

The Fine Structure of Active Regions and Weak Magnetic Fields from MDI Images

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Proposal Team

1. Principal Investigator: Dr. Judit M. Pap (UMBC/GSFC)
2. Co-Investigators: Dr. William D. Pesnell (GSFC) and Dr. Luca Bertello (UCLA)
3. Collaborators: Dr. Jerry Harder (LASP/CU) and Dr. Roger Ulrich (UCLA)
4. Research is a collaborative effort with Dr. Gary Chapman and Dora Preminger, CSUN/SFO

Fundamental Problems to be Understood – Goals:

1. Differences between Solar Activity Indices and Irradiance at the Maximum of Solar Cycle 23
2. Spectral Distribution of Total Solar Irradiance Variations
3. Detection and Parametrization of Weak Magnetic Fields Outside of Active Regions
4. Origin and Evolution of Sunspots, Active Regions, and Activity Complexes
5. Energy Balance of Active Regions

Science Rationale – Overview

The most important environmental problems facing humanity today is to understand and predict global change (both natural and man-induced) as well as the rapid changes in our space environment.

CRITICAL ISSUE: What is the relative impact of natural and anthropogenic influences on changes in the Earth's atmosphere?

REQUIREMENT: Accurate long-term total and spectrally resolved solar irradiance measurements are required to fully understand the response of the Earth's atmosphere and climate to irradiance changes.

Overview – Continued

UNDERSTANDING 1: The three-decade long irradiance measurements convinced the skeptics that solar irradiance (both total irradiance and spectral irradiance at various wavelengths) varies on various time scales: from minutes to the 11-year solar cycle.

UNDERSTANDING 2: Similar to solar irradiance variations, other solar-type of stars also show changes in their luminosity.

Overview – Continued

PROBLEM 1: The time period of interest far exceeds the lifespan of any single experiment, thus composite irradiance time series must be compiled from data of several irradiance experiments.

PROBLEM 2: On time scales longer than the almost three-decade long irradiance measurements, surrogates (magnetic activity indices) for irradiance have to be used to mimic the observed irradiance changes.

Overview – Continued

QUESTION 1: How well these indices used for irradiance modeling are reliable for predicting long-term irradiance changes?

QUESTION 2: What are the underlying mechanisms of irradiance variations and to what extent surface magnetic activity and to what extent global solar changes, like temperature or radius changes, contribute to irradiance variations?

QUESTION 3: What new tools we have/need to better predict solar irradiance variability than the currently available empirical models?

Total Solar Irradiance (TSI) – Measurements and Composites

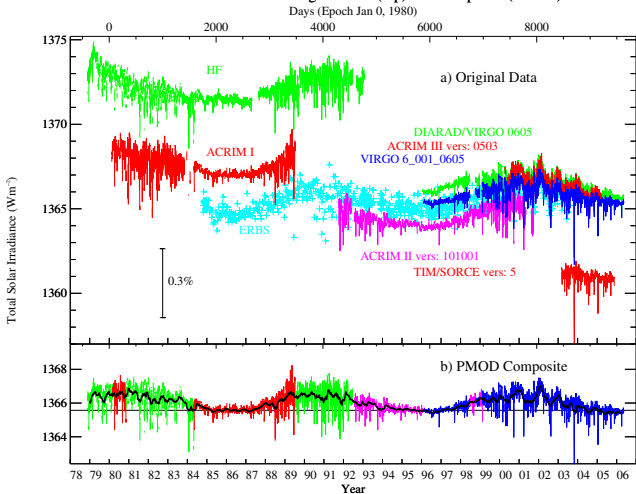
To study the long-term variations and possible climate effect of irradiance variations, two composites have been compiled: the ACRIM composite and the PMOD composite (PMOD version d41_61_0510 is shown here).

Willson and Mordvinov (2003) adjust the ACRIM I and ACRIM II data via their mutual inter-comparison with the Nimbus-7/ERB measurements, using TSI data as published by the original instrument teams. This composite shows a small (0.05%) increase from the minimum of solar cycle 21 to the minimum of cycle 22.

In contrast, Fröhlich and Lean (1998) make adjustments to the Nimbus-7 and ACRIM I data for 1980 and to the Nimbus-7 data between 1989 and 1991, arguing about instrumental drifts and improper correction for degradation effects on the ACRIM I and Nimbus-7 data at the beginning of their operation.

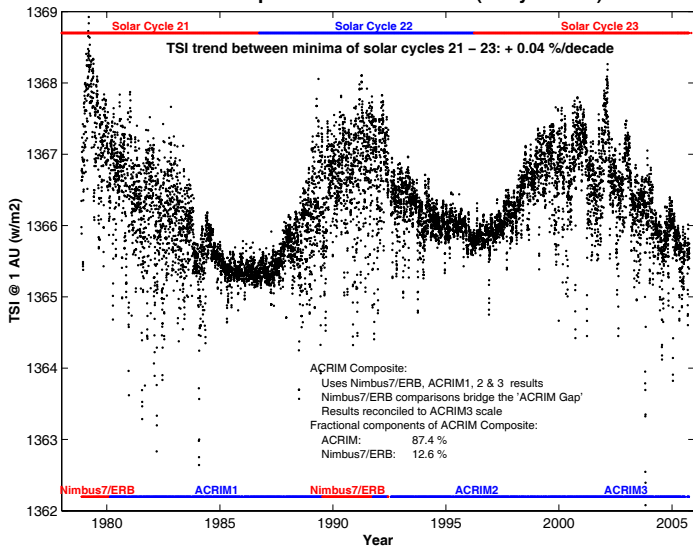
Total Solar Irradiance (TSI) – Measurements

Total Solar Irradiance: Original Data (top) and Composite (bottom)



adapted and updated from: Quinn and Fröhlich, Nature, 401, p.841, 1999, with composite (vers d41_61_0605), ACRI-III/III (vers II:101001) and VIRGO 6_001_0605 data (May 24, 2006)

ACRIM Composite TSI Time Series (Daily Means) *



* Willson & Mordvinov, GRL, 2003

Solar Activity Indices for Empirical Models

The Mg II h & k core-to-wing ratio derived from the vicinity of 280 nm (as derived at NOAA/SEC, Rodney Viereck). This index is considered as a good proxy for faculae

Ca II K-line observations are available from several observatories, providing a good indicator for chromospheric activity

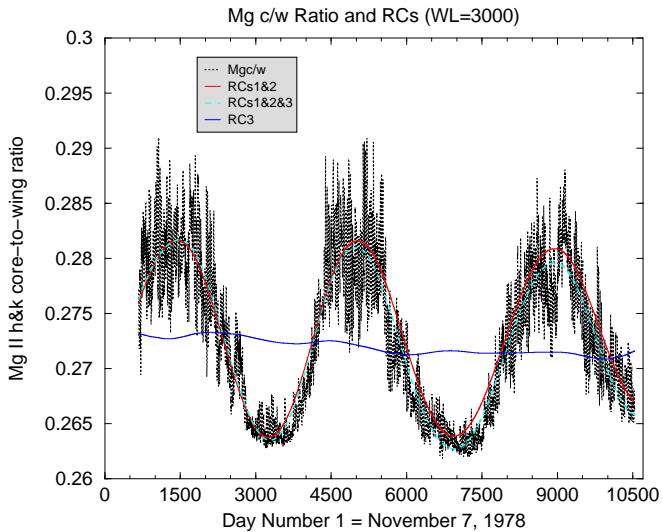
The 10.7 cm radio data which are available since 1947 and considerable effort has been devoted to extend irradiance models using this index

The sunspot number (SSN), which is the longest solar time series available for solar modeling (other than the cosmogenic isotopes)

Full disk magnetic field strength data from the National Solar Observatory at Kitt Peak

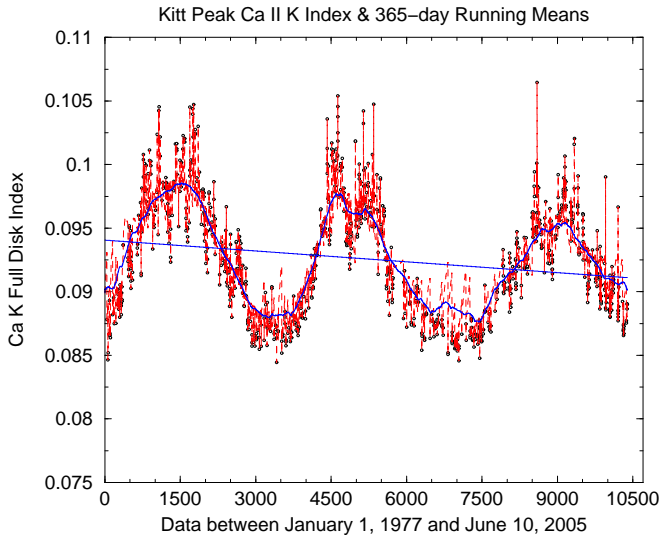
Variations in the Activity Indices

Mg II Core-to-Wing Ratio (Mg c/w)



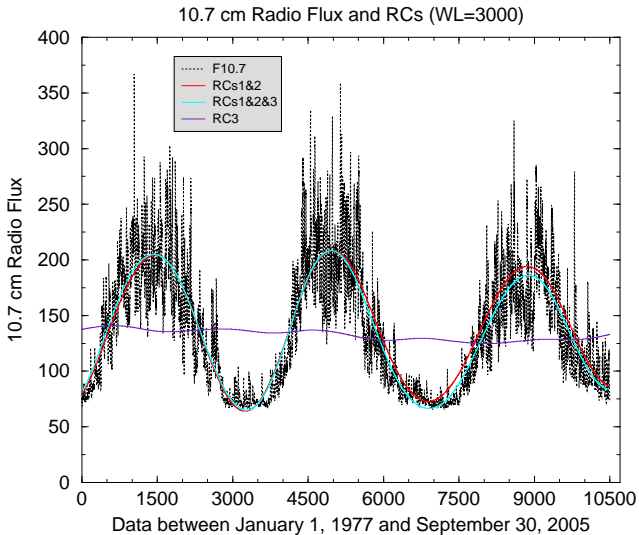
Variations in the Activity Indices – Continued

Ca K line



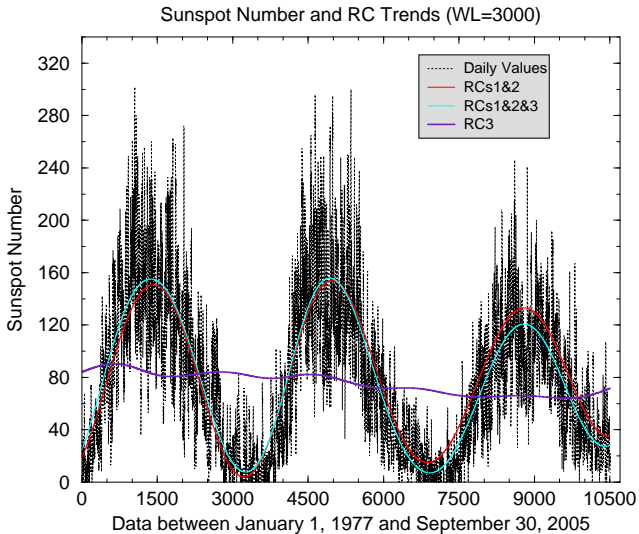
Variations in the Activity Indices – Continued

F10.7 Time Series



Variations in the Activity Indices – Continued

Sunspot Number Time Series



Variations in the Activity Indices – Continued

Analyses based on the Mg c/w ratio and the CaK index have led to the conclusion that the long-term variations in total irradiance are mostly related to the bright features, such as faculae and the network.

However, significant differences exist between these indices. For example, the maximum of the Mg c/w ratio is somewhat lower during the declining phase of solar cycle 23. In contrast, the CaK line shows a much lower maximum, and it is far from its minimum level during the declining phase of cycle 23.

Although the overall shape of F10.7 and SSN is similar, the maximum amplitude of F10.7 is much higher at cycle 23 relative to the previous cycles than that of SSN.

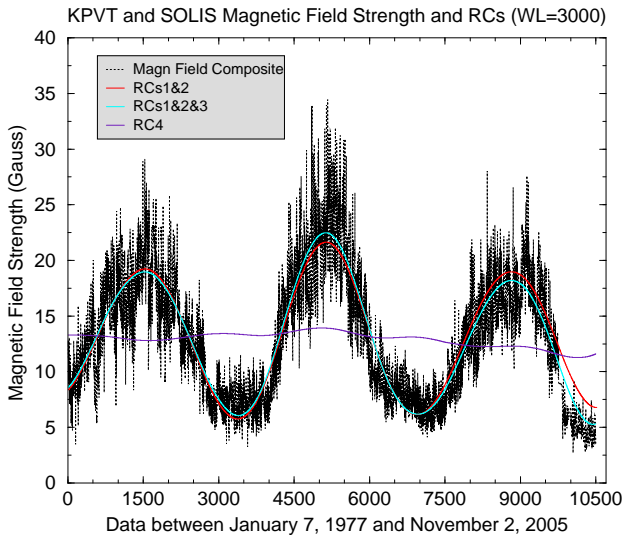
As the long-term trend components show, while SSN does not yet show solar minimum, F10.7 - similar to TSI indicate that we are close to minimum.

Solar Magnetic Indices

Since 1975 full disk magnetograms are taken to produce two numbers for each one: the average field strength (sum of all the individual measurements divided by the number of measurements) and the average absolute field strength (same but take absolute value of the measurements first). Major changes occurred in 1992 and 2003 when the instruments changed. Minor changes occurred at other times when software changed.

The KPVT observations were carried out in the 868.8 nm starting in 1977. For day numbers between 8146 and 8357, a different spectrum line (550.7 nm) has been used. After day number 8357 (11/30/03), the new SPMG was in use with the 868.8 nm line.

Solar Magnetic Indices – Continued



Solar Magnetic Indices – Continued

As estimated, the magnetic field values are all on the same scale (this is probably correct to of order 10%). As can be seen, the maximum of cycle 23 was far lower than the last cycle – despite the fact that solar irradiance was almost as high as during the last strong cycles. By mid-2005, the KPVT data were close to minimum condition, and the SOLIS data indicate that we are already at solar minimum conditions.

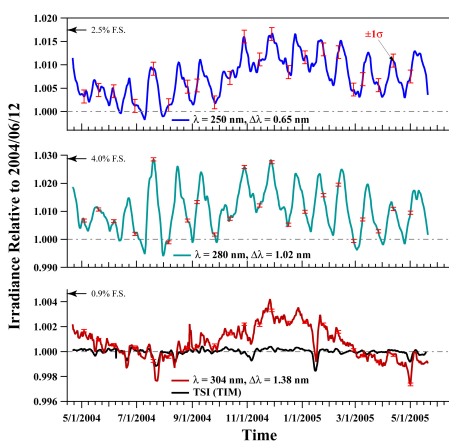
However, in the case of the absolute values of the measured field can be at error due to various effects (error in the zero point level, image resolution, instrumental noise). Thus, further studies are required to confirm whether the low level of the absolute magnetic field strength during the declining portion of cycle 23 is entirely (or to what extent) due to the Sun.

Spectral Distribution of Total Irradiance Variations

1. UV irradiance is quite well measured, and it is estimated that as much as 30 to 60% of total irradiance variations may come from UV variations
2. However, the variations above 300 nm are not well understood (or measured from space over a long time interval)

Spectral Distribution of Total Irradiance Variations – Continued

Solar Variability in the Ultraviolet



250 nm: UV Pseudo-Continuum

- Mix of photospheric continuum and densely spaced chromospheric lines.
- Continuum contribution decreases with sunspots, and line intensity increases with plage.
- Chromospheric component tends to dominate.

280 nm: Mg II

- Pseudo-continuum & cores of the Mg II lines.
- 280 nm irradiance peaks when the plage area is the largest.
- Flux is affected by active network.

304 nm: Near-UV Pseudo-Continuum

- Photospheric with less densely spaced spectral lines compared to 250 nm.
- Sunspot depression ~2x deeper than TSI.

By courtesy of Dr. Jerry Harder

Analysis Techniques: Image and Time Series Decomposition

1. **Image Processing:** StarTool, developed within SOHO/GI program (Judit M. Pap, Michael Turmon, UCLA/JPL/UMBC effort), based on Bayesian Technique, developed for SOHO/MDI, to be applied for HMI
2. **Time Series Analysis:** VARKIT (Variability Analysis and Reduction ToolKit), developed by Dr. Ferenc Varadi (UCLA), co-worker: Dr. Judit M. Pap
3. **Weak Field Recognition:** Based on Instrument Calibration Curves, originally developed for Mt. Wilson Magnetograms at 535.5 nm by Roger Ulrich (UCLA) and to be applied to MDI by Judit M. Pap and Luca Bertello

Image Processing

1. StarTool, developed specifically to analyzing MDI images, uses both full-disk (1024^2 pixels) magnetograms (level 1.5, about 15 per day), and quasi-white-light photograms (level 2.0, about 4 per day).
2. It handles image preprocessing, synchronization, and feature registration. Recognized that analyzing magnetograms alone is not sufficient to correctly recognize sunspots and faculae since magnetic field values between 25 and about 400 Gauss in MDI unit may cause either sunspots or faculae (Turmon, Pap, Mukhtar, 2002).

Identified three specific structures: sunspots (umbra and penumbra), faculae, and background (the so-called quiet-Sun/network).

StarTool Sample:

Synchronized full disk magnetogram and photogram, with scatter plots of sites within the two indicated regions. The top two panels are details from a magnetogram and a photogram; the photogram was taken at 17:58 UTC on September 7, 1997 and preprocessed to remove various instrumental effects; the magnetogram has been synthesized from bracketing one-minute magnetograms taken at 6:24 and 19:11 UTC on that day.

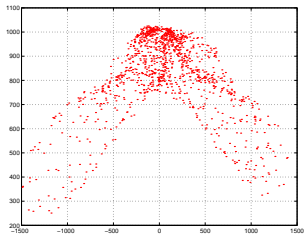
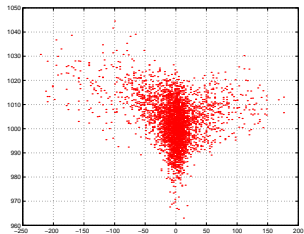
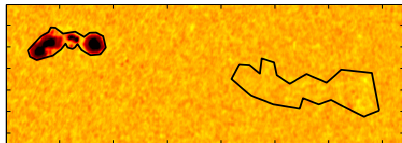
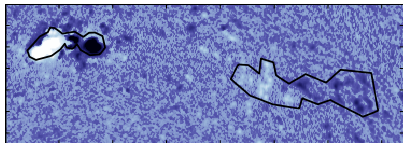
The selected regions are “255×725”. The scatter plots of data for the two indicated subregions are in the bottom panels. The bipolar spot (left panel) shows clearly as having lower intensity, and the penumbra is visible at the knee of the plot. Most encouraging, the brightness enhancement of the decayed facula (right panel), far from the limb at $\mu = 0.81$, is clearly visible, increasing with magnetic flux strength.

StarTool Sample – Continued:

The maximum brightness enhancement amounts to about 3-4% of the nominal intensity level. They also show how various region types, here faculae and sunspots, may be identified on the basis of the joint observables, but not either alone.

MDI Magnetograms and Photograms

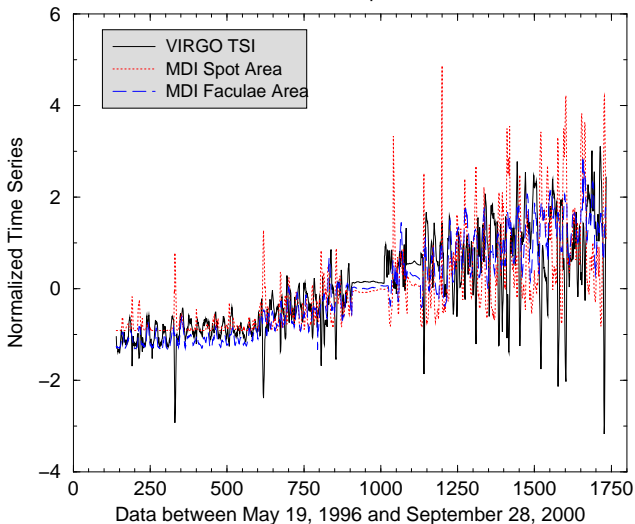
StarTool Intensity and Magnetic Field Relations



Application of Startool to Irradiance Time Series:

SOHO/VIRGO and MDI Results

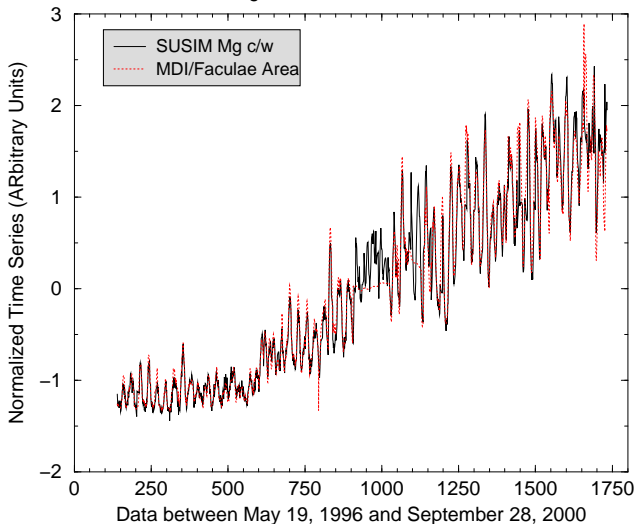
Total Irradiance and Spot, Faculae Area



Application of Startool to Irradiance Time Series:

SOHO/MDI Results

UARS/SUSIM Mg c/w Ratio and Faculae Reconstruction



Shortcomings of Startool:

- (1.) With the current version of StarTool and using the full disk MDI images, the weak magnetic network structures cannot be identified well, and these weaker structures are classified into the quiet Sun or background structures.
- (2.) To identify and characterize the weak network magnetic components, as a first step we need to properly define and identify the quiet Sun values.
- (3.) For this purpose, we apply the results gained from the “standard instrument distribution curve” technique – as used to analyze the Mt Wilson magnetograms (Ulrich et al., 2002.)

Standard Instrument Distribution Curves:

1. Since StarTool uses both the magnetograms and the intensity images to extract features from the MDI images, these “*standard instrument distribution curves*” need to be derived from the continuum images as well.
2. In this way, we can derive the necessary parameters for the quiet Sun values from the high resolution MDI images and these parameters, together with the currently available parameters for faculae and sunspots, would define the MDI weak field structures.
3. Technically, the weak field parameters will be determined by the maximum magnetic field and intensity values of the instrument distribution curves and the minimum values for the already identified faculae.

Standard Instrument Distribution Curves –Continued:

1. *Our approach:* reduce the uncertainty and/or minimize the effect of the zero-offset of the images.
2. Since both the zero offsets and the uncertainties are changing from exposure to exposure, our goal is to minimize the uncertainties (for example by 50×50 pixels binning) and to derive an averaged, constant zero offset.
3. Apparently, for this purpose we need to rely on the high resolution images. To derive a “constant” zero-offset, we propose to select those exposure times when the Sun was quiet and make the distribution curves of all the observable pixels, which are expected to be Gaussian.

Standard Instrument Distribution Curves –Continued:

(4.) Since both the uncertainty and zero-offset vary from exposure to exposure, we expect that these Gaussian curves will change also slightly. However, from these various exposure curves we will be able to derive an averaged curve that we can use to represent the distribution curve of the quiet Sun or better to say, the distribution curve of the instrument (called a “*standard instrument distribution curve*”).

(5.) Because changes occurred in the MDI system during the 2-month long “SOHO-vacation” in the summer of 1998, we propose to derive and compare these curves from the observations before and after the SOHO vacation.

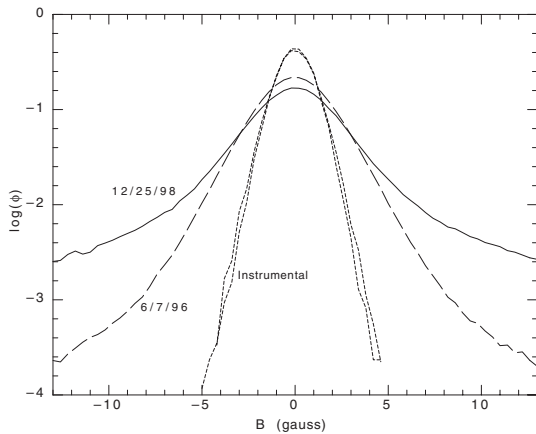
(6.) It is still an open question whether or not the quiet-Sun is constant over time so it is prudent to calculate these averaged, *standardized distribution curves* from time to time, and if necessary, to make adjustments.

Standard Instrument Distribution Curves –Continued:

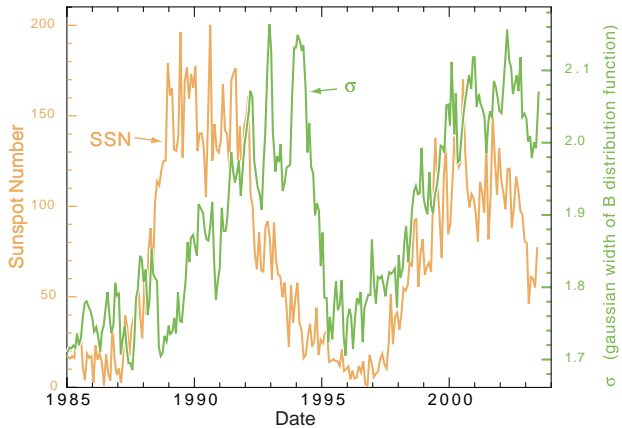
(7.) This procedure would ensure that we set up a limit, although artificial but consistent, for the MDI pixel distribution due to instrumental effects.

(8.) We propose to save and archive all of the averaged instrumental distribution curves derived within various phases of the solar cycle, which may give us further information whether the so-called quiet-Sun is changing over the time.

Mt Wilson Curves:



Mt Wilson Results:



Standard Instrument Distribution Curves –Continued:

The above mentioned procedure has two applications:

- 1. Relevance to HMI:** Since the HMI instrument on SDO is an improved version of MDI, and the HMI image resolution will be equal to the resolution of the high resolution MDI images (1.3 arc sec), the proposed calculation of the “*standard instrument distribution curve*” could guide also the development of the HMI calibration factors and procedures.
- 2. Relevance to Current MDI Image Processing:** The above described method will significantly improve the “StarTool” image processing algorithm that was developed by Turmon and Pap (1997) to analyze the MDI images, and was described in detail by Turmon, Pap, and Mukhtar (2002).

Conclusions

While the sunspot number and magnetic field strength show that the maximum of solar cycle 23 is lower than the maxima of the two previous cycles, the maximum level of total irradiance, the Mg II h & k core-to-wing ratio, He 1083, and $F_{10.7}$ flux is higher during solar cycle 23 than the maximum of the magnetic indices.

Further discrepancies can be found between the level of total irradiance and various activity indices during the declining phase of cycle 23.

Additional interesting events are the consecutive large activity outbursts - during the declining phase of the weak cycle 23.

Conclusions – Continued

These results highlight that during solar cycle 23 solar activity indices, which describe magnetic features, cannot properly account for solar variability, as measured by solar irradiance; thus these indices used in long-term irradiance variation may not account for longer term changes.

Solar cycle 23 is the first measured example of the non-linear relationship between solar activity (local magnetism) and solar variability (changes in solar global properties).

Conclusions – Research to be Conducted:

Problems with indices used in irradiance models:

1. **Effect of Sunspots:** A simple model (Photometric Sunspot Index, PSI) has been developed to describe the effect of sunspot darkening on total irradiance
 - (a) However, we lack long-term high precision sunspot area measurements
 - (b) The dependence of the contrast change of sunspots over their evolution and the solar cycle, and effect of magnetic configuration has not been included in PSI

Conclusions – Continued

2. **Effect of Faculae:** We do not have good faculae models
 - (a) In many cases, full disk and chromospheric indices are used to describe the effect of photospheric faculae
 - (b) From the MDI and Kitt Peak observations new efforts have been made to identify faculae
 - (c) However, the area measurements differ - and the faculae contrast change is not taken into account

Conclusions – Continued

3. **Effect of Network:** We do not have good network models

(a) Network is estimated from full disk indices

(b) Attempts to combine continuum and Ca K images have been made to identify the network - these again describe mostly the chromospheric network

(c) Further, we do not know whether the "quiet-Sun" or the weak magnetic field are indeed quiet or they change over time, thus contributing to long-term climate changes

Conclusions – Continued

4. Effect of Global Changes:

(a) Temperature changes: small changes in the photospheric temperature may explain the 0.1% solar cycle variations

(b) Results on radius changes are quite contradictory, we need to have (BOTH HMI and PICARD measurements)

Conclusions – Continued

Improvements in long-term solar irradiance models for climate studies will require:

1. Long-term and better quality measurements;
2. Improvement of radiometry;
3. Improvement of the sunspot and faculae area and contrast measurements
4. Use of high resolution images to better account for the weak field component which is excluded from the current empirical models;
5. Most importantly, we need to understand the physics of all surrogates and thus the origin of irradiance variations to better predict their effect on past and future climate changes.

Specific Science Tasks

Study high resolution MDI images to extract network and include it to irradiance models (2nd and 3rd year)

Study the contrast changes of sunspots and faculae over time (active regions time scale and over cycle 23) (2nd year)

Include these parameters either into empirical or semi-empirical models (synthetic models) (3rd year)

Study the energy budget of active region using more accurate sunspot/facular areas and their contrast (3rd year)

Systematic study of the evolution of active regions, particularly ones with δ spots (space weather application) (2nd year)

Apply results to current data (SOLIS, MDI, Solar-B) and forthcoming SDO measurements (3rd year + new proposal)

Active Regions Mosaic – AR Evolution

Tracked Active Region: Magnetogram, Photogram, Labeling
1996 July 27 — August 08

