Sunspots: From Spatially-Resolved to Sun-as-a-Star Observations

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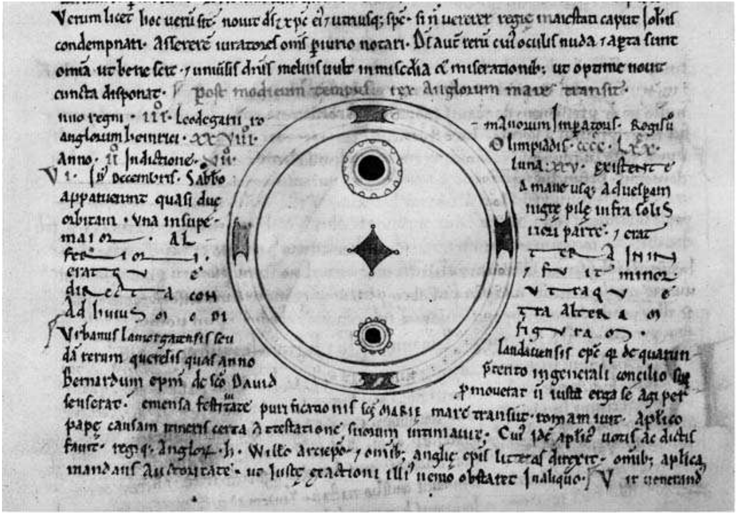
Outline

- A brief history of sunspots observations.
- The sunspot cycle of solar activity.
- Sun-as-a-star measurents at NSO.
- Recent results from the NSO SOLIS/ISS instrument.

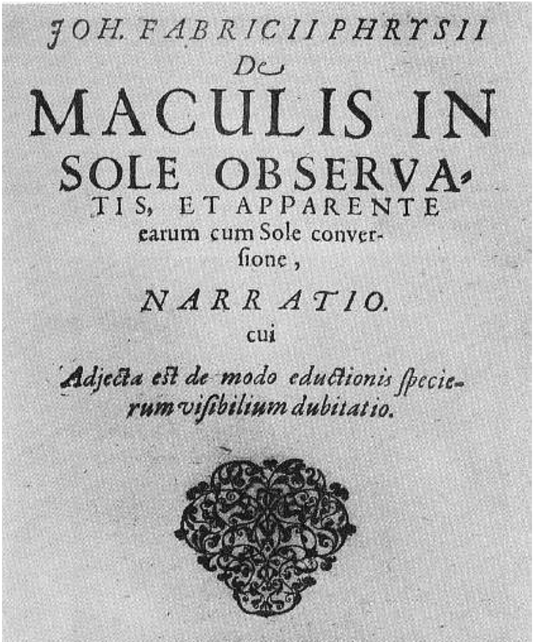
Sunspots: Early Observations

- The earliest surviving record of sunspot observation dates from 364 BC, based on comments by Chinese astronomer Gan De in a star catalog. By 28 BC, Chinese astronomers were regularly recording sunspot observations in official imperial records.
- Sunspot activity in 1129 was described by John of Worcester, and Averroes provided a description of sunspots later in the 12th century; however, these observations were also misinterpreted as planetary transits, until Galileo gave the correct explanation in 1612.



A drawing of a sunspot in the Chronicles of John of Worcester. December 8, 1128. Unaided eye method.

Johannes Fabricius (1587 - 1616)



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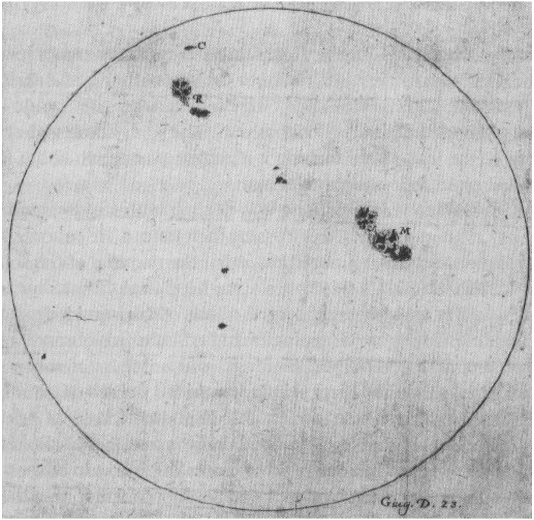
- Credited with Galileo Galilei for making the first observations of sunspots using a telescope.
- Johannes first observed a sunspot on February 27, 1611 and published the results of his observations the same year in his 22 page pamphlet De Maculis in Sole observatis.... It was the first publication on the topic of sunspots.
- Galileo did not know of the Fabricius' work when he first reported his observations.

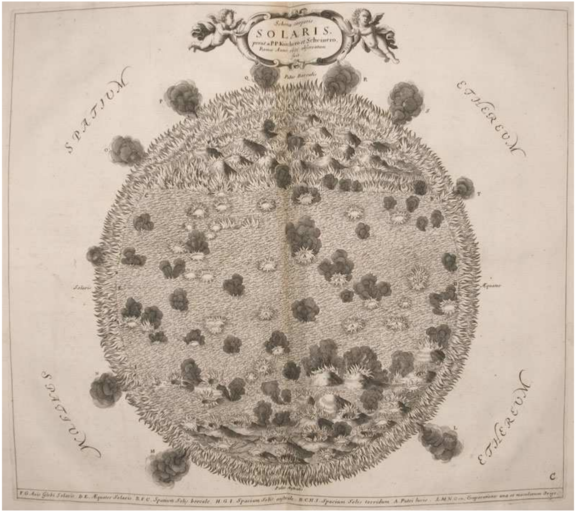
Galileo Galilei (1564 - 1642)



Drawing: June 23, 1612

In 1612 during the summer months, Galileo made a series of sunspot observations which were published in "Istoria e Dimostrazioni Intorno Alle Macchie Solari e Loro Accidenti" ("History and Demonstrations Concerning Sunspots and their Properties"), published 1613. Because these observations were made at approximately the same time of day, the motion of the spots across the Sun can easily be seen.

The sphere of Marcus Manilius (1675)



Engraved illustration showing a volcanic looking Sun with various features including sunspots and "solar winds" (circa 1614).

Christian Horrebow (1718 - 1776)

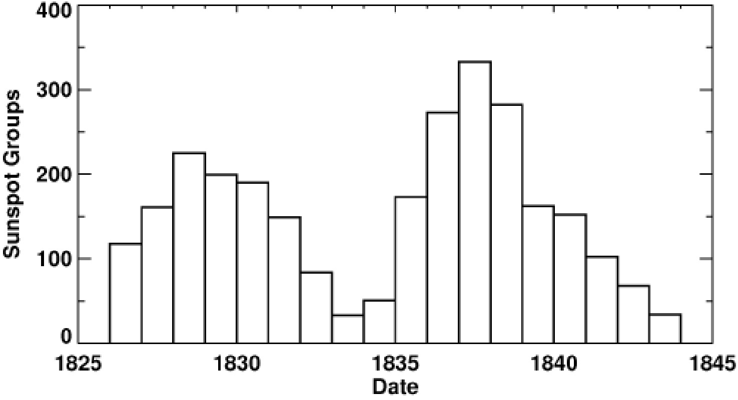
The first mention of possible periodic behavior in sunspots came from Christian Horrebow who wrote in his 1776 diary:

Even though our observations conclude that changes of sunspots must be periodic, a precise order of regulation and appearance cannot be found in the years in which it was observed. That is because astronomers have not been making the effort to make observations of the subject of sunspots on a regular basis. Without a doubt, they believed that these observations were not of interest for either astronomy or physics. One can only hope that, with frequent observations of periodic motion of space objects, that time will show how to examine in which way astronomical bodies that are driven and lit up by the Sun are influenced by sunspots.

From David H. Hathaway 2010, *The Solar Cycle*, Living Rev. Solar Phys., 7

Samuel Heinrich Schwabe (1789 - 1875)

Heinrich Schwabe reported in Astronomische Nachrichten (Schwabe, 1844) that his observations of the numbers of sunspot groups and spotless days over the previous 18-years indicated the presence of a cycle of activity with a period of about 10 years.



Sunspot groups observed each year from 1826 to 1843 by Heinrich Schwabe. These data led Schwabe to his discovery of the sunspot cycle (From David H. Hathaway 2010 *The Solar Cycle* , Living Rev. Solar Phys., 7)

George Ellery Hale (1868 - 1938)

The Astrophysical Journal, Vol. 28, 315. 11/1908

ON THE PROBABLE EXISTENCE OF A MAGNETIC FIELD IN SUN-SPOTS[1]

By GEORGE E. HALE

The discovery of vortices surrounding sun-spots, which resulted from the use of the hydrogen line *Hα*, for solar photography with spectroheliograph,[2] disclosed possibilities of research not previously foreseen. Photographs taken daily on Mount Wilson with this line suggest that all sun-spots are vortices, and provide material for a discussion of spot theories which will soon be undertaken. Revealing, as they do, the existence of definite currents and whirls in the solar atmosphere, they afford the requisite means of testing the operation in the sun of certain physical laws previously applied only to terrestrial phenomena. The present paper describes an attempt to enter one of the new fields of research opened by this recent work with the spectroheliograph.

ELECTRIC CONVECTION

In 1876 Rowland discovered that an electrically charged ebonite disk, when set into rapid rotation, produced a magnetic field, capable of deflecting a magnetic needle suspended just above the disk.[3] It thus appeared, in accordance with Maxwell's anticipation, that a rapidly moving charged body gives rise to just such effects as are caused by an electric current flowing through a wire. Rowland's whirling disk therefore corresponds to a wire helix, within which a magnetic field is produced when a current is passed through it.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 30. A preliminary note bearing the title "Solar Vortices and the Zeeman Effect," was sent to *Nature* for publication June 30. A brief abstract of this note appeared in *Nature* for August 20, together with a very interesting paper by Professor Zeeman, who was kind enough to examine some copies of my photographs, taken with the rhomb and Nicol in June. My own note was subsequently printed in *Publications of the Astronomical Society of the Pacific*, **20**, 220, 1908.

[2] Hale, "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Rowland, "On the Magnetic Effect of Electric Convection," *American Journal of Science* (3), **15**, 30, 1878.

If subsequent work proves this to be the case, it will appear very improbable (as indicated by theory) that terrestrial magnetic storms are caused by the direct effect of the magnetic fields in sun-spots. Their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots.

CONCLUSION

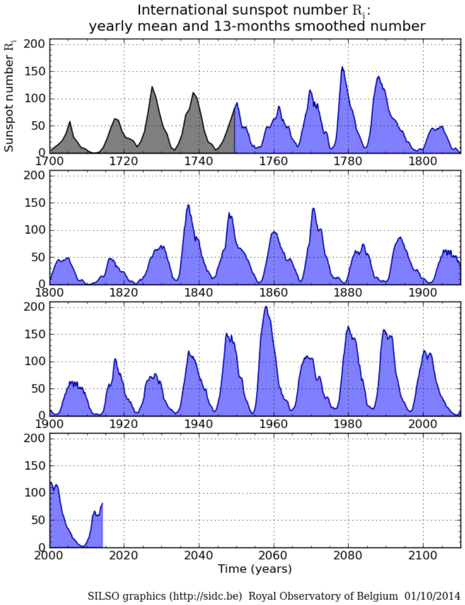
Although the combined evidence presented in this paper seems to indicate the probable existence of a magnetic field in sun-spots, the weak points of the argument should be clearly recognized. Among these are the following:

1. The failure of our photographs to show the central line of spot triplets before the spots are very close to the limb.
2. The presence in the spot spectrum of at least one triplet, which appears as a doublet when observed along the lines of force in the laboratory.
3. The absence of evidence to support the hypothesis that the imperfect agreement between spot and laboratory results is due to differences in the mean level of absorption.
4. The apparent constancy of the field strength, as indicated by the nearly uniform width of the doublets in different spots.
5. The difficulty of explaining, on the basis of our present fragmentary knowledge of solar vortices, the observed strength of field in the umbra and penumbra, and especially its variation with level.

As the resolving power of the 30-foot spectrograph is sufficient to resolve completely only the wider spot doublets, the central line could not be separately distinguished in other cases, even if it were present. Hitherto it has been possible to photograph the spectra of only the largest spots, because the images of other spots, as given by the tower telescope, are too small. The need of a telescope giving a much larger image of the sun, and a spectrograph of greater resolving power and focal length, which has been felt in previous work, is strongly emphasized by this investigation. Such apparatus would also permit the spectrum of the chromosphere, and many other solar phenomena, to be studied to great advantage.

As regards the nature of the vortices, the principal question is whether the gyratory motion primarily concerned in the production

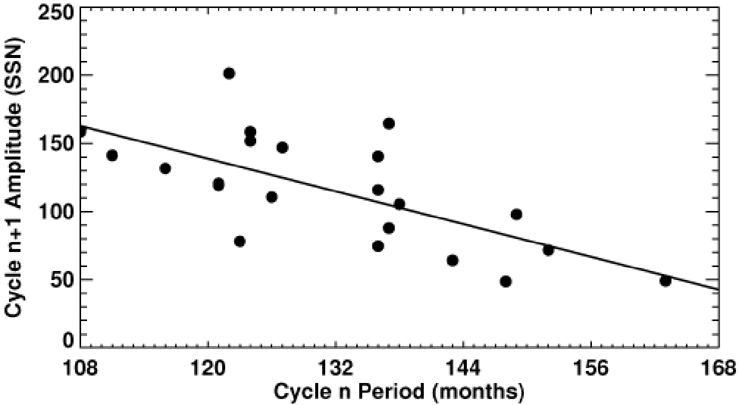
Sunspot Cycle



Characterization of Sunspot Cycles

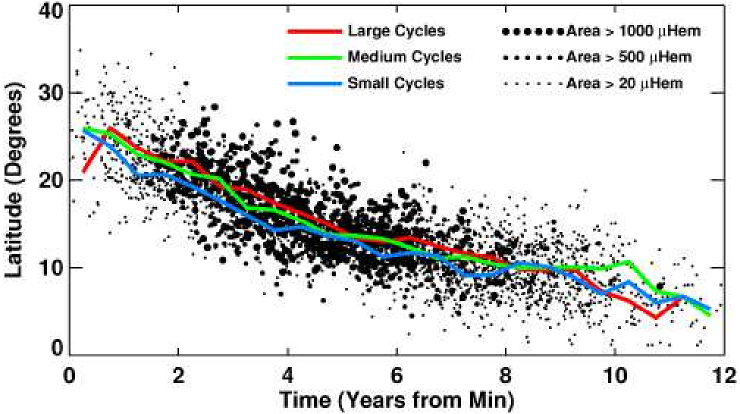
- The "sunspot number" is given by the sum of the number of individual sunspots and ten times the number of groups. Its variation in time is known as the sunspot cycle.
- The period of a sunspot cycle is defined as the elapsed time from the minimum preceding its maximum to the minimum following its maximum. It varies from about 100 months to 168 months. Cycle # 1 was March 1755.
- In general, amplitude and shape of each solar cycle are different. The sunspot cycles are asymmetric with respect to their maxima.

Period vs. amplitude



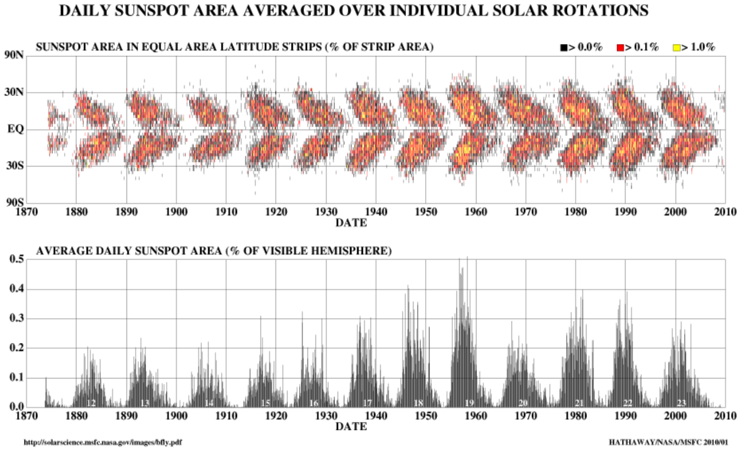
The amplitude-period effect. The period of a cycle (from minimum to minimum) is plotted versus following cycle amplitude for International Sunspot Number data from cycles 1 to 22. This gives an inverse relationship between amplitude and period shown by the solid line with Amplitude(n+1) = 380-2×Period(n) (From David H. Hathaway 2010 *The Solar Cycle* , Living Rev. Solar Phys., 7).

Active Latitudes



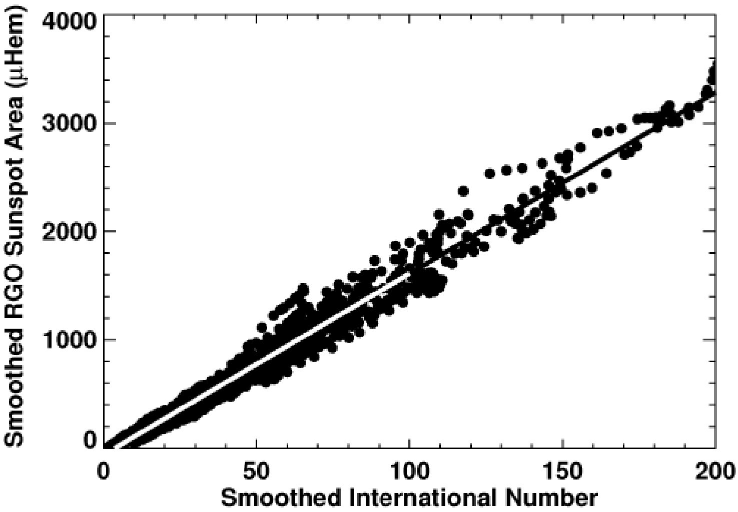
Latitude positions of the sunspot area centroid in each hemisphere for each Carrington Rotation as functions of time from cycle minimum. Symbol sizes differentiate data according to the daily average of the sunspot area for each hemisphere and rotation. The centroids of the centroids in 6-month intervals are shown with different colors, according to the amplitude of the cycles (From David H. Hathaway 2010 *The Solar Cycle* , Living Rev. Solar Phys., 7).

Sunspot Areas



Sunspot area as a function of latitude and time. The average daily sunspot area for each solar rotation since May 1874 is plotted as a function of time in the lower panel. The relative area in equal area latitude strips is illustrated with a color code in the upper panel (From David H. Hathaway 2010 *The Solar Cycle* , Living Rev. Solar Phys., 7).

Sunspot Area vs. Sunspot Number

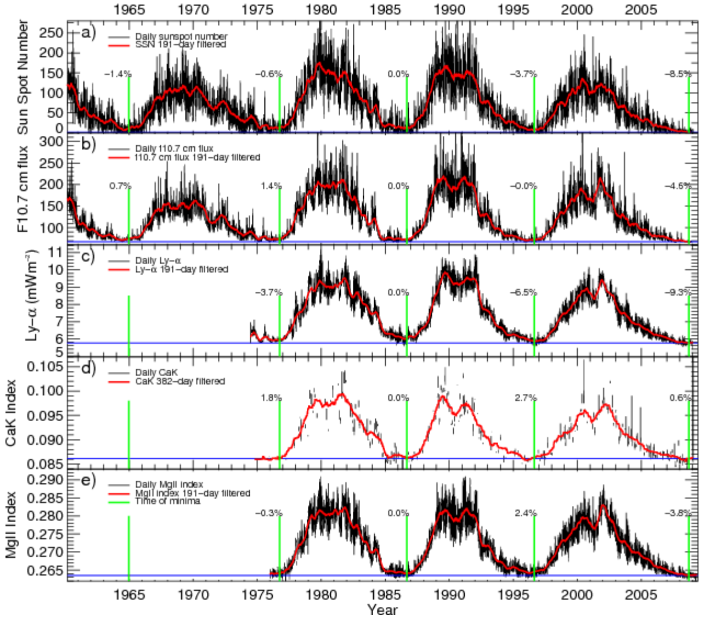


RGO Sunspot Area vs. the International Sunspot Number at monthly intervals from 1997 to 2010. The two quantities are correlated at the 99.4% level (From David H. Hathaway 2010 *The Solar Cycle* , Living Rev. Solar Phys., 7).

Solar Cycle: Summary

- The solar cycle has a period of about 11 years but varies in length with a standard deviation of about 14 months.
- Solar cycles are asymmetric with respect to their maxima - the rise to maximum is shorter than the decline to minimum and the rise time is shorter for larger amplitude cycles.
- Sunspots erupt in low latitude bands on either side of the equator and these bands drift toward the equator as each cycle progresses.
- The activity bands widen during the rise to maximum and narrow during the decline to minimum.
- The magnetic polarities of active regions reverse from northern to southern hemispheres and from one cycle to the next.
- The polar fields reverse polarity during each cycle at about the time of cycle maximum.

Indices of Solar Activity - Fröhlich, 2009



Sun-as-a-Star Measurements at NSO

- Ca II K-Line monitoring program at Sacramento Peak (1976 - present). Several K-line parameters, including the emission index and various measures of asymmetry, are extracted from the calibrated line profiles and stored on the NSO ftp site.
- Measurements by W. Livingston with the McMath-Pierce solar telescope at Kitt Peak, from 1974 to present. They consist of both photospheric and chromospheric spectral lines, including the Ca II K-line.
- Measurements with the SOLIS/ISS instrument. Observations on several spectral lines started at the end of 2006 (Bertello et al. 2012; Pevtsov et al. 2014).

The Synoptic Optical Long-term Investigations of the Sun (SOLIS) is a NSO synoptic facility for solar observations that will provide unique observations of the Sun on a continuing basis for several decades.

SOLIS INSTRUMENTS

- Vector SpectroMagnetograph (VSM): since 2003
- Integrated Sunlight Spectrometer (ISS): since 12/2006
- Full-Disk Patrol (FDP): since $\sim$ 2/2011

SOLIS/ISS

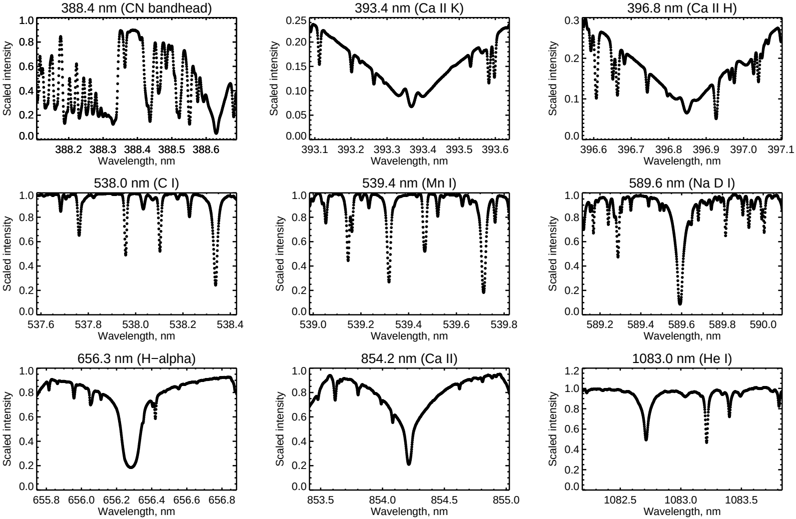
Observations of integrated sunlight with the ISS are accomplished through the use of a fiber optic feed. A small optical system utilizing a lens of 8-mm diameter installed on the side of main mount of SOLIS/VSM focuses a 400 μm diameter image of the Sun on the input face of a 600 μm diameter fiber. The fiber assembly transmits light to a McPherson 2-m Czerny-Turner double-pass spectrograph located in a temperature-controlled room below the telescope.

- R $\sim$ 300,000 ($\sim$ 8.2 mÅ/pixel at 393.4 nm)
- Spectral stability $\leq 1 \times 10^{-6}$
- Integration time $\sim$ 17s/frame (C I, Mn I, Hα) to 304s/frame (He I)
- Accuracy $\sim$ 1 s
- Typically, 1 observation a day for each band.

Spectral bands measured by the SOLIS/ISS

Type	λ_0 nm	$\Delta\lambda$ nm	$d\lambda/dx$ pm/px	Start date
CN band	388.40	0.58	0.564	12/4/2006
Ca II K	393.37	0.55	0.541	12/1/2006
Ca II H	396.85	0.53	0.522	12/4/2006
C I	538.00	0.84	0.824	12/4/2006
C I (with iodine lines)	538.00	0.84	0.824	1/7/2008
Mn I	539.41	0.83	0.816	12/4/2006
H-alpha	656.30	1.14	1.12	8/31/2007
Ca II	854.19	1.61	1.58	12/13/2006
He I	1083.02	1.65	1.61	12/4/2006
NaD1	589.59	0.98	0.956	3/23/2011

SOLIS/ISS Spectral Bands: July 1st, 2014



Extracting SDR from SOLIS/ISS: Motivations

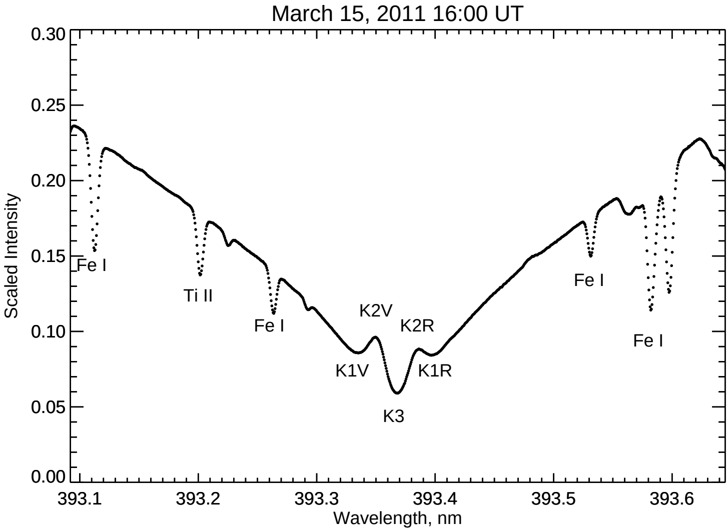
- Rotation plays a fundamental role in processes of stellar formation and evolution, through the modification of hydrostatic balance and the redistribution of chemical elements.
- Assessing the properties of solar surface differential rotation from disk-integrated measurements has a very important diagnostic value for the interpretation of stellar observations. Our goal is to establish an effective method for extracting the rotational components from time series of photometric measurements under unfavorable conditions of low magnetic activity and relatively low duty cycle (∼60%).

Bertello, L, Pevtsov, A.A., & Pietarila, A. 2012, ApJ 761, 11 (10 pp)

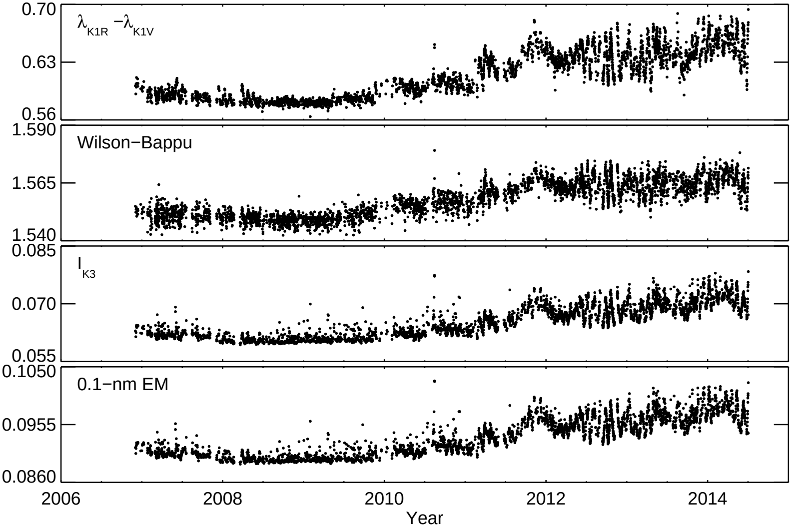
Data sets

- High spectral resolution (R $\cong$ 300,000) observations of the Sun-as-a-star in the Ca II K spectral line centered at 393.37 nm taken daily by the SOLIS/ISS instrument (Dec. 2006 - present).
- Time series of disk-averaged longitudinal magnetic field flux density measurements derived from daily SOLIS Vector Spectromagnetograph (VSM) magnetograms taken in the FeI 630.15 nm spectral line (Dec. 2006 - present).
- Time series of mean fluxes derived from simulated magnetograms generated from a simplified flux transport model. The model evolves the radial magnetic field by the effects of flux emergence, differential rotation, meridional flow, and diffusion.

SOLIS ISS Ca II K line profile



Ca II K parameter time series



Solar cycle dependency of four (out of nine) ISS Ca II K parameters.

Data reduction

- Rejection of outliers from the time series. This is achieved by fitting a cosine function with period of $\sim$11 years to the data and eliminating points that are 3-σ away from the model. The procedure is repeated until no points are eliminated.
- Dealing with irregularly sampled data: nearest neighbor resampling with the slotting principle + interpolation.
- Time series are detrended using a 4-th order B-spline
- A low-pass filter is applied to the data.
- Time series are prewhitened to reduce the non-stationary components of the signal.

Maximum entropy spectral estimator

- If $\{x_i\}$ is a zero-mean Gaussian stochastic process $N(0, \sigma^2)$ with white noise variance z (our time series), the spectral density $S(\nu)$ at frequency ν is given by

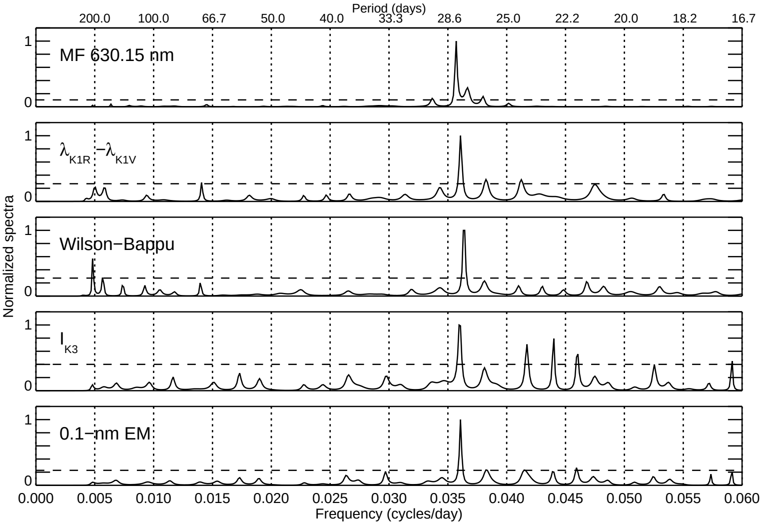
$$S(\nu) = \frac{\sigma^2}{|1 + \sum_{k=1}^{p} a_k \exp(-ik\nu)|^2},$$

  where a_k and p are the coefficients and order of the AR process:

$$x_i = \sum_{k=1}^{p} a_k x_{i-k} + z_i.$$

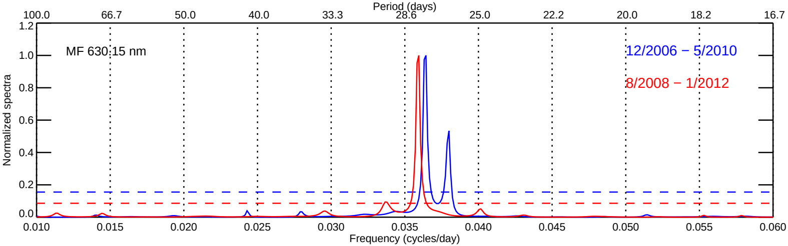
- The statistical significance of the spectral features is assessed with a permutation test (shuffle test). A 99.9 % confidence level is chosen for this study.

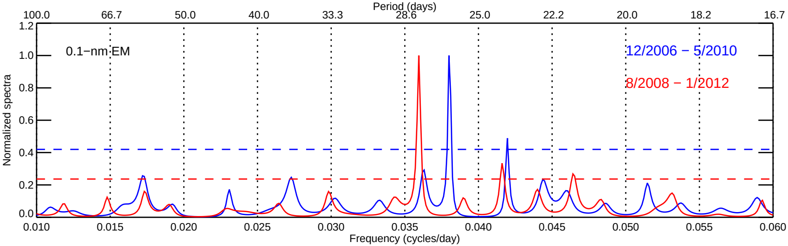
Power spectra of full-length time series



Spectral estimation of four ISS time series and VSM mean longitudinal magnetic field flux density data (MF 630.15 nm).

Power spectra of fractional time series





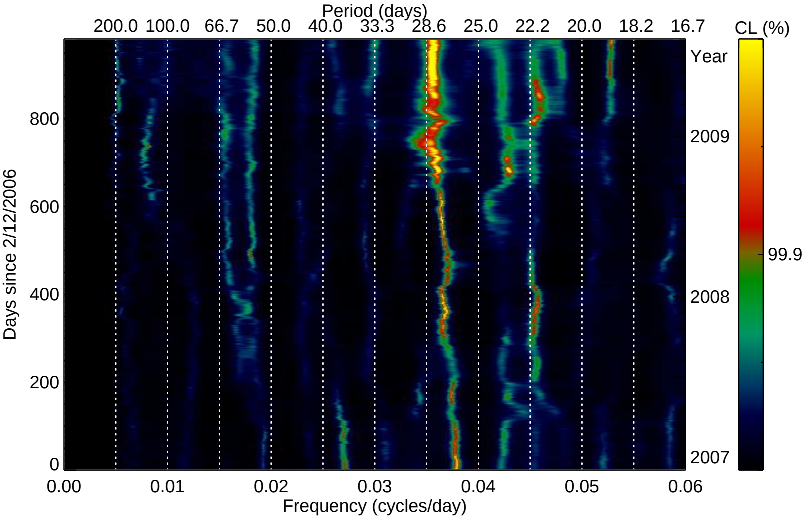
Spectral estimation of the first and the last 2/3 portions of the Ca II K 1-ÅISS time series and VSM mean longitudinal magnetic field flux density data (MF 630.15 nm).

Results from the spectral analysis

Parameter	Full-length	First 2/3	Last 2/3
	Synodic rotation period (days)		
1-Å EM	27.7	26.3	27.8
0.5-Å EM	27.7	26.3	27.7
I_{K3}	27.8	26.3	27.8
Wilson-Bappu	27.4	26.4	27.6
$\lambda_{K1R} - \lambda_{K1V}$	27.7	26.2	27.7
$(I_{K2V}-I_{K3})/(I_{K2R}-I_{K3})$	27.5	26.0	27.7
I_{K2V}/I_{K3}	27.7	51.3	27.8
MF 630.15 nm	28.0	27.4	27.8

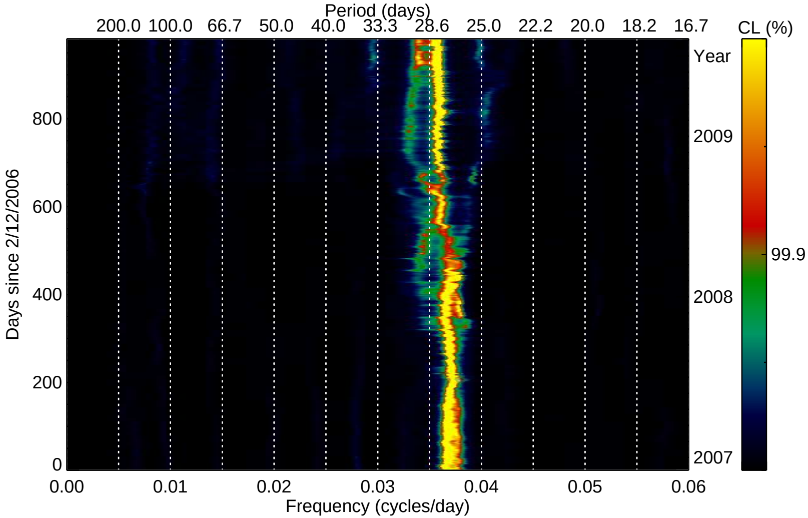
Note: the estimated uncertainty of these values is $\pm$ 0.3 days.

Time-frequency analysis: ISS Ca II K3 intensity



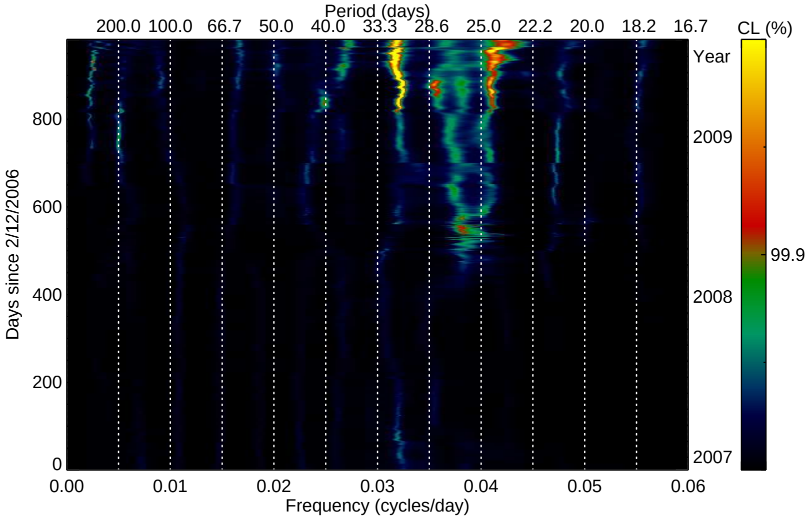
A 900-day sliding window was used, with a difference between consecutive segments of 1 day.

Time-frequency analysis: VSM mean flux

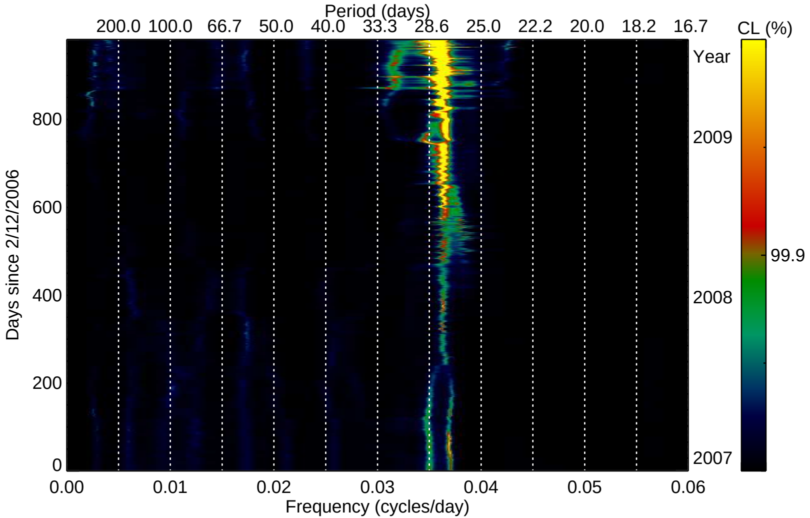


A 900-day sliding window was used, with a difference between consecutive segments of 1 day.

Flux transport model with *fast* diffusion



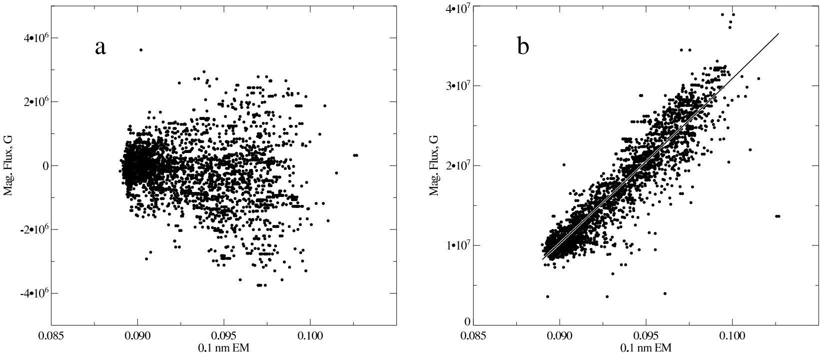
Flux transport model with *slow* diffusion



SDR: Summary

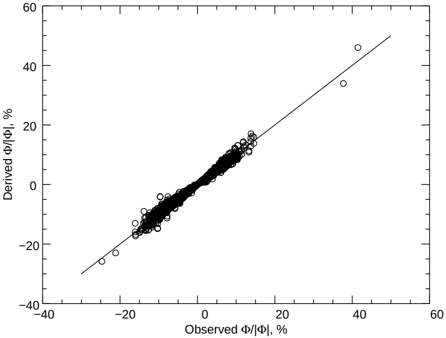
- Our approach is able to unambiguously detect the signature of differential rotation, even under unfavorable conditions of low levels of solar activity.
- In our tests, the adopted spectral estimator has been proven to be significantly more effective than the Lomb-Scargle periodogram method in providing spectra with a reduced number of significant peaks.
- The results of our numerical modeling suggest that the diffusion rate of active regions plays the most important role in detection of solar rotation from Sun-as-a-star observations. The rate of emergence and the presence of active longitudes seem to play a less relevant role.

1-Å Emission Index as Proxy for Magnetic Flux



Correlation between net (a) and total unsigned magnetic flux (b) from SOLIS/VSM and Ca II K 0.1 nm emission index (EM) from SOLIS/ISS (Pevtsov et al. 2014). SOLIS daily measurements from December 2006 to August 2013 were used in this analysis.

Fractional Magnetic Field Imbalance

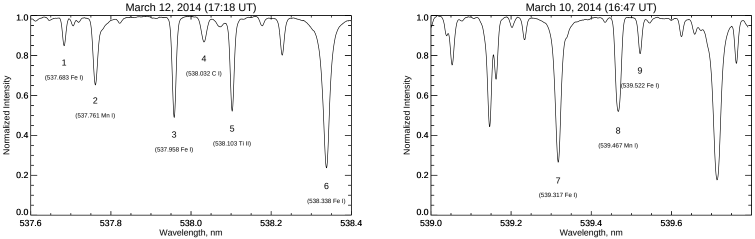


Correlation between observed fractional magnetic imbalance and one derived from the flux-0.1 nm emission index correlation shown in the previous slide (Pevtsov et al. 2014). Knowing the net magnetic flux and the fractional imbalance of a star allows one to compute the total amplitude of positive and negative fluxes separately.

Using Photospheric lines for magnetic flux

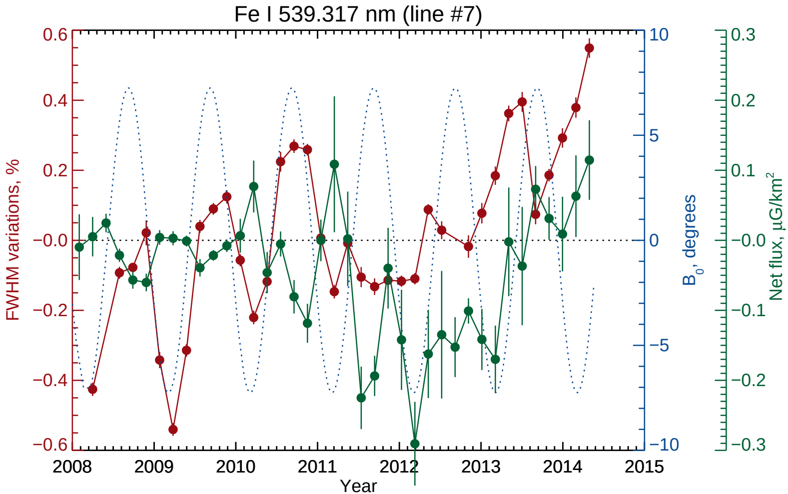
- We investigated the variations of several photospheric spectral lines observed during the decline of solar cycle 23 and the rising phase of cycle 24.
- We compared time series of line parameters (e.g. core intensity, FWHM, EQW) with time series of the net magnetic flux and chromospheric emission. Different line parameters have different response to variations in the thermodynamic and magnetic structures of the solar atmosphere.
- We used measurements taken by the SOLIS/ISS instrument.

Selected ISS Spectral Bands



SOLIS/ISS C I (left) and Mn I (right) bands. The spectral sampling is about 8.2 mÅ.

Correlation with Magnetic Activity



Comparison between variations in the 539.317 nm FWHM (red points) and the net magnetic flux computed at 630.15 nm from SOLIS/VSM (in green). Also shown (blue dotted line) are the variations of the heliographic latitude of the central point of the solar disk (B_0).