The Concept of NSO SPRING...and more

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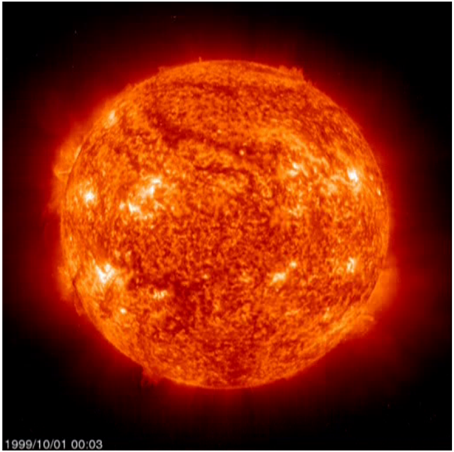
Overview

- Importance of solar synoptic observations
- Current synoptic programs at NSO: GONG, SOLIS
- Future synoptic program at NSO: Solar Physics Research Integrated Network Group (SPRING)
- Sun-as-a-star measurements at NSO: Some results from the analysis of Ca II K and photospheric spectral lines (SDR, magnetic response of spectral lines to the cycle of solar activity)

Understanding the variable Sun

- The Sun is not a constant star
- Level and character of its output change with time
- Long- and short-term variations



Question:
What is the origin of this variability?

The need for synoptic observations of the Sun

Long term monitoring of the solar magnetic fields

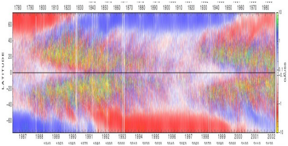
- to understand solar dynamo
- evolution with solar cycle
- active region evolution for space weather studies

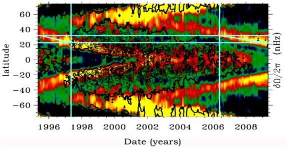
Long term monitoring of velocity fields

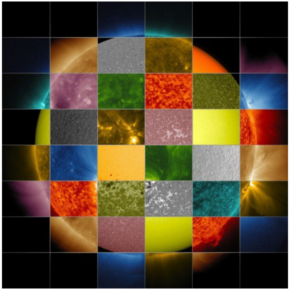
- subsurface flows via helioseismology
- solar cycle variations and relationship to solar dynamo
- flows beneath emerging flux and active regions for space weather studies

Context imaging for next generation high-res telescopes (DKIST)

- large scale effects of small scale events (e.g. flares, filament eruptions)
- full-disk image could support the poiting system

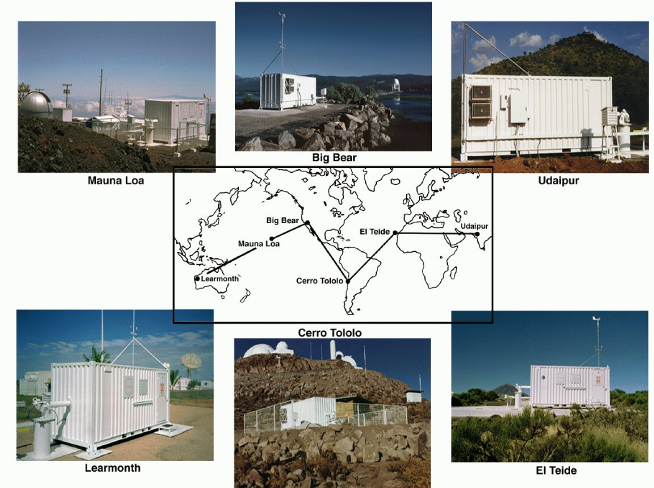






NSO: GONG (1995 - Present)

The Global Oscillation Network Group (GONG) provides Ni I 6768 full disk 2.5-arcsecond pixel velocity, intensity, and magnetic-flux images of the Sun every minute, with an approximate 90% duty cycle, enabling continuous measurement of local and global helioseismic probes from just below the visible surface to nearly the center of the Sun. Near-real-time seismic images of the farside of the Sun, and 2K x 2K Hα intensity images obtained at a 20-second cadence are also available.



NSO: SOLIS (2003 - Present)

The Synoptic Optical Long-term Investigations of the Sun (SOLIS) is a NSO synoptic facility for solar observations. SOLIS is composed of a single equatorial mount carrying three telescopes: 1) the 50 cm Vector SpectroMagnetograph (VSM), 2) the 14 cm Full-Disk Patrol (FDP), and 3) the 8 mm Integrated Sunlight Spectrometer (ISS).

VSM

Data products include, among others:

- Full-Stokes, Fe I 6301/2 and Ca II 8542 spectra
- Fe I 6301/2 vector/LOS and Ca II 8542 LOS full-disk magnetograms
- Image scale: 1-arcsecond/pixel. Coverage: 1 or 2 magnetograms of each type per day.

FDP

High temporal cadence full-disk images in H-α and He I 10830, core and wing sum

ISS

More on that later...

SPRING: Science-driven questions

- How is the solar magnetic field generated, maintained and dissipated?
- How are the solar corona and the solar wind maintained and what determines their properties?
- What triggers transient energetic events?
- How does solar magnetism influence the internal structure and the luminosity of the Sun?

For answering these questions, both high-resolution observations with upcoming future telescope of the 4m class (e.g. DKIST) and full-disk view synoptic observations of the Sun (e.g. SPRING) are necessary.

SPRING: Technical requirements

Objectives 1) Large field-of-view observations of the Sun with a network of solar telescopes, 2) support of observations with current/future high-resolution solar telescopes, 3) measurements of quantities relevant for space weather

Instruments wish-list

- Full-disk vector magnetograph
- Full-disk broad band imager
- Full-disk multi wavelengths helioseismic/Doppler imager
- High spectral resolution disk-integrated spectrograph
- Irradiance device

Observational requirements for SPRING

HIGHLIGHTS:

GOAL	Obs. Params	Cadence	Spectral/Spatial
Long-term behavior of solar magnetism	Accurate vector Magnetic Field measurements Senstivity Goal: B-los <1G, B-trans <50G	Few per day (long-term statistics only, not for short term evolution)	High spectral resolution (spectrograph), Fulldisk, seeing limited spatial resolution, Sensitive polarimetry.
Long-term behavior of solar internal flows	Accurate velocity field Measurements Sensitivity Goal: vel <10m/s	For photosphere: ~1 min, chromosphere ~30 sec	Moderate spectral resolution (filtergraph), fulldisk, seeing limited, Sensitive Doppler measurements
Space weather	High-cadence vector magnetic fields Sensitivity Goal: <10G for B-los, <150G for B-trans	Photo & Chromosphere: ~5-10 minute	Moderate spectral (filtergraph), fulldisk, seeing limited
High Resolution Contextual Imaging	High-resolution images of the sun in various wavelengths	Broad and Narrow band images at a cadence of 1 per minute	High spatial resolution (~1 arcsec; 4kx4k), fulldisk acquisition, Tip-tilt system for image stabilization **Image reconstruction only for desired FOV

Possible spectral lines: Ni I 6768, Fe I 6301/2, Na D, H-α, Ca H&K, He I 10830, Fe I 1.5μ

Expected improvements: Magnetometry

Multi-line high-resolution magnetic observations of the SUN

Several advantages:

- 3-D magnetic topology of active regions
- Improved coronal field exrapolations due to force-free behavior in upper layers of solar atmosphere
- Ground based continuous vector magnetometry for near real time space weather predictions
- Flare related changes in magnetic fields and electric currents in the chromsphere
- Long-term magnetic field records with improved spatio-temporal resolution

Expected improvements: Helioseismology

Multi-line high-resolution Doppler observations of the Sun

Several advantages:

- Improved accuracy and precision of helioseismic mapping, in vicinity of active regions (Hill 2009)‘
- Reduction in systematic errors (Baldner & Schou 2012)
- Multi-wavelength (Multi-height) observations are useful for seismic mapping of the solar atmosphere (e.g. Wisniewska et al. 2016)
- Study of the transport of convective energy through the solar atmosphere (Jefferies et al. 2006)

...more details in the review by Elsworth et al 2015, Space Sci. Review, 193, 137

Technical requirements for SPRING

Multiple instruments on a single platform is the way to go!

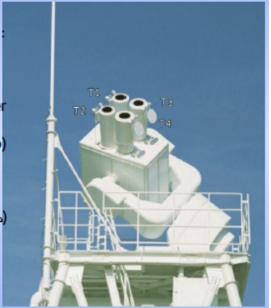
SOLIS

Representative Examples for the concept :

1. SOLIS NSO
   - -Spectro-Polarimeter
   - -Fulldisk Patrol Telescope
   - -Integrated Sunlight spectrometer

2. SMART (Hida Obsrvatory, Kyoto)
   - -Fulldisk H-alpha Imager
   - -Fulldisk vector Magnetograph
   - -High-resolution Magnetograph
   - -High-resolution Flare patrol (Hα)

3. SFT Mitaka, Japan
   - -H-alpha fulldisk
   - -Whitelight fulldisk
   - -Infrared spectropolarimeter
   - -G-band imager



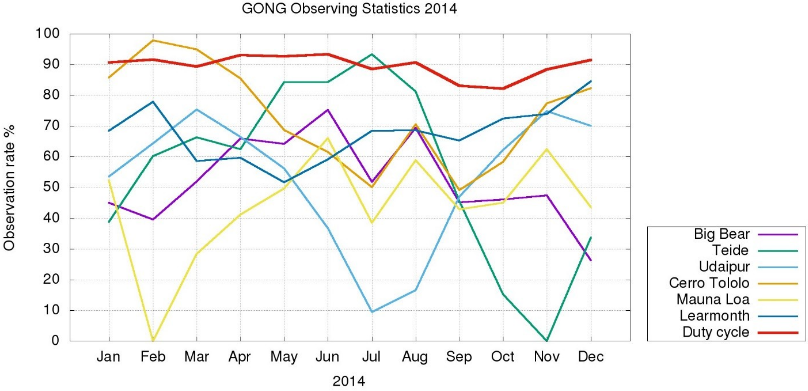
SMART

SFT

Location of the telescopes: NSO is willing to offer the six GONG sites

Duty cycle at the GONG sites

- Duty cycle around 90% throughout the year – even when only five sites are active. At all sites seeing is between 2 and 8 arcseconds, depending on day/time and season
- Adding more sites will increase duty cycle only marginally



TIME FOR SOME SCIENCE!

1) Sun-as-a-star in Ca II K

2) Response of photospheric lines to solar activity

Importance of Sun-as-a-star measurements

Disk integrated observations of the Sun represent important input data to both stellar and solar research.

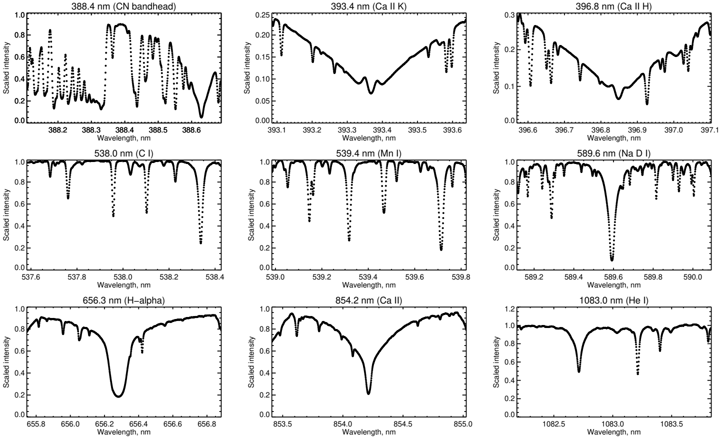
- Analysis of simultaneous disk-resolved and disk-interated observations allow for investigation of the contribution of individual solar feature and physical processes of the solar atmosphere to the solar spectrum. This provides interpretation of stellar spectra with unique data that cannot be obtained from observation of other stars due to poor (spatial) resolution.
- Regular sun-as-a-star observations have been taken since late 1960s. These measurements constitute a record of the long-term variation in solar activity available for use in models.

Sun-as-a-star measurements at NSO

- Ca II K-Line monitoring program at Sacramento Peak (November 1976 - September 2015). Seven K-line parameters, including the 1-Å emission index.
- Measurements by W. Livingston at Kitt Peak, from November 1974 to July 2013.
- Measurements with the SOLIS/ISS instrument (December 2006 - ongoing). These measurements include the Ca II K-line, from which nine different parameters are extracted (Bertello et al. 2012; Pevtsov et al. 2014).

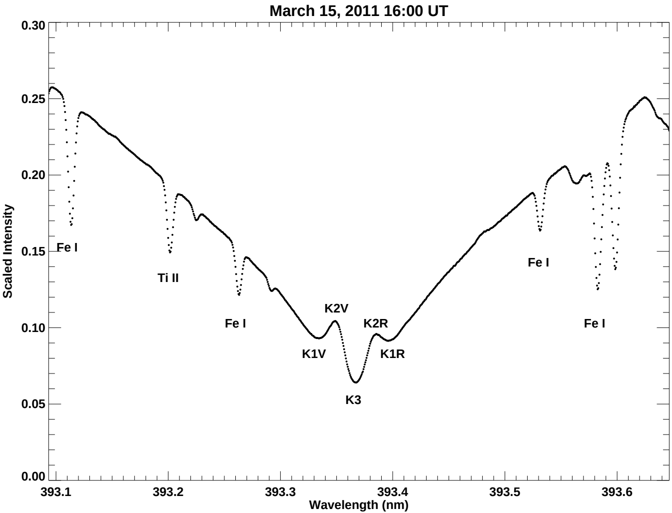
NSO: SOLIS/ISS

- Nine spectral bands, R $\sim$ 300,000 ($\sim$ 8.2 mÅ/pixel at 393.4 nm)
- Spectral stability $\leq 1 \times 10^{-6}$
- Typically, 1 observation a day for each band, 2 for the Ca II K line.

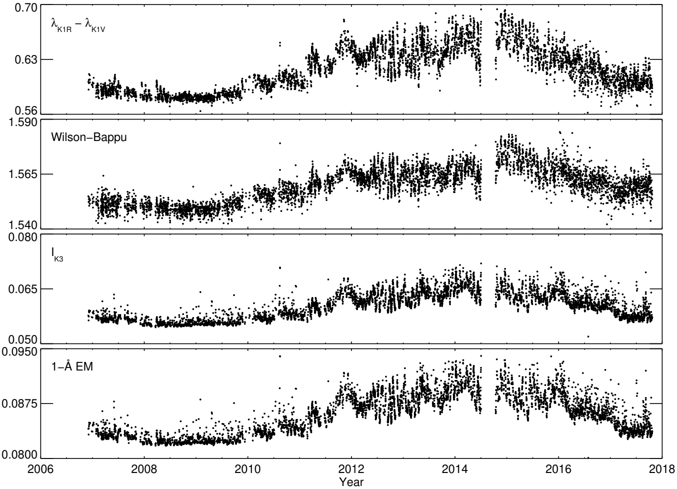


SOLIS ISS Ca II K line profile

Ca II K Sun-as-a-star measurements are important not only for a better understanding of the long-term variability of the solar chromospheric energy output, but they should also give insight into solar-terrestrial relationships as well as the solar-stellar connection.

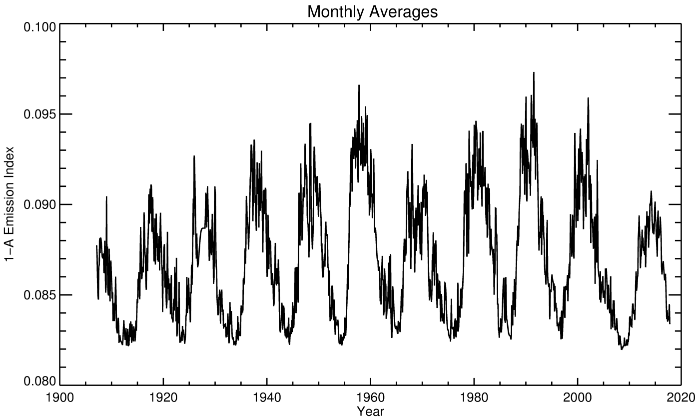


Ca II K parameter time series



Solar cycle dependency of four (out of nine) ISS Ca II K parameters. Question: Can we derive SDR from these time series? Determining the properties of SDR from disk-integrated measurements has a very important diagnostic value for the interpretation of stellar observations (Bertello et al. 2012).

Ca II K 1-A Emission index: 100+ years of data



Composite of observations taken at Kodaikanal, Sacramento Peak, Mount Wilson, NSO/ISS (Bertello et al. 2016, 2017).

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 - 2012).
- 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 - 2012).
- 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.

Data reduction: Irregularly sampled data

- Time series is detrended (model or 4-th order B-spline)
- Rejection of outliers from the time series, e.g. 3-σ rejection

Option #1: Lomb-Scargle periodogram and you are done (I hate it!)

Option #2: Resampling (I love it!)

- Nearest Neighbor Resampling with the Slotting (NNRS) principle + (linear) interpolation for missing data.
- A low-pass filter is applied to the data (R-E algorithm).
- Prewhitening (AR model) is necessary to reduce the non-stationary components of the signal.
- Choice between FFT and MEM

Maximum entropy spectral estimator (MEM)

- 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

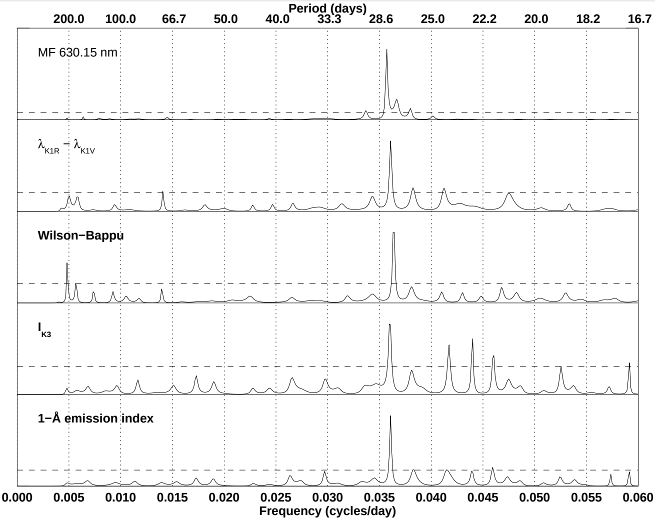
$$S(\nu) = \frac{\sigma^2}{|1 + \sum_{k=1}^{p} a_k \exp(-ik\nu)|^2},$$

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

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

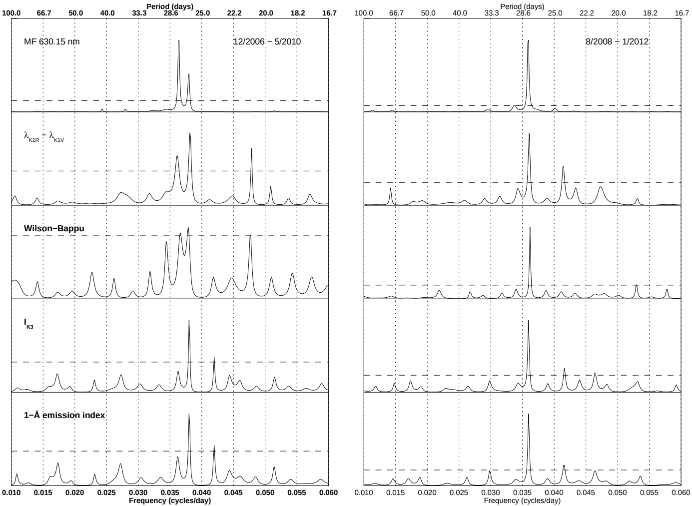
- The statistical significance of the spectral features is determined with a permutation test (shuffle test). A 99.9 % confidence level is chosen for this study.

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



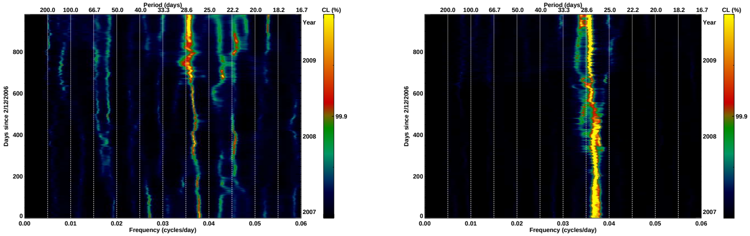
Spectral estimation of the first and the last 2/3 portions of four ISS time series and VSM mean longitudinal magnetic field flux density data (MF 630.15 nm).

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
$\lambda_{K2R} - \lambda_{K2V}$	141.0	none	none
I_{K2V}/I_{K3}	27.7	51.3	27.8
λ_{K3}		No used	
MF 630.15 nm	28.0	27.4	27.8

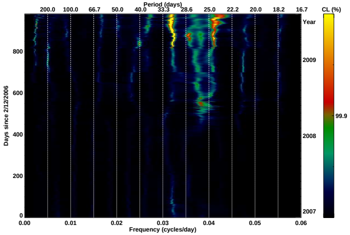
Note: the estimated uncertainty of these values is $\pm$ 0.3 days.

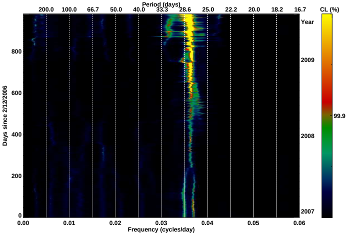
Time-frequency analysis: K3 intensity



Comparison between changes in the power spectrum properties with time of the Ca II K core intensity (left) and mean field solar magnetic field (right) derived from SOLIS/VSM observations. A 900-day sliding window was used, with a difference between consecutive segments of 1 day.

Flux transport model with *fast* diffusion





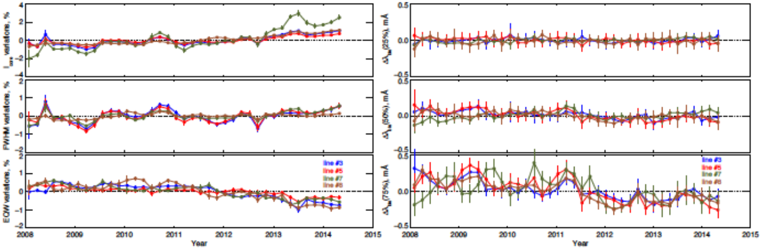
Fast (left) and slow (right) diffusion. The results of our numerical modeling suggest that the diffusion rate of active regions plays the most important role in detection of solar rotation from Sun-as-a-star observations. The rate of emergence and the presence of active longitudes seem to play a less relevant role.

ISS selected photospheric spectral lines

λ_0 (nm)	Elem.	Transition	Low EP (eV)	High EP (eV)	g_{eff}	I_{core}	EQW (mÅ)
537.6833	Fe I	b^1D2_2 - $v^3P^\circ_1$	4.29	6.60	0.750	0.85	13
537.7612	Mn I	$z^4P^\circ_{5/2}$- $e^4S_{3/2}$	3.83	6.12	1.300	0.65	45
537.9579	Fe I	b^1G2_4 - $z^1H^\circ_5$	3.69	6.00	1.000	0.49	56
538.0323	C I	${}^1P^\circ_1$ - ${}^1P_1$	7.68	9.99	1.000	0.87	26
538.1026	Ti II	$b^2D2_{3/2}$ - $z^2F^\circ_{5/2}$	1.57	3.87	0.900	0.52	56
538.3379	Fe I	$z^5G^\circ_5$ - e^5H_6	4.31	6.61	1.083	0.23	204
539.3174	Fe I	$z^5D^\circ_3$ - e^5D_4	3.24	5.54	1.500	0.26	153
539.4672	Mn I	$a^6S_{5/2}$ - $z^8P^\circ_{7/2}$	0.00	2.30	1.857	0.51	74
539.5218	Fe I	$z^5G^\circ_2$ - g^5F_1	4.45	6.74	0.500	0.81	20

Spectral lines of special interest deserving further investigations

Temporal variations of line parameters

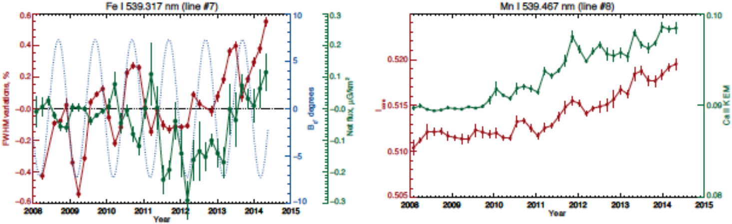


Shown here are the results for four of the nine ISS spectral lines. The other lines exhibit similar behavior. Data were averaged in 60-day intervals, and the variations are computed with respect to the median value of the original time series. The error bars are 3-σ of the mean.

Left: Variations in core residual intensity (I_{core}), FWHM, and equivalent width (EQW).

Right: Variations in the line bisector. The wavelength position of the line bisector is computed at three different residual intensity levels (I): $I_i = f_i(1 - I_{core}) + I_{core}$, with $f_i = \{0.25, 0.50, 0.75\}$.

Correlation with magnetic activity



Left: Comparison between variations in the FWHM of one of the strongest lines used in this investigation (red points) and the net magnetic flux computed at 630.15 nm from SOLIS/VSM observations. Also shown, as a reference, are the variations of B_0. Data were averaged in 60-day intervals, and the error bars for both sets of points are the standard deviation of the mean.

Right: Residual intensity variations in the core of Mn I 539.467 nm and their correlation with the chromospheric ISS Ca II K 1-Å emission index (EM). Error bars in both sets are 3 standard deviations of the mean value. The good correlation between these two parameters indicates that the core of this line is a good proxy for monitoring chromospheric activity in the Sun and, maybe, in solar-like stars.