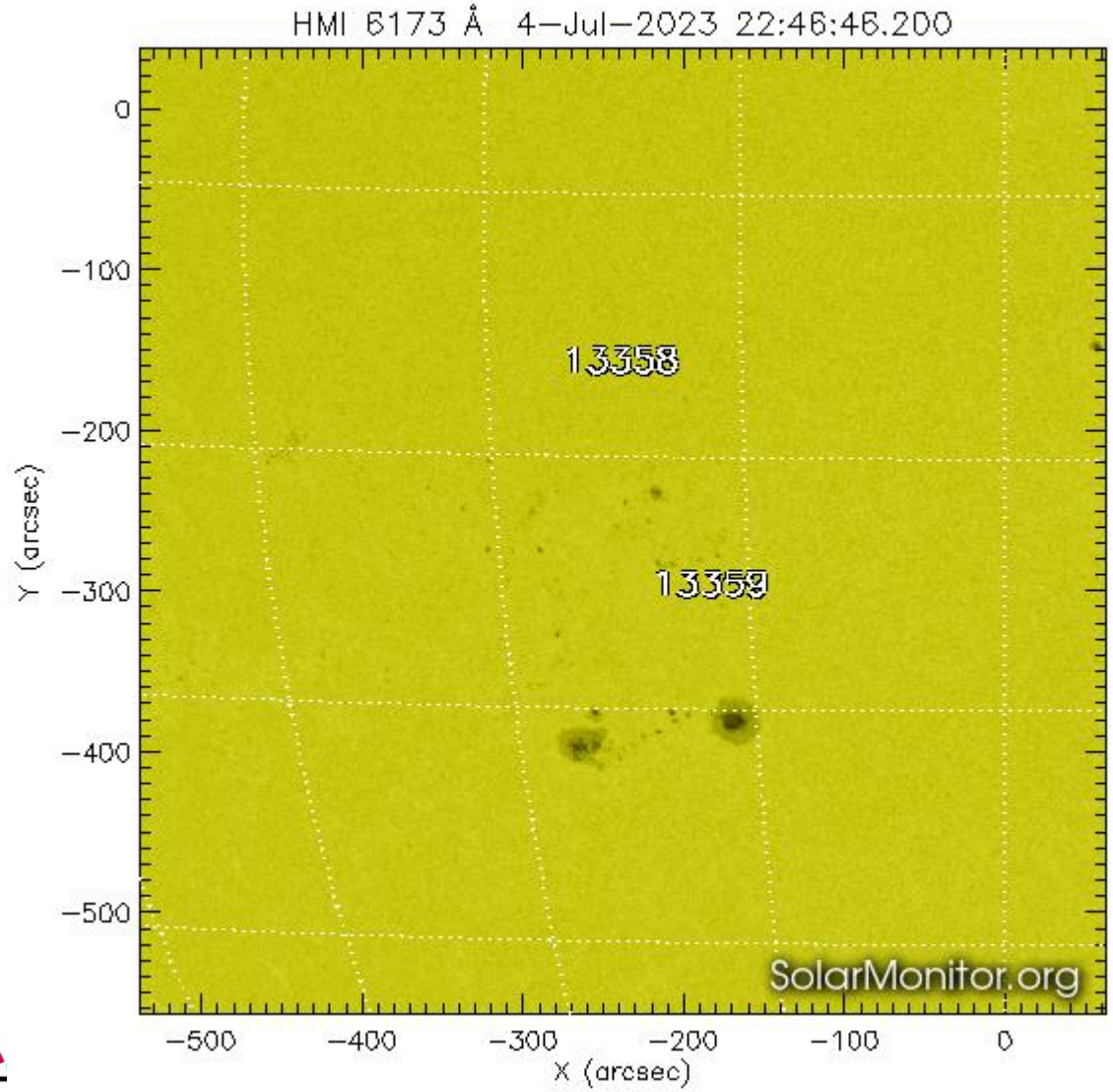


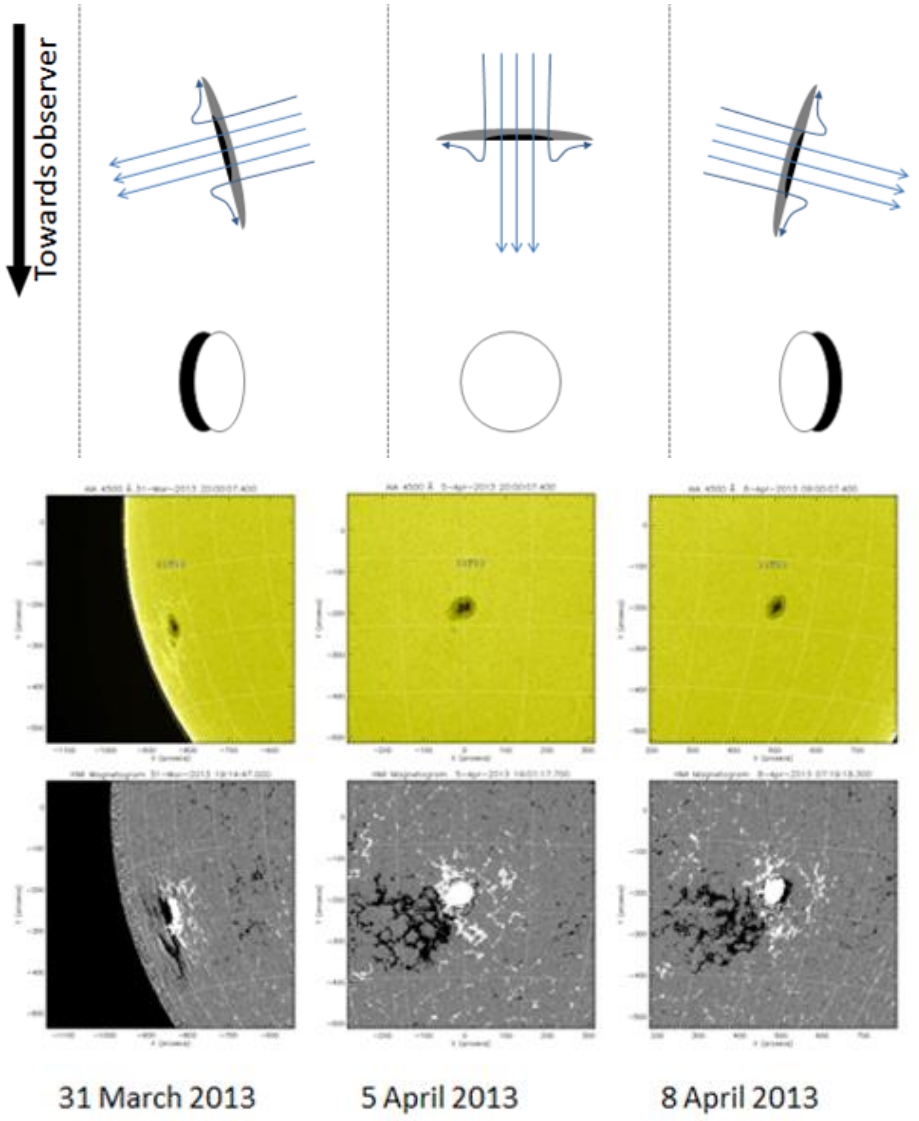
TABLE I

Logic sequence for determining McIntosh sunspot types

Unipolar or bipolar?
Penumbra or no penumbra?
Penumbra on one end or both ends?
Length of group?
Rudimentary or mature penumbra?
Symmetric or asymmetric largest spot?
N–S diameter of largest spot?
Spots between leader and follower?
Mature penumbra in interior?

Sunspot groups - The Mount Wilson classification

- Developed by Hale in the early 20th century
  - Supplemented by Künzel (1960)
    - "Mount Wilson" classification
- Based on magnetic structure of sunspot groups
  - Sunspots, not ephemeral magnetic structures
  - Attention for line-of-sight effects!
    - Near solar limb
- Only 7 classes
  - A (α)
  - B (β), BG (βγ), G (γ)
  - BD (βδ), BGD (βγδ), GD (γδ)



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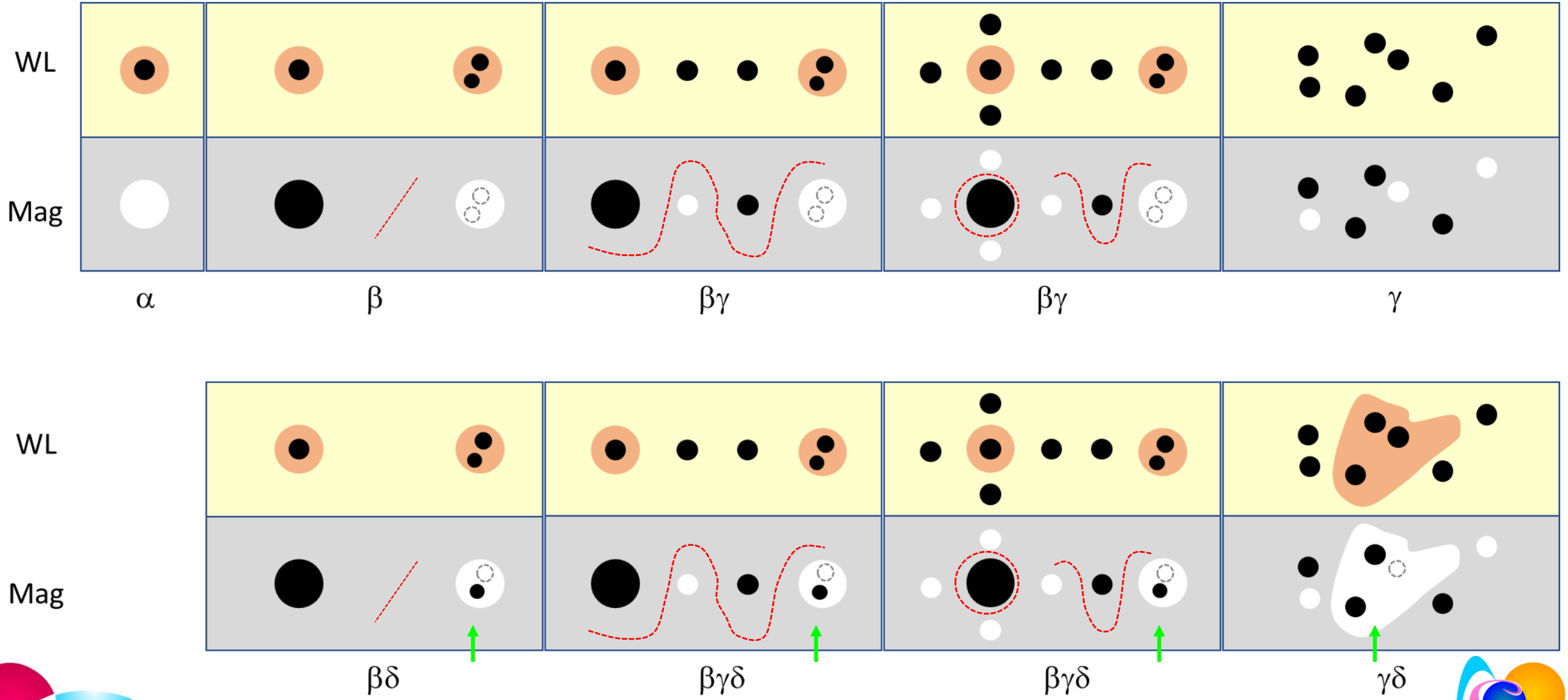
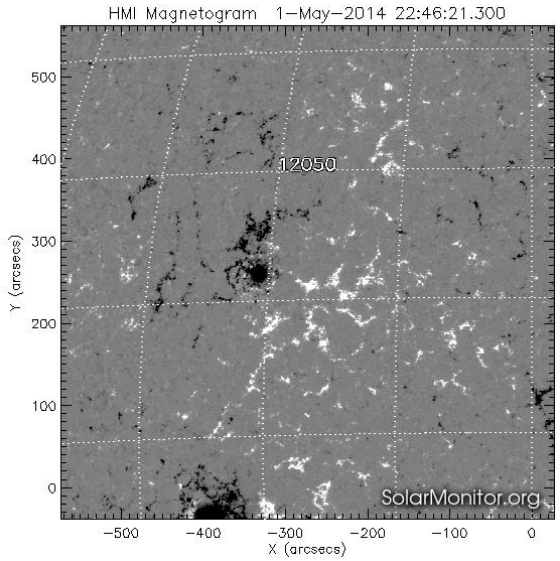
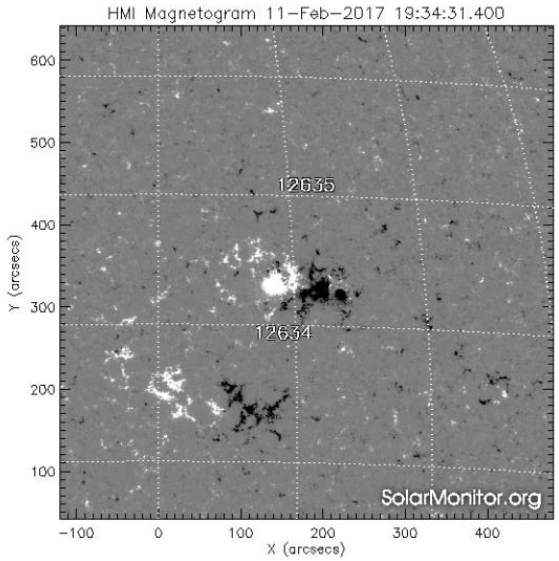
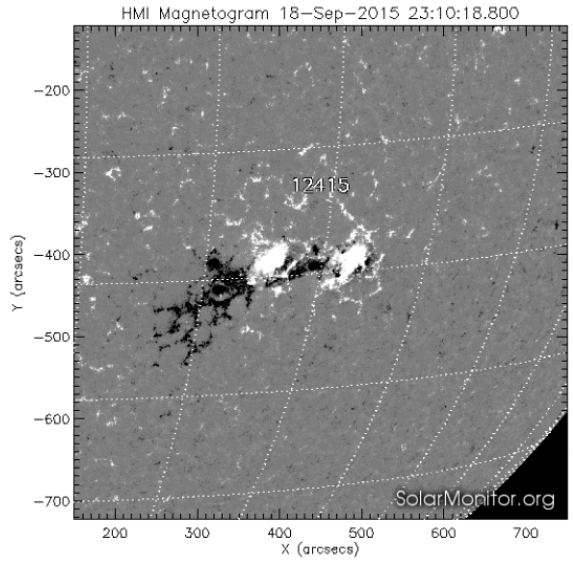
Sunspot groups - The MtW classification - sketch

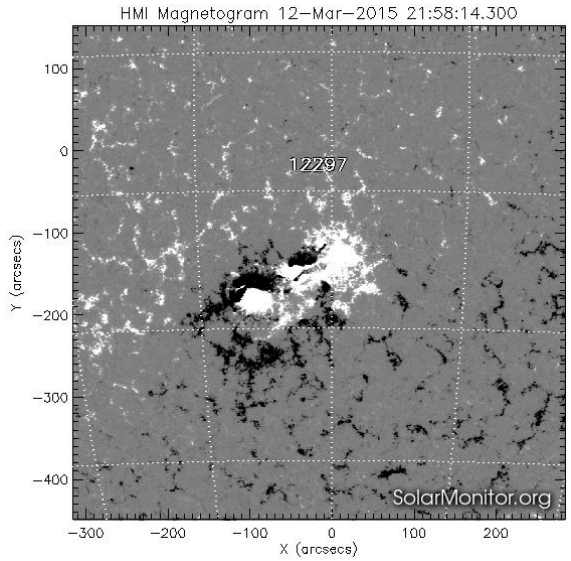


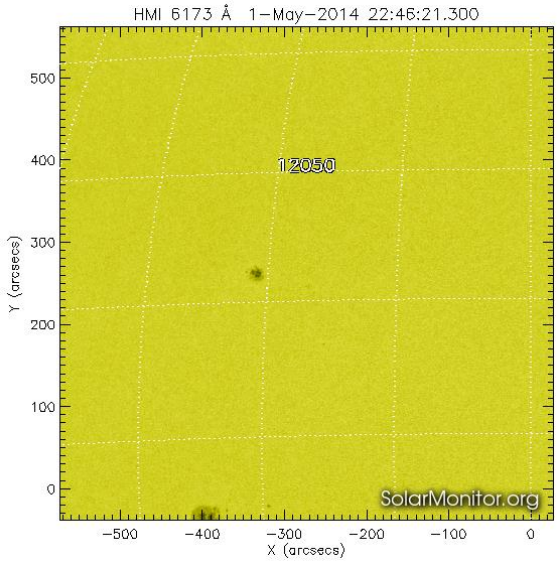
Sunspot groups - The MtW classification - Examples

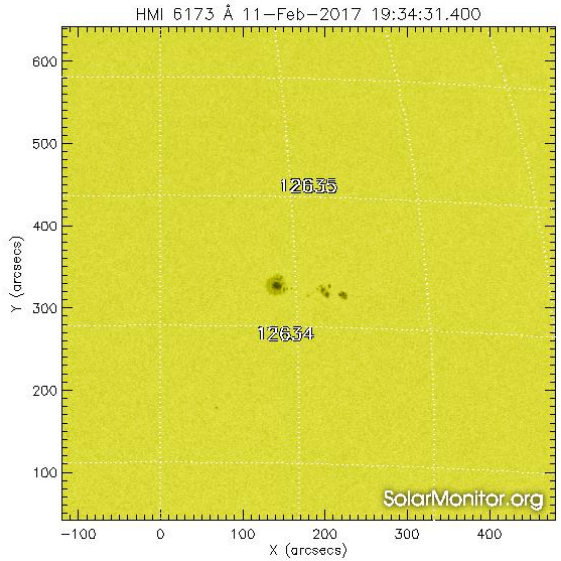


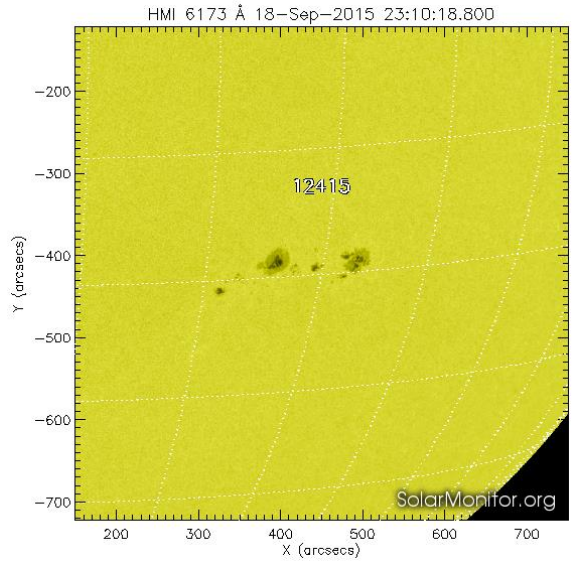


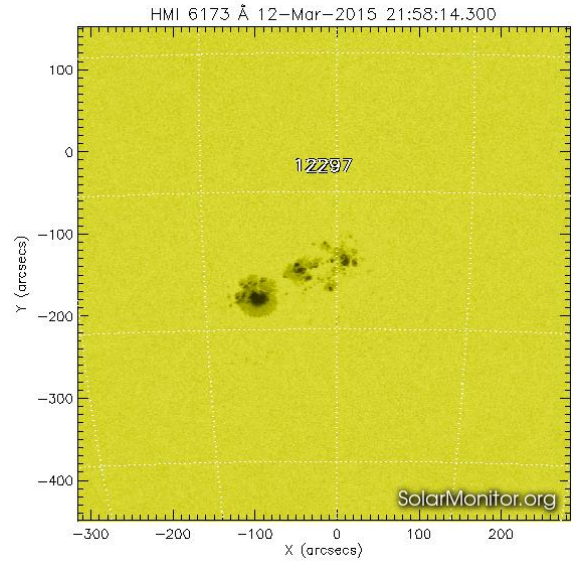








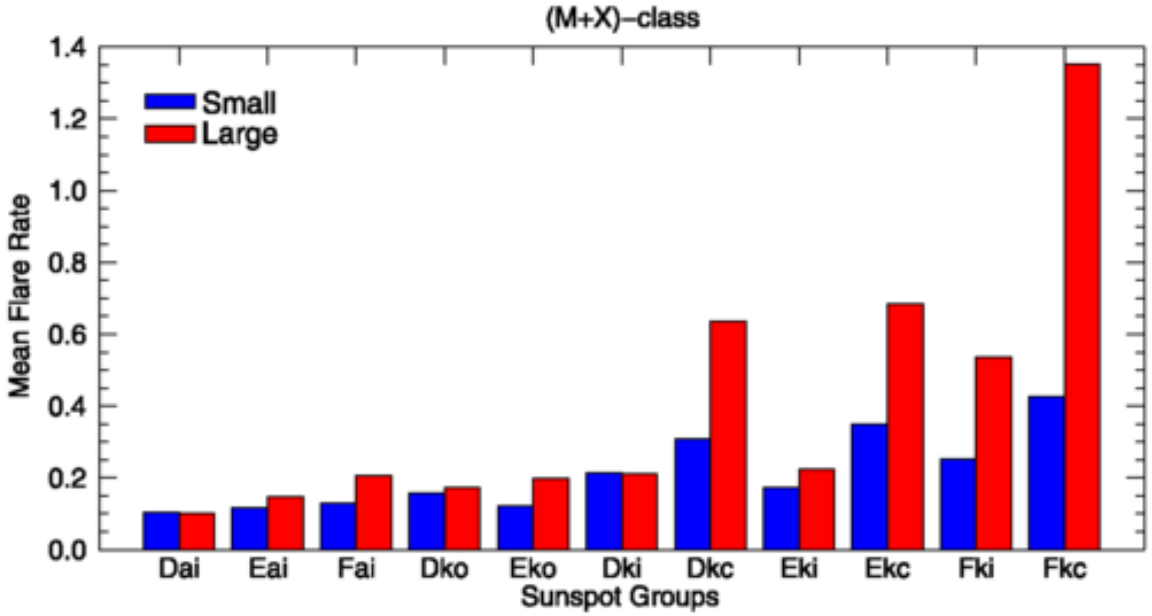




α β βγ βγδ

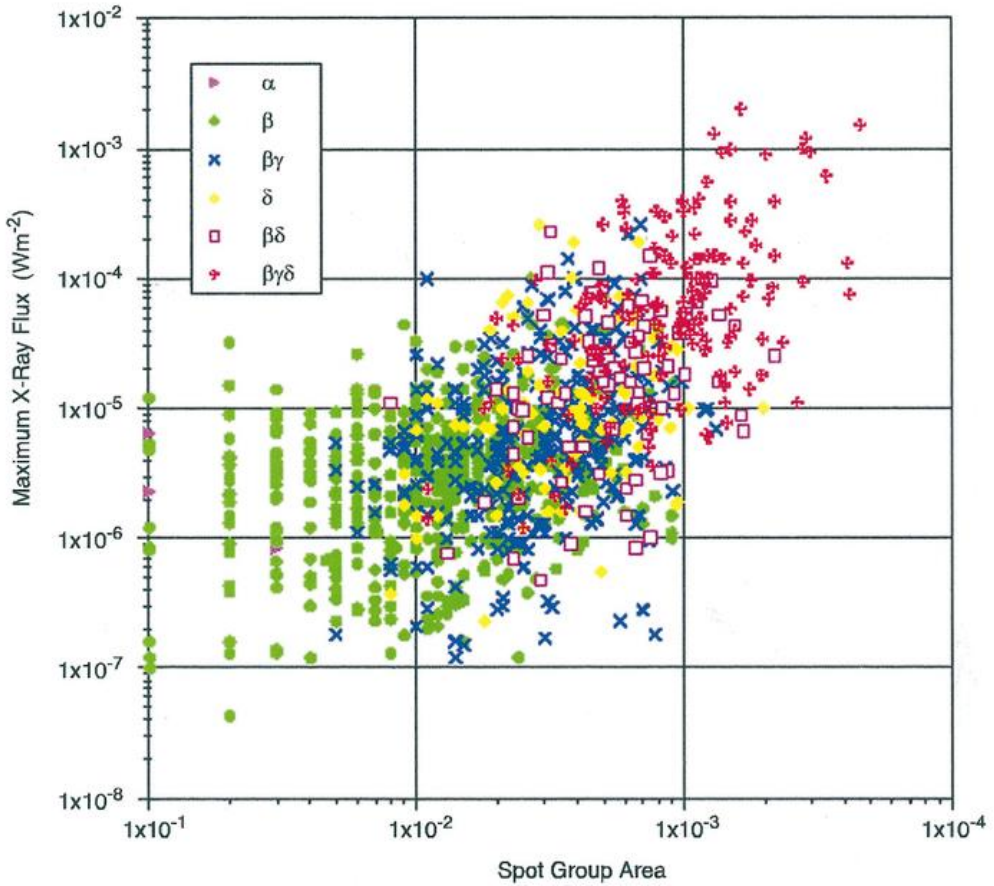
Sunspot groups – Flare rates

McIntosh classification



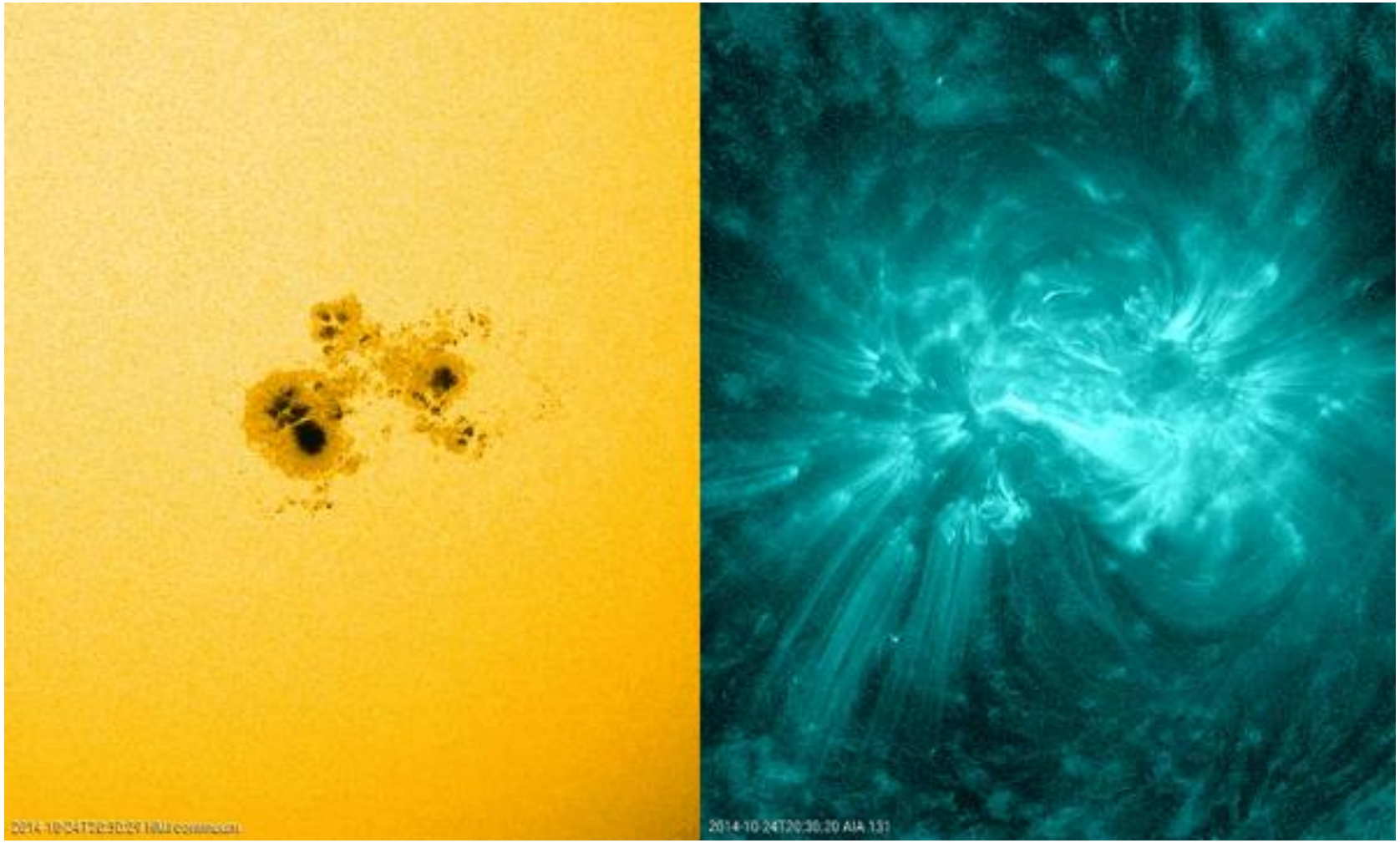
Credits: Lee et al. 2012

MtWilson classification



Credits: Toriumi & Wang 2019

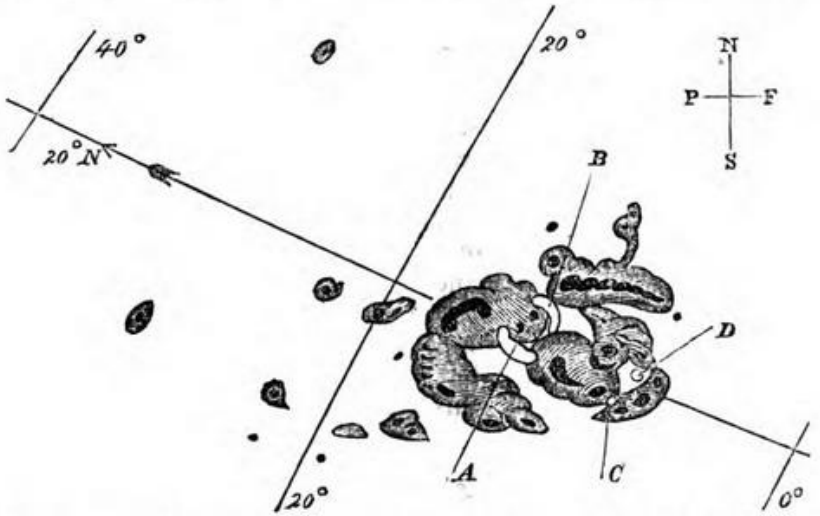
Sunspot groups - Flares



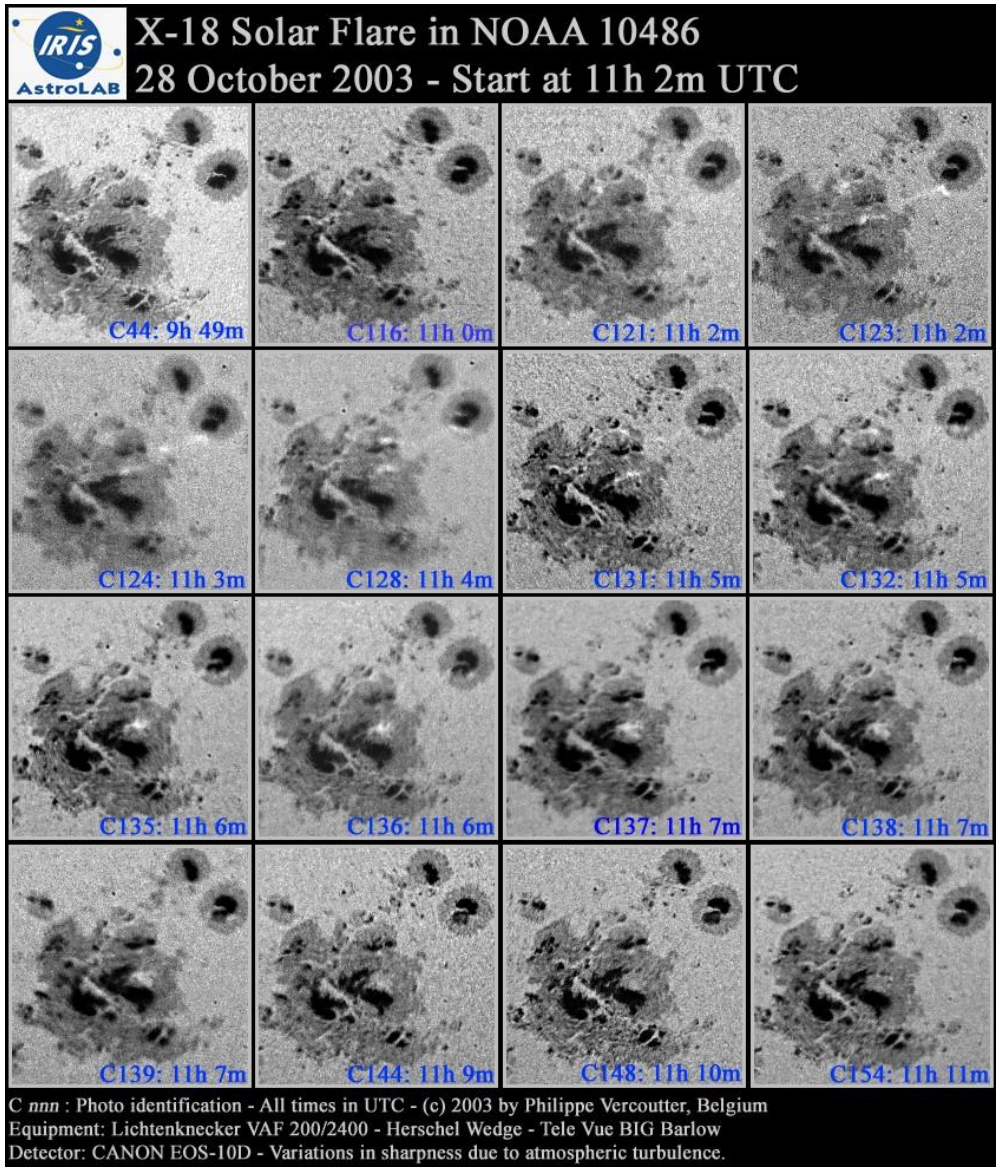
Sunspot groups – White Light Flares (WLF)

Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by



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Sunspot number – What is it?

- Developed by Rudolf Wolf

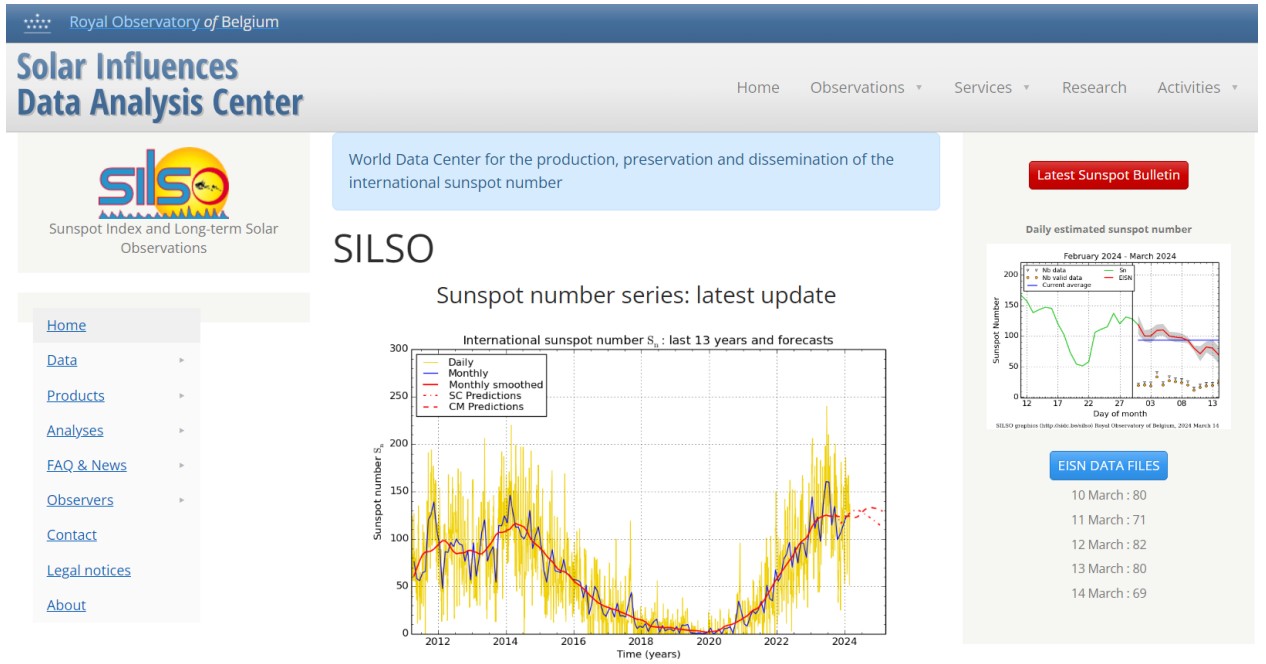
- *Sn = k(10g + f)* , with
  - g: number of sunspot groups (*"Gruppe"*)
    - "10" : avg. # of sunspots/group
  - f: number of individual spots (*"Fläche"*)
  - k: correction factor for the observer
    - Size telescope
    - Observation method used
    - …

    ➢ *Wolf as reference observer (initially)*

    ➢ *"Relative" sunspot number ("R")*

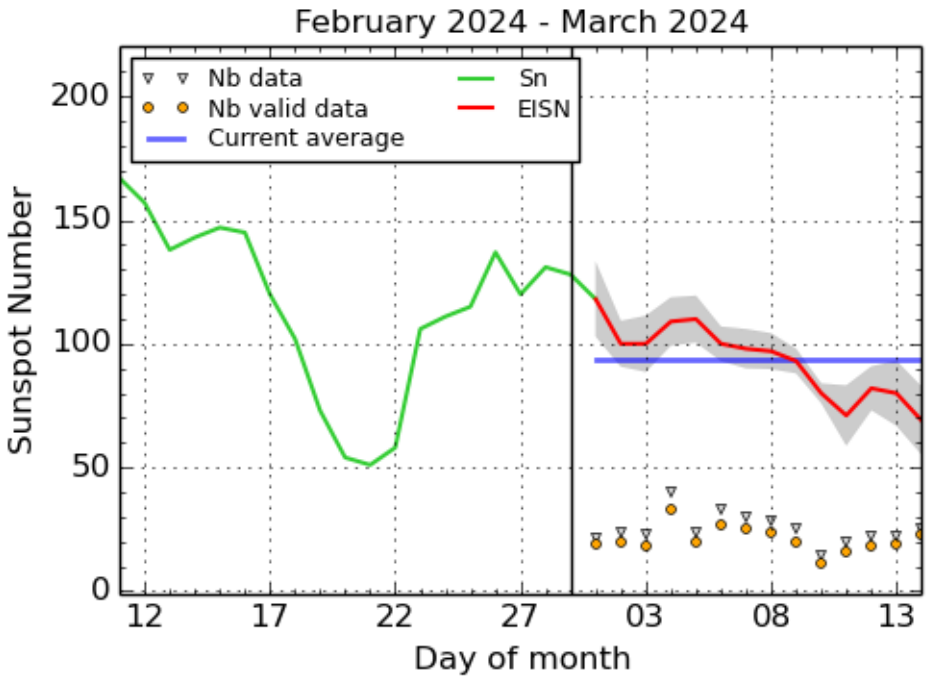
Sunspot number – What is it?

- Developed by Rudolf Wolf
- Since 1981 compiled by the SIDC
  - SILSO: Sunspot Index and Long-term Solar Observations
    - World Data Center for the international sunspot number
    - Global network of +/- 80 stations
  - Fully revised in 2015
    - https://www.sidc.be/SILSO/datafiles
    - Alfred Wolfer as reference base
      - 8 cm refractor
      - Specola/Locarno pilot station
    - Corrected for weighted sunspot count after 1947



Sunspot number – Several “flavors”

- Daily Estimated International Sunspot Number (EISN)
- Provisional International Sunspot Number
- Definitive International Sunspot Number

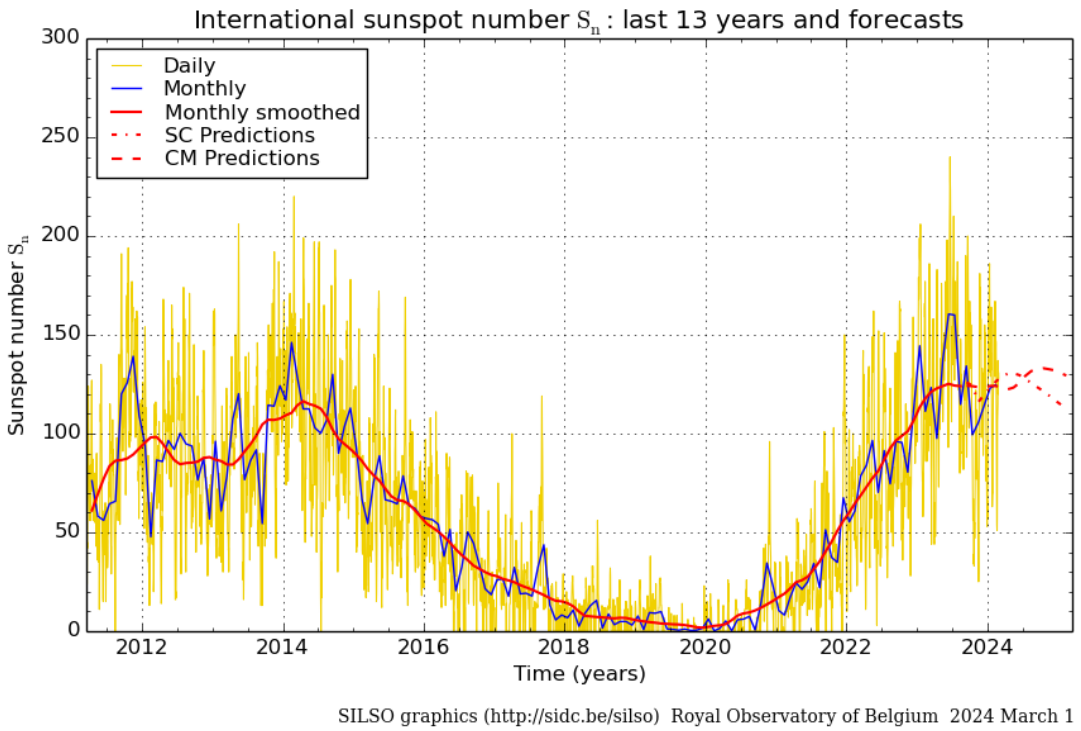


SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium, 2024 March 14

Sunspot number – Several “flavors”

- Daily Estimated International Sunspot Number (EISN)
- Provisional International Sunspot Number
- Definitive International Sunspot Number
- Smoothed monthly Sn

$$Sn_{ms} = \frac{1}{12}\left[\sum_{n-5}^{n+5} R_k + \frac{1}{2}\left(R_{n+6} + R_{n-6}\right)\right]$$



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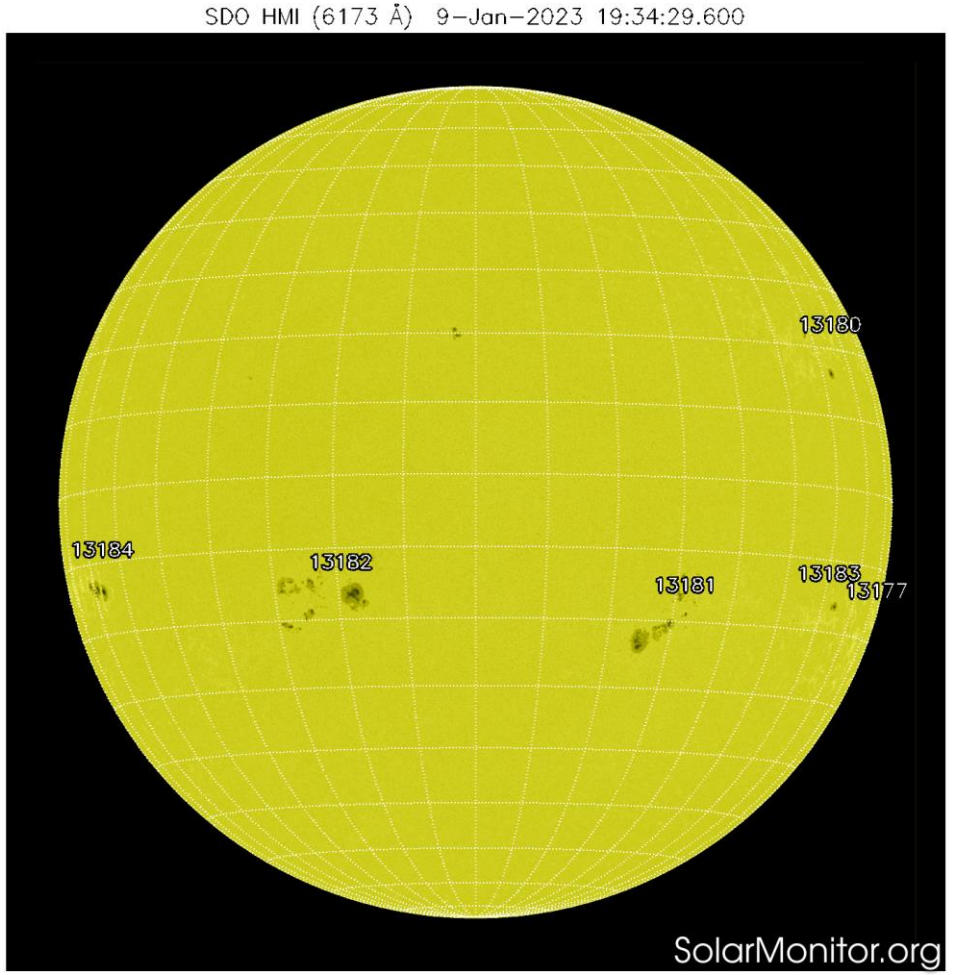
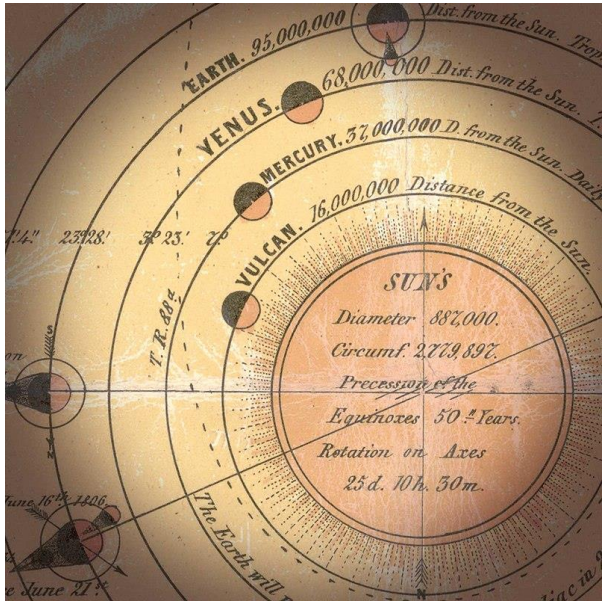
- Hemispheric sunspot number
  - Sn(N) , Sn(S)

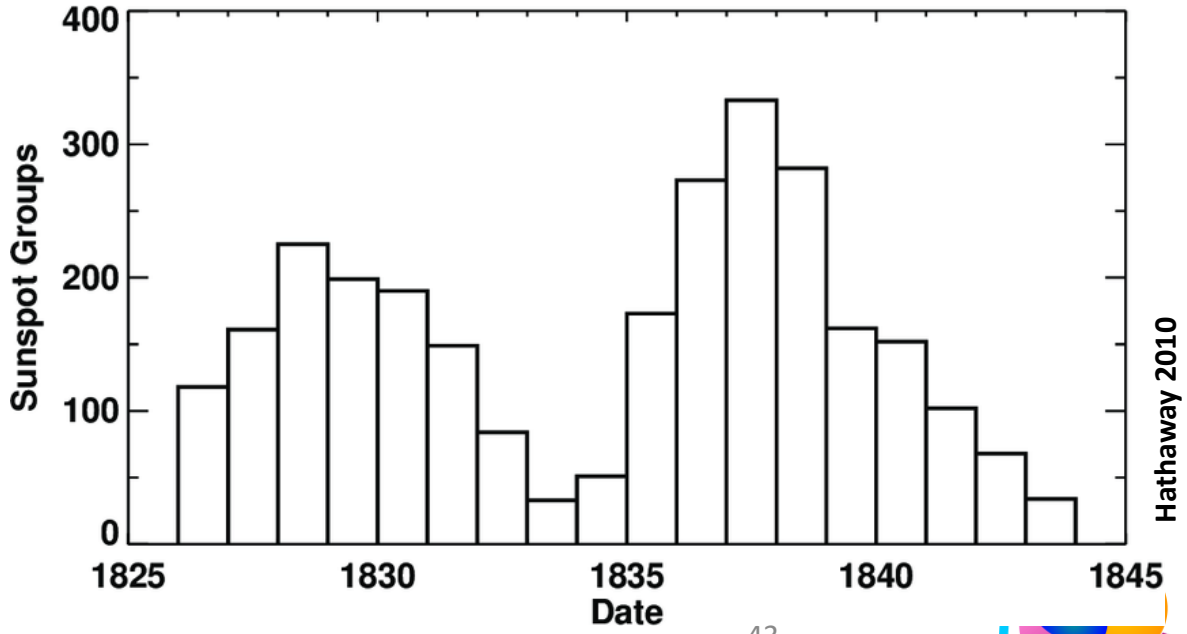


Sunspot cycle – History

- Discovered by Heinrich Schwabe
  - 1844
  - Observations from 1826-1843
  - Actually looking for the planet “Vulcan”
  - Based on the number of
    - Sunspot groups
    - Spotless days
  - Period of about 10 years



Lith. of E. Jones & G.W. Newman, 1846



Hathaway 2010

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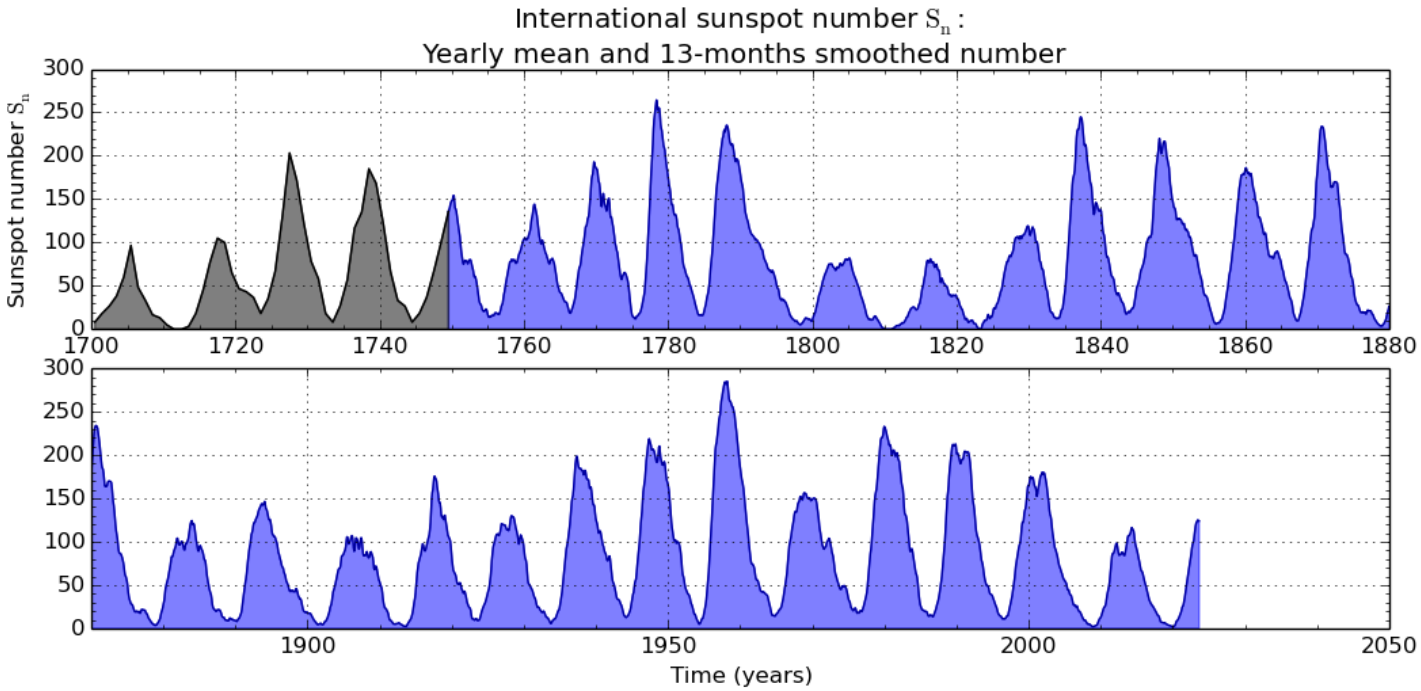
  - Period of about 10 years
- Finetuned by Rudolf Wolf
  - Sunspot number
  - Traced back to 1749
    - SC01 starts in 1755
    - Period of about 11.1 years



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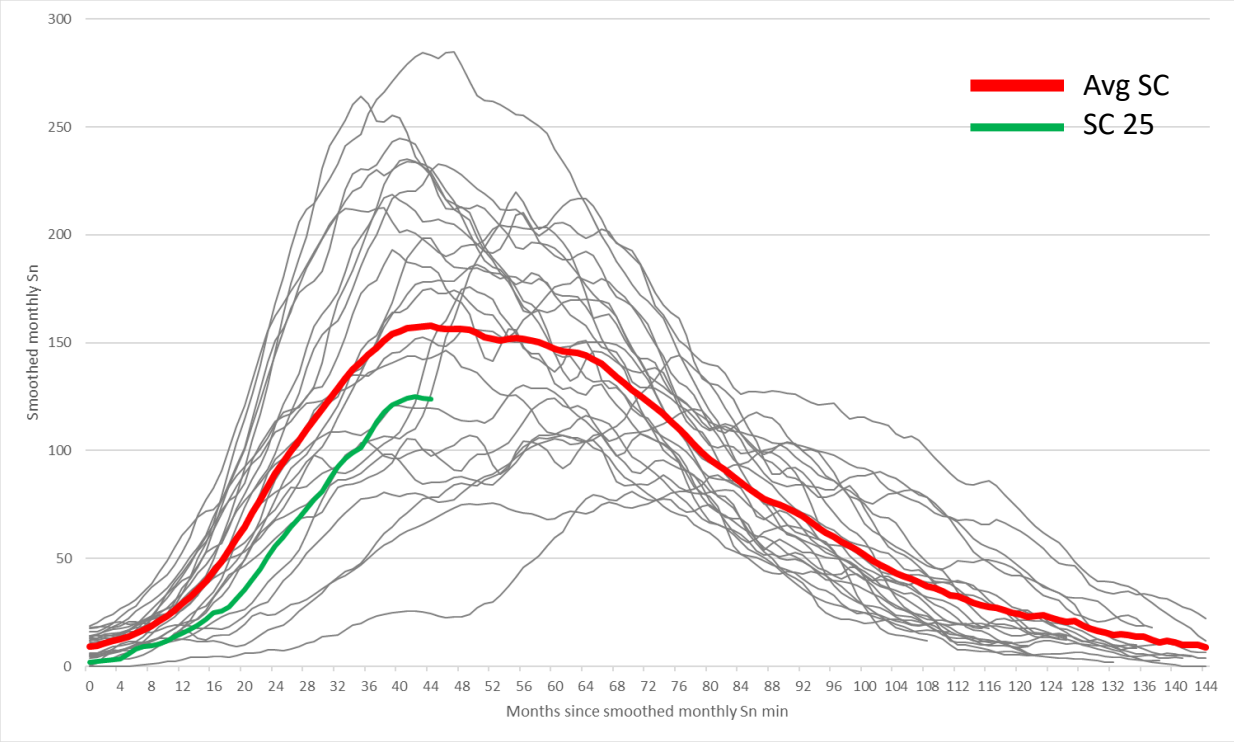
Sunspot cycle – Properties *(SILSO: SC01-24)*

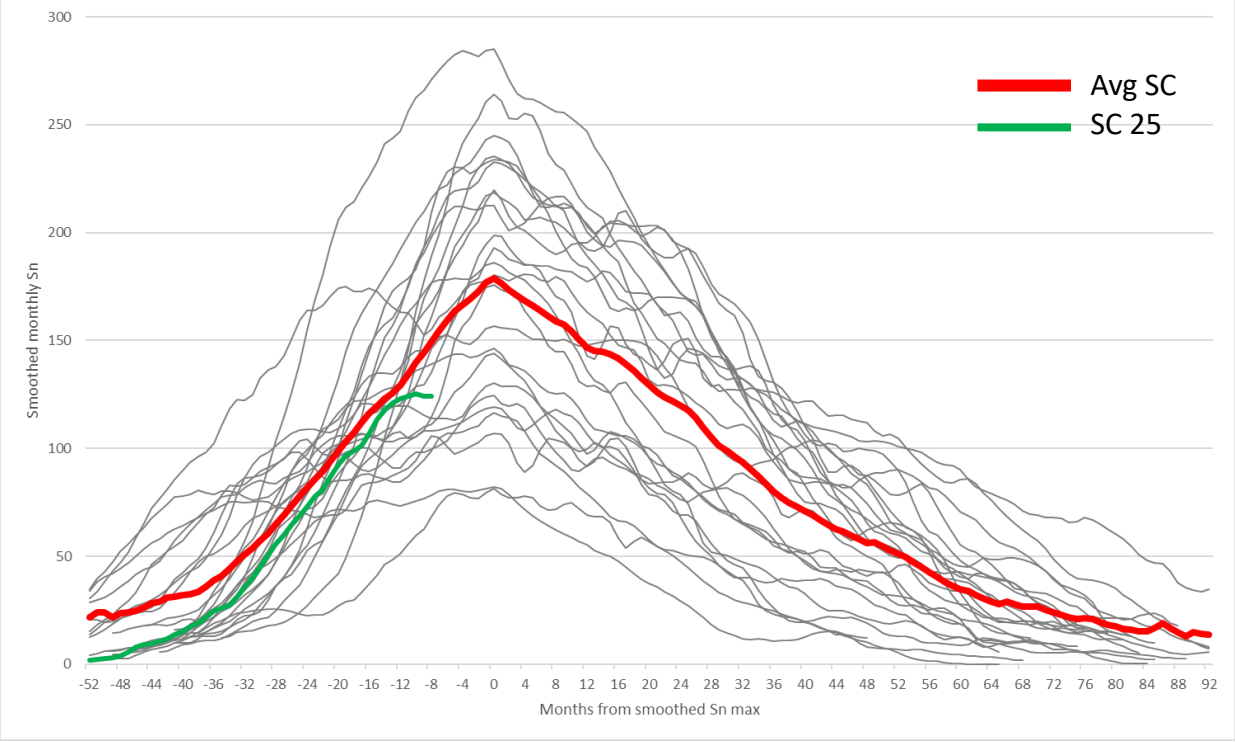
Sn_{min} = 9.3 ± 5.7

T_{dur} = 132 ± 14 months

Sn_{max} = 178.7 ± 57.8

T_{rise} = 52 ± 14 months



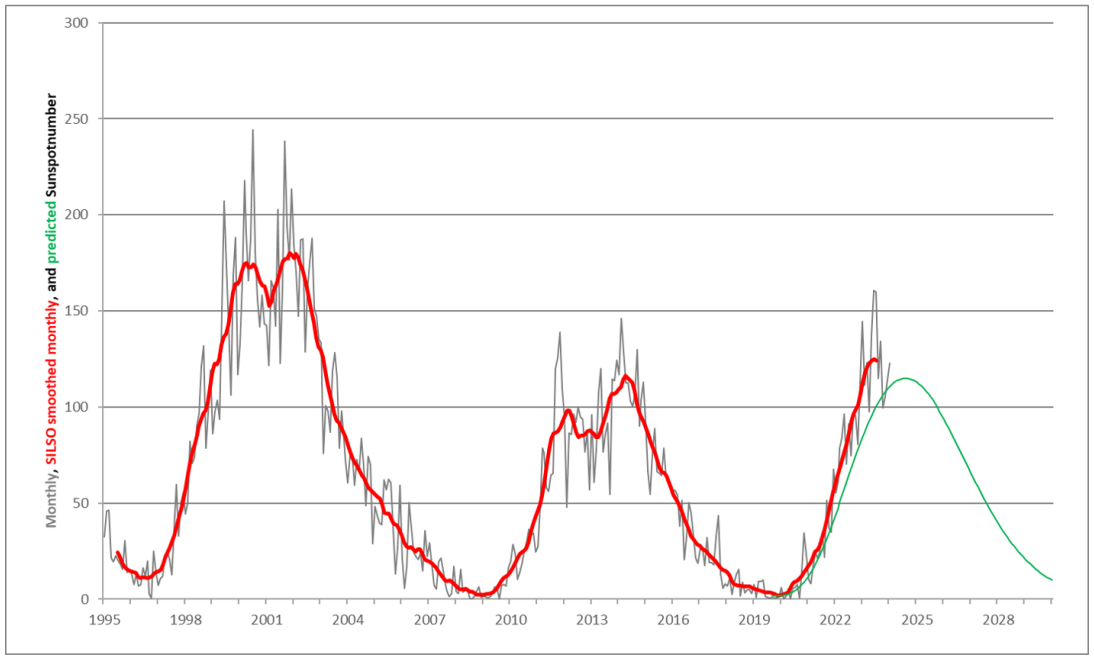


	Sn min	Sn max	Tdur	Trise
Minimum	0.0	81.2	108	35
Maximum	18.6	285.0	163	82

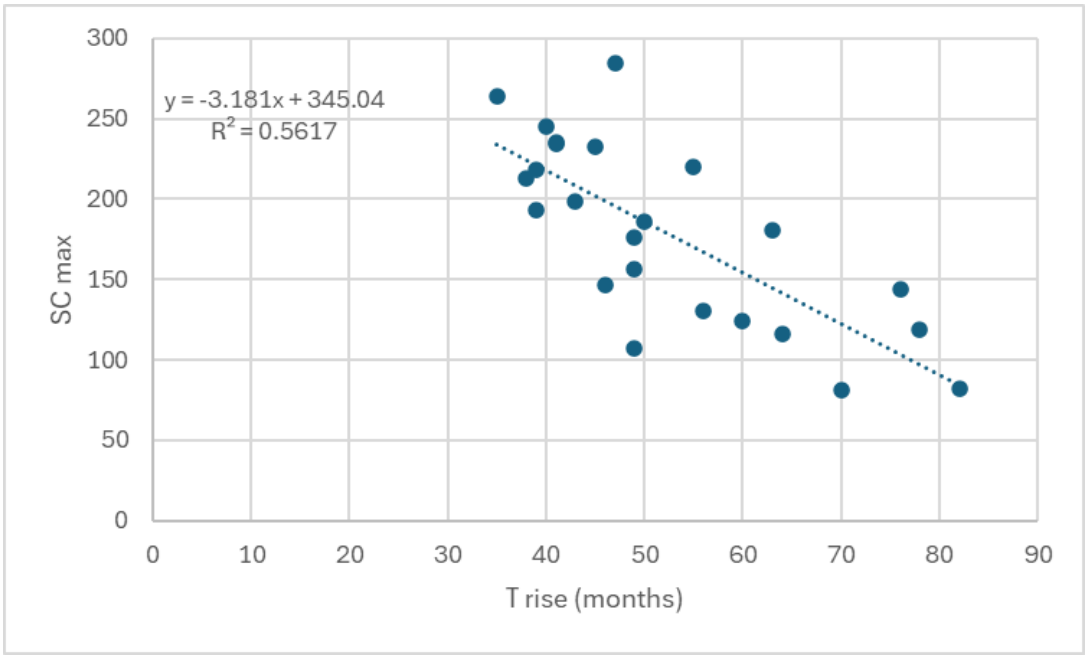
Sunspot cycle - Properties

Double peaked SC (40%)

Gnevyshev peaks and gap (1967)



T_{rise} vs SC_{max} *(Waldmeier effect)*



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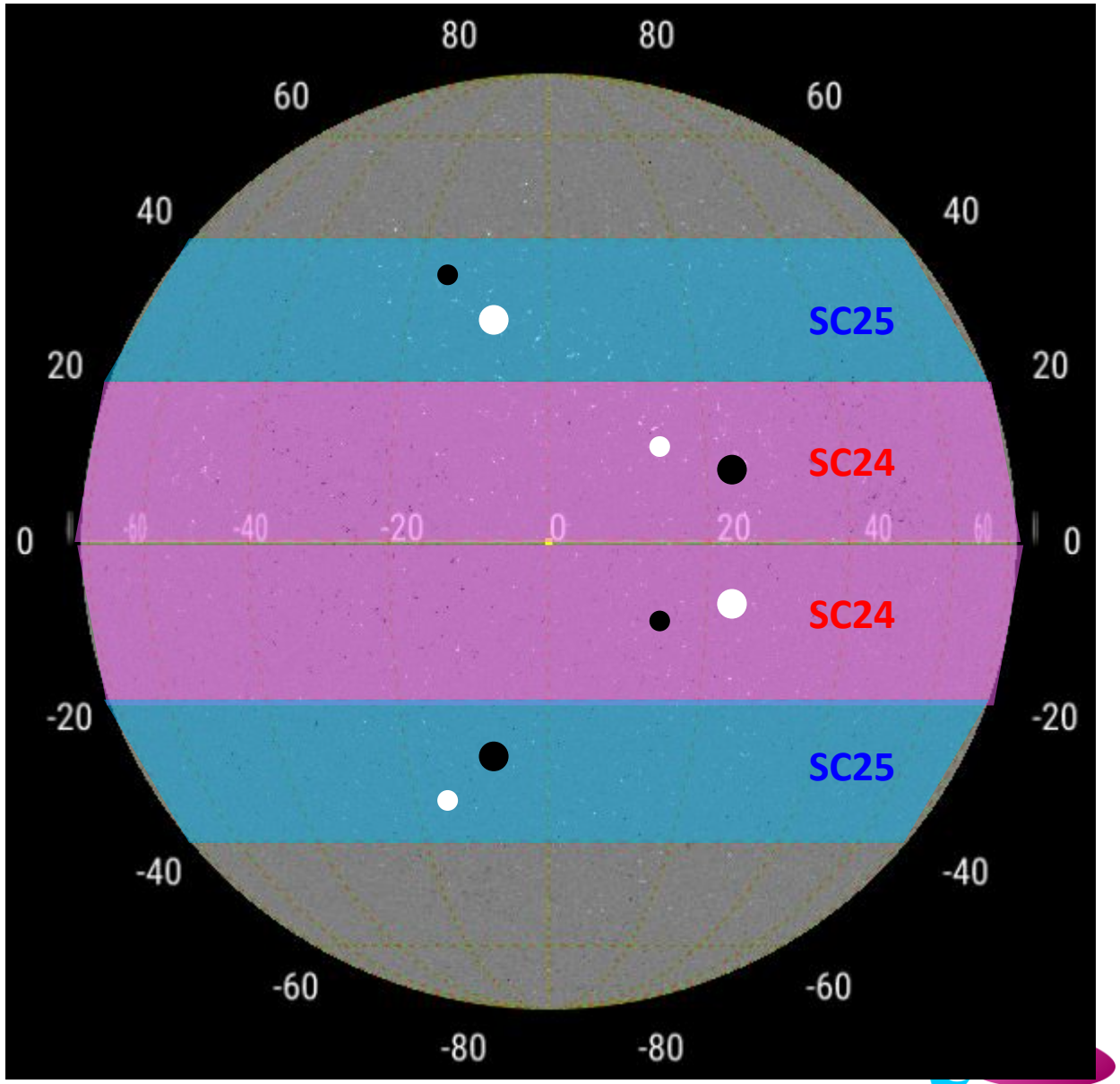
Sunspot groups – “The” laws (2/2)

- Leading spots tend to have larger MF than trailing spots
  - Form earlier, last longer
- The leading spot is usually more inclined towards the solar equator than the trailing one
  - Effect becomes more pronounced with increasing latitude (“Joy’s law”)
- Leading and trailing sunspots usually have opposite magnetic polarities
  - Opposite between solar hemispheres
  - Magnetic polarities reverse from one solar cycle to the next (“Hale’s law”)
    - 22 year magnetic cycle (“Hale cycle”)
- Over the course of a solar cycle, sunspot groups emerge closer and closer to the solar equator (“Spörer’s law of sunspot zones”)



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- Over the course of a solar cycle, sunspot groups emerge closer and closer to the solar equator (“Spörer’s law of sunspot zones”)
  - Butterfly diagram (Maunder, 1904)

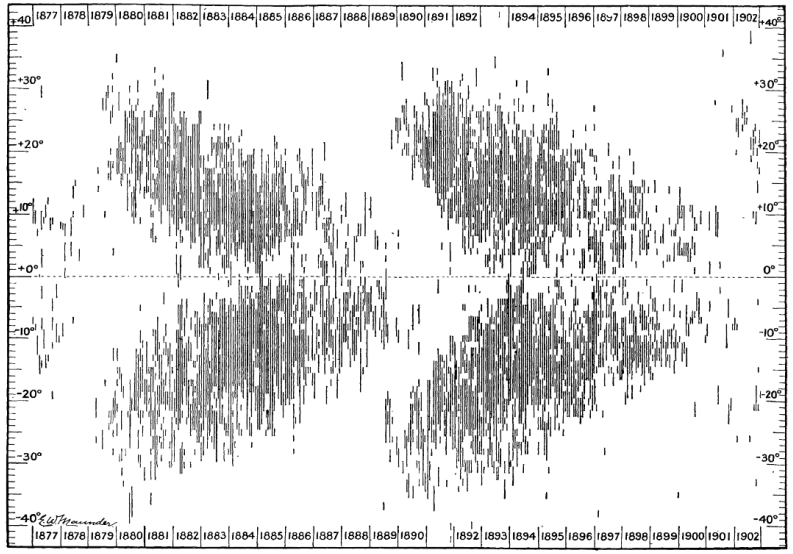
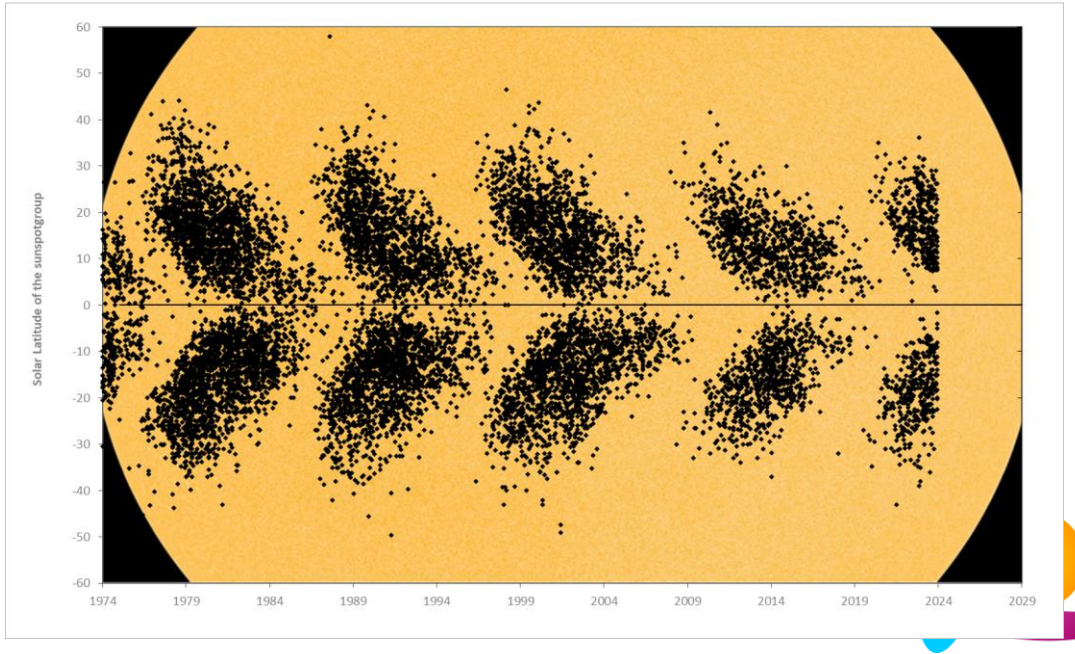


FIG. 8.—DISTRIBUTION OF SPOT-CENTRES IN LATITUDE, ROTATION BY ROTATION, 1877–1902.

Maunder, 1904



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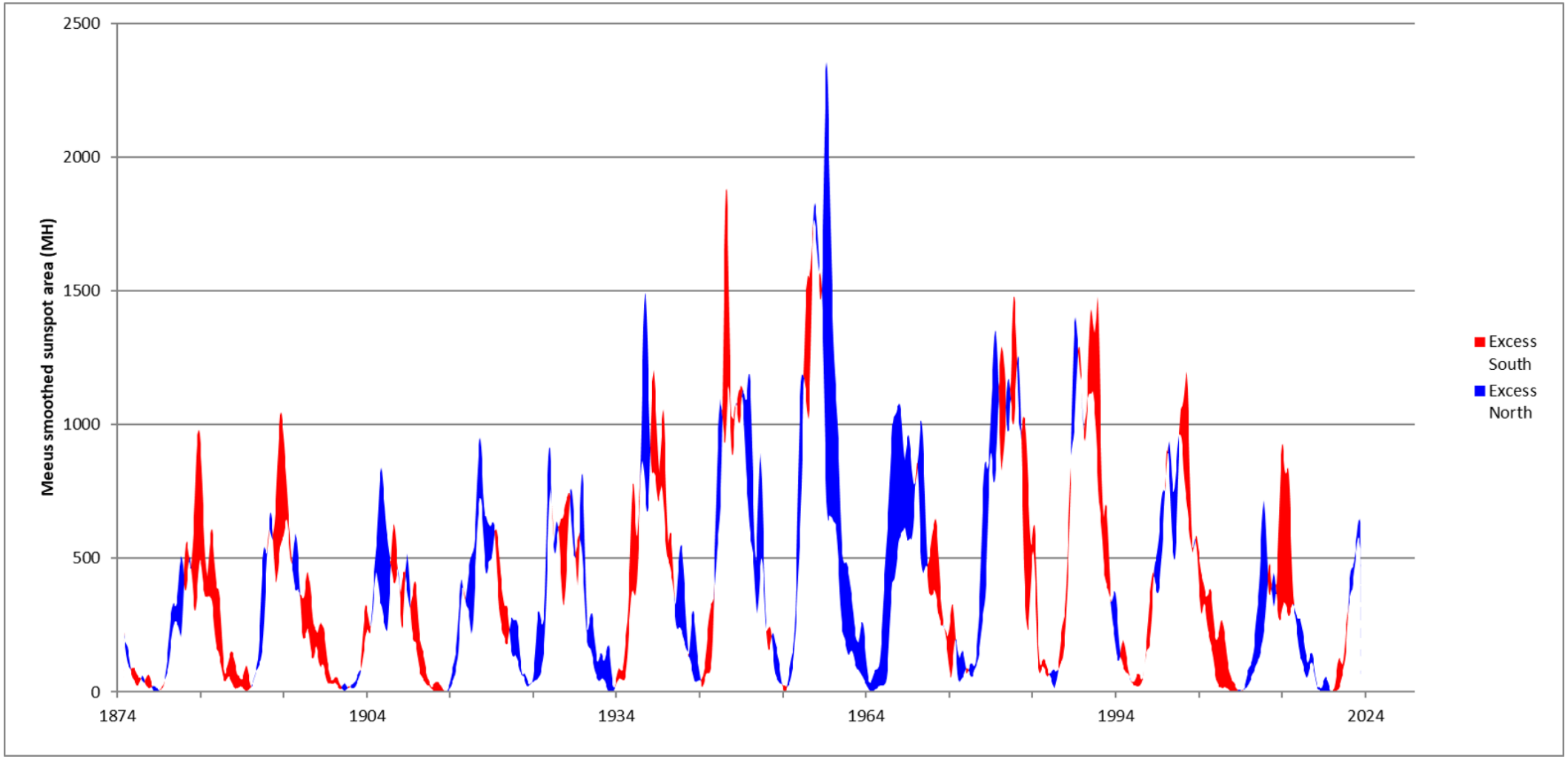
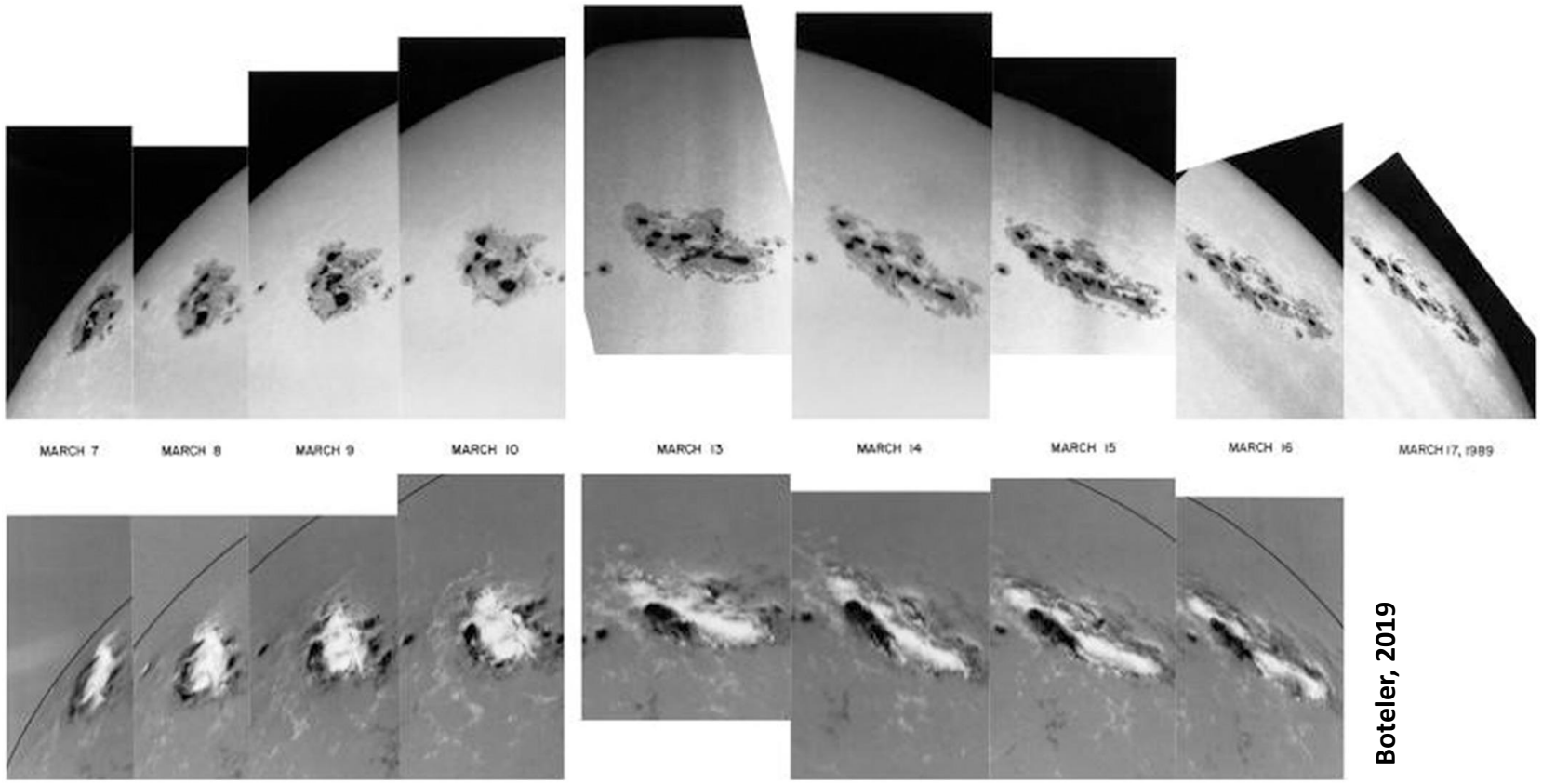
Sunspot cycle – Hemispheric evolution



STCE - https://www.stce.be/content/sc25-tracking

Summary

- Sunspots
  - History
  - How to observe
  - Properties
- Sunspot groups
  - Origin
  - Properties
  - Classifications
    - Solar flares
- Sunspot number
  - What is it
  - Types
- Sunspot cycle
  - History
  - Properties



Boteler, 2019

NOAA 5395, 7-17 March, Kitt Peak National Observatory, 1.6 m McMath-Pierce Solar Telescope

Questions?