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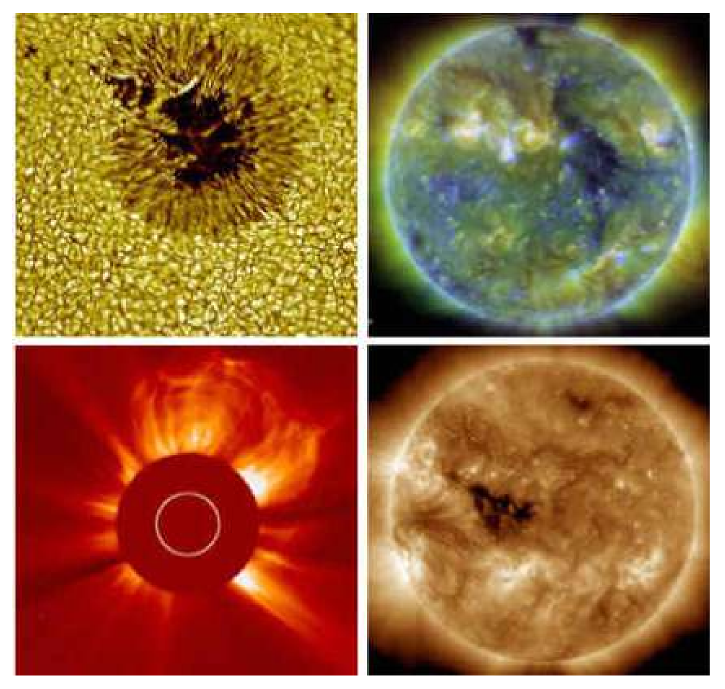

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Solar Ca II K Observations

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Some of the most important archives of past and current long-term solar synoptic observations in the resonance line of Ca II K are described here. These observations are very important for understanding the state of the solar magnetism on time scales up to several decades. The first observations of this kind began in 1904 at the Kodaikanal Observatory (India), followed by similar programs at different other locations. Regular full-disk Ca II K monitoring programs started in 1915 at the Mount Wilson Observatory (USA) and in 1917 at the National Solar Observatory of Japan. Beginning in 1919 and in 1926 regular observations were taken also at the Paris-Meudon Observatory (France) and at the "Donati" solar tower telescope of the Arcetri Astrophysical Observatory in Italy, respectively. In 1926 the the Astronomical Observatory of the Coimbra University in Portugal started its own program of Ca II K observations. Although some of these programs have been terminated over the years, their data archives constitute a unique resource for studies of solar variability. In the early 1970s, the National Solar Observatory (NSO) at Sacramento Peak (USA) started a new program of daily Sun-as-a-star observations in the Ca II K line. Today the NSO is continuing these observations through its Synoptic Optical Long-term Investigations of the Sun (SOLIS) facility.

Keywords: Sun: activity - Sun: chromosphere - Sun: surface magnetism

1 Introduction

Observations of the solar surface reveal magnetic fields with complex hierarchical structures, evolving on a wide range of different spatial and temporal scales. The most prominent aspect of this variability is the solar cycle of activity, with a period of approximately 11 years for the sunspot numbers and a period of about 22 years for the magnetic polarity. Forty years of satellite measurements of the Sun's energy output have revealed that also the solar irradiance changes over the full range of time scales from minutes to decades (e.g., [1]), and this variability is wavelength dependent [2, 3]. Empirical models have shown that the variability in solar irradiance is indeed modulated by the area variations of the solar surface magnetic features, to a high degree of correlation [4-6]. However, there is still disagreement about the contribution of individual solar features for changes in the solar output, in particular over decadal time scales. Two of these features, plages and chromospheric magnetic network, account for a significant portion of the Sun's total magnetic flux. They also play a critical role in modulating the UV and EUV variability, which directly affects the conditions in the heliosphere and directly influence the Earth's magnetosphere (see the references in the paper by Foukal *et al* [7] for a discussion on this subject). Observations near the core of the ionized calcium K line (393.37nm) provide one of the most effective tools to investigate the morphology and evolution of both plages and chromospheric magnetic network. These observations have been available now for more than 100 years, and they constitute a major resource for studies of solar activity over multiple cycles. For example, they have been widely used as proxies to reconstruct the history of the

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solar magnetism and solar irradiance over the last 100 years and beyond [8, 5]. In this paper, we describe some of the most important historical archives of such measurements, and current observations that are being carried out at the US National Solar Observatory.

2 Ca II K historical archives

The spectroheliograph was invented independently by George Ellery Hale (1868-1938) and Henry-Alexandre Deslandres (1853-1948) between 1890 and 1891. Deslandres's apparatus consisted of a one-prism spectroscope of small dispersion placed on a carriage so it could move in a horizontal direction, perpendicular to the axis of the collimator. The photographic plate was moved behind the second slit by a system of levers attached to a fixed point. In Hale's spectroheliograph, the scanning was achieved by driving the solar image by means of the telescope's declination axis. Figure 1 shows a very early observation of the Sun taken in 1895. The bright patches visible on the disk are known as plages, and are associated with concentrations of magnetic fields. They are part of the network of bright emissions that characterize the solar chromosphere. In 1932, Robert Raynolds McMath (1891-1962) extended the spectroheliograph functionality in order to take motions pictures of the Sun. Soon after the invention of the spectroheliograph, and over the course of few decades, systematic observations in the Ca II K line started at several observatories. Over time, these observations have made available to the scientific community a huge number of solar images. We summarize here the main properties of some of these relevant databases, which cover most of the Sun's activity during the 20th century. Some of these programs are still ongoing, while others have been terminated due to various reasons. Altogether they constitute a rich resource for studies of solar activity at different time scales. For a comparative study of some of these databases we refer the reader to the paper by Ermolli *et al* [9].

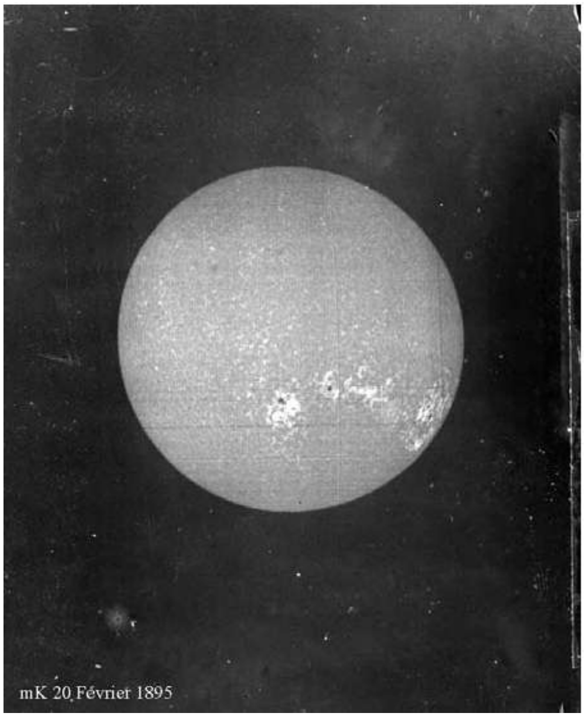

Fig 1. An early observation of the solar chromosphere in the Ca II K line. This image was taken on February 20, 1895 and it is part of the Meudon archive of historical spectroheliograms available at *bass2000.obspm.fr/gallery2/main.php?g2 itemId=9081.*

2.1 The Mount Wilson archive

Since 1915, the monitoring program of the Mount Wilson Observatory has produced an archive contains over 150,000 images of the Sun, including broad-band images, ionized Ca II K line spectroheliograms and Hydrogen Balmer alpha spectroheliograms, obtained at the 60-foot tower. Unfortunately, the Ca II K series of observations was terminated in 1985 due to lack of funds. The images were first digitized by Cambridge Research and Instrumentation, Inc. using a 512-pixel format, 8-bit camera [10]. The same data were re-digitized later at the University of California, Los Angeles (UCLA), by using a higher resolution (3000×3000), 12-bit digitizer [11]. The latest digitization includes almost 40,000 solar images and step wedge images (available after 1962) extracted and identified with original log-book parameters of observation time and scan format. Figure 2 shows the distribution of the Mount Wilson solar Ca II K spectroheliograms per year.

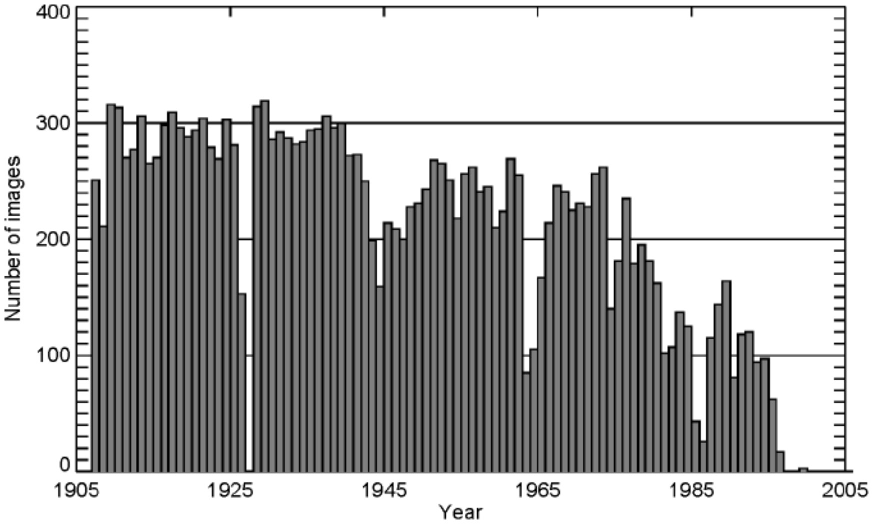

Fig 2. Number of solar Ca II K spectroheliograms per year available from the Mount Wilson Archive.

Prior to their public distribution, the group at UCLA has processed the raw data to mitigate some of the artifacts present on the images. In particular, the presence of some dust and pit in the images was reduced via a Laplacian filter. The size of the images was then reduced from its original scanned resolution of ≈ 3000 × 3000 to ≈ 866 × 866 spatial pixels, by averaging the pixel values within each 4 × 4 portion of the image.

One of the main problems in calibrating these images is the presence of a vignetting function. This function is linked to the relative position between the pupil and the grating, which depends on the celeostat mirror positions and shifts during each exposure due to the scanning of the spectrograph across the solar image. As a result, the intensity and its gradient are highly variable from one image to another. Step-wedge exposures on the Ca II K spectroheliograph sequence are available only since 9 October 1961. For those images it impossible to use, following the ideas presented by de Vaucouleurs [12], the H&D curve calibration approach to obtain well calibrated intensity images. Unfortunately, the bulk of the sequence does not offer this possibility and a different approach is required. Two main investigations of this database have been conducted using different calibration techniques. In Bertello *et al* [13], vignetting and limb darkening were removed using a running median filter. A more elaborated scheme was used in Tlatov *et al* [14]. Under the assumption that the center-to-limb variation in quiet Sun corresponds to a standard curve, and does not change with the overall level of solar activity, one can derive an estimate for the contribution from scattered light (from the spectral grating, telescope, etc.) and film/plate contrast. Ultimately, both methods provide calibrated and normalized images, where the contribution of the large-scale background due to instrumental effects has been significantly removed. Time series of quantities derived from images calibrated using these two methods are in excellent agreement with each other. For example, Fig 3 shows a comparison of the disk-integrated Ca II K plage index and the average plage contrast obtained by these two studies. The most interesting feature of this figure is the increasing in the plage contrast during solar cycle 19, from about 1953 to 1961. A similar analysis performed by Tlatov *et al* [14] on the archive of the Kodaikanal Observatory, India (KKL) for the same period does not show any significant variation in the plage contrast. It is speculated that the increase in the plage contrast during solar cycle 19 in the Mount Wilson data is due to the exit slit width being narrower during that period [14].

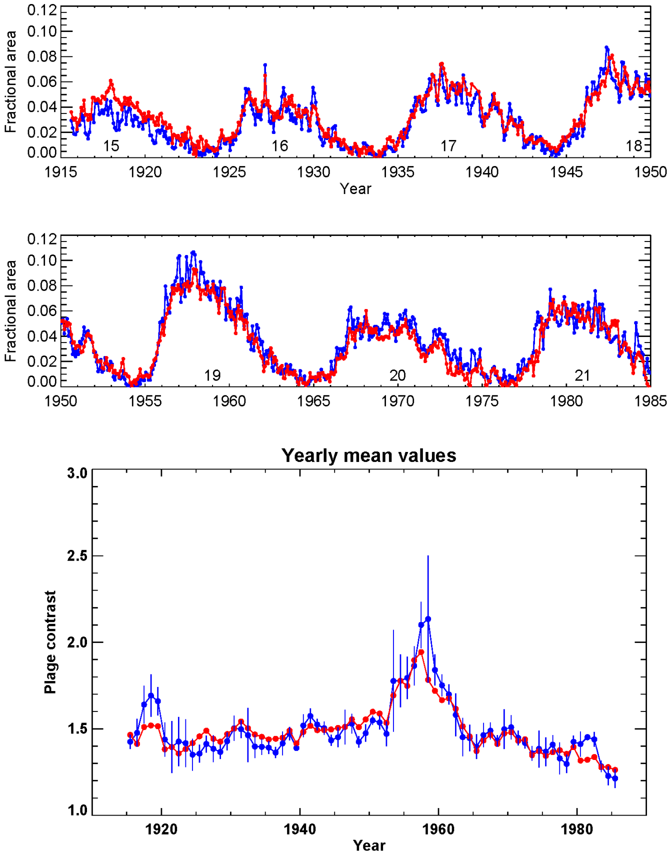

Fig 3. Top two panels: Monthly mean values of the disk-integrated Ca II K plage index (red) derived from the analysis described in Bertello *et al* [13] and, in blue, the same quantity derived by Tlatov *et al* [14]. The index is given in units of the fraction of the visible solar hemisphere covered by plages and network. Bottom: Comparison between the annual mean values of the plage contrast (blue) measured by the same two groups. The error bars are 3 standard deviations of the mean.

2.2 The Kodaikanal archive

The archive at the Kodaikanal Observatory of the Indian Institute of Astrophysics in Bangalore hosts the longest record of spectroheliograms currently available. After the Cambridge spectroheliograph was put into operation, in late 1904, there was some problem with the settings of the second slit at the correct wavelength. Generally, the photographic plate remains fixed and the spectroheliograph along with the second slit moves. If second slit is moving than the image need to move, but not the carriage. Although spectroheliograms were obtained in 1905 and 1906, the instrument did not perform to its potential until 1907, when regular observations began [15]. The 70-micron exit slit of the spectroheliograph corresponds to a 0.5 Å bandpass centered on the core of K3 at λ393.37 nm. Spectroheliograms in the Ca II K line were obtained using the photographic emulsion until 2007. In particular, from the 1970s to late 2007 Scientia EM 23D56 emulsions from the AGFA company was used. After this stock was exhausted, in 2007, images in Ca II K were taken using Kodak film, but the results were not satisfactory and the program was terminated the same year. Observations in Ca II K at Kodaikanal Observatory were also acquired using other instruments. For example, beginning in 1997 observations were obtained using a filter-based instrument (Daystar), with a 1.2 Å bandpass, and PhotometricsCCD camera. After 2008 Ca II K measurements, along with broadband images of the Sun, were recorded on two ANDOR CCD cameras simultaneously using the TWIN telescope [16]. While the TWIN telescope is still operational, due to problems with the CCD cameras, observations in Ca K line were not obtained since October 2013. Overall, the number of days available at Kodaikanal for making observations of the Sun had become less in the later part of the 20th century as compared to the first half of 20th century.

Figure 4 shows the distribution of the Kodaikanal solar Ca II K spectroheliograms per year. A quick comparison with Fig 2 indicates the number of daily observations taken at the Kodaikanal Observatory were typically less than those at the Mount Wilson Observatory.

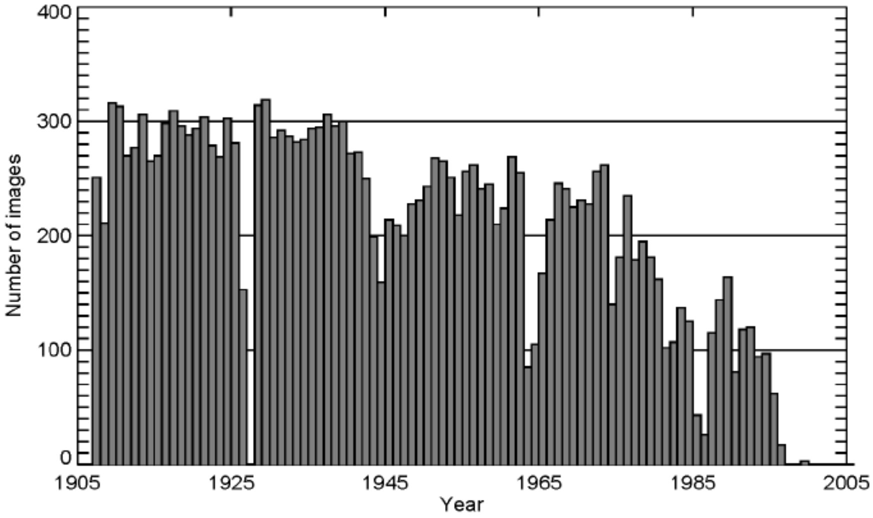

Fig 4. Number of calibrated solar Ca II K spectroheliograms per year available from the Kodaikanal Archive.

At least two major projects have been undertaken in the past to digitize this archive of observations. Makarov *et al* used a commercial scanner, with the setting 1200 × 1200 dpi, to produce 1800×1800 8-bit images [17]. More recently, Priyal *et al* have used a 4k × 4k CCD camera, a pixel size of 15μ square, and a 16-bit readout to digitize the images [18]. Images from the first of these two projects were calibrated by Tlatov at al. to compute a Ca II K plage index and plage contrast using the same identical approach adopted for the Mount Wilson data [14]. Their analysis shows that the mean plage contrast in the Kodaikanal data is slightly lower than the corresponding value determined from the Mount Wilson images. This is consistent with the fact that the Mount Wilson observations were taken with a moderately narrower spectral bandpass, meaning those two data sets sample different layers in the solar atmosphere. On the other hand, the two monthly averaged plage index time series show a fairly good agreement over the seven solar cycles (cycle 15 to cycle 21) covered by these observation. The relationship is linear, as shown in Fig 5.

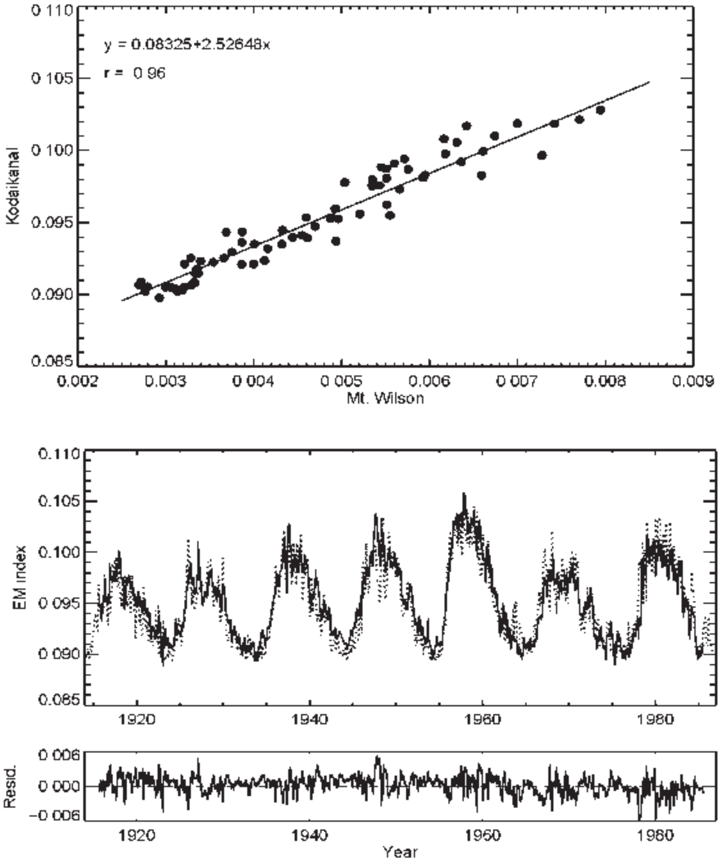

Fig 5. Top: Relationship between the annual mean values of the plage index derived from the Mount Wilson and Kodaikanal archive of Ca II K observations taken between 1916 and 1985. The statistical significance (t-test) of this linear correlation (r) is greater than 99.9%. Middle: Monthly averages of Kodaikanal (dotted line) and Mount Wilson (solid line) full-disk plage index measurements. Both time series were rescaled into a K line 1-Å emission index equivalent. Bottom: The lower panel shows the residuals.

2.3 The Meudon archive

The series of spectroheliograms of the Paris-Meudon Observatory dates back to 1919. Around 300 daily measurements can be acquired every year in Hα, Ca II K1v, and Ca II K3 (core). Two spectrographs are operated behind the entrance slit: a prism-spectrograph (2.1 Å mm^{-1}) for K1v and K3, and a grating spectrograph (3.22 Å mm^{-1} for Hα [19]. The output slits are moved in front of the photographic plates so that the solar images are restored automatically. Both input and output slits are curved in order to reduce the geometrical distortions. Despite many improvements were made to the instrumentation between 1919 and 1988, the data collection exhibits a remarkable homogeneity. In its current configuration, images are taken with a 1300 × 1300 14-bit pixels CCD camera, with an image scale of about 1.5 arcsec/pixel. The spectral passband is 0.15Å centered on either K1v or K3. These images have been used to construct butterfly diagrams and synoptic chromospheric maps to study solar activity, more recently, to locate radio bursts in connection with active regions.

A subset of images from this database was investigated by Ermolli *et al* [9] and compared to similar images from other archives, including those previously discussed here. The investigations have shown significant differences between observations taken on the same day available from these historical archives.

For example, the Mount Wilson images show filaments over the solar disk which are not found in some of the other data. The Kodaikanal images show sunspot regions which are not visible in the Mount Wilson spectroheliograms. On the other hand, the Meudon data show both of these features. However, due mainly to differences in the spectral bandpass, the size of the visible bright features (plages) are quite different in all of these images. Geometrical distorsions, as revealed by the parameters of the ellipse that best fits the solar limb, are a common problem with those images. The average disk eccentricity for both the Kodaikanal and Mount Wilson images is about 0.12 ± 0.04, while for the Meudon images is 0.14 ± 0.02 [9]. The same study found that, on average, the Kodaikanal images appear to have a slightly higher spatial resolution than the Mount Wilson images, which spatial resolution is close to the one of current Meudon images. Large-scale image inhomogeneities introduced by variations in sky transparency during observations and by instrumental problems vary significantly between the different observing sites. In average, the Kodaikanal images show the larger variations in intensity across the disk, followed by the Mount Wilson and Meudon images.

2.4 The Arcetri archive

The digitized archive of the Arcetri spectroheliograms has been described in details in Ermolli *et al* [20]. We provide here some basic information about the properties of those images. The archive contains almost 13,000 photographic plates of full-disk Ca II K and Hα spectroheliograms acquired from July 1926 to September 1974. Almost half of those images (5976) consist of Ca II K measurements. Between 1926 to 1955 an average of about 100 Ca II K observations per year were taken. This number increased significantly after 1955, reaching almost 400 around 1959-1960. During the last 14 years of the program the number of observations has continuously and systematically decreased as clearly indicated by Fig 2 in Ermolli *et al* [9]. Observations were taken with a 600 lines/mm grating, and a dispersion of 0.33 mm/Å at 3934Å. Several instrumental changes were made and different photographic products were used made during the lifetime of this program. In particular, original plates stored in the archive have different dimensions and content as described in Ermolli *et al* [20]. One of the major issues related to these observations is the limitation for the study of details of the solar surface imposed by the local seeing at the Arcetri solar tower which on average is about 5 arcseconds [21, 22]. On the other hand, unlike other similar historical datasets, most plates from the series of Arcetri observations contain the step-wedge exposures for the calibration of the photographic emulsion to the flux of the incident radiation. This makes this series very suitable for cross-calibration purposes with other archives.

The digitization of this archive was performed by Ermolli *et al* [20] using a commercial scanner, at 1200dpi, and a system equipped with a 1K × 1K CCD camera. Images were digitized with 16-bit gray-scale dynamic range, and the entire database can be accessed from http://www.oa-roma.inaf.it/solare/index.html.

2.5 The Coimbra archive

In 1907 the Astronomical Observatory of the Coimbra University (Portugal), in collaboration with the Paris- Meudon Observatory, started assembling its first spectroheliograph. It was designed to be a replica of the same instrument operating in Meudon, having identical and interchangeable components. A significant advantage of this close collaboration between the two observatories is that in general observations at one site cannot always be obtained every day, mostly due to meteorological conditions. However, the two observatories are very close in longitude to have almost the same window of observations but quite separated from each other to be affected by different weather conditions. Consequently, missing daily observations in one site can be filled with observations from the other site, resulting in a higher duty-cycle.

However, it was not until 1926 that the Coimbra instrument began taking regular observations of the full solar disk in the Ca II K spectral line. In the late 1960s the instrument was relocated from the old location in the city to a new observatory in Santa Clara, near Coimbra. The spectroheliograph was completely renovated in the early 1990s, and equipped with a new objective lens and a new optical branch with diffraction grating to allow for both Ca II K and Hα observations. In 2007 the use of photographic plates was terminated and since then observations were acquired with a 12-bit CCD camera. Several parameters of solar activity are recorded and tabulated from the daily spectroheliograms including position, dimension, type and evolution of sunspots, plages, filaments, and prominences.

Between 1926 and 2007, photographic spectroheliograms were taken at three different wavelengths: 393.37 nm (Ca II K3), 393.23 nm (Ca II KV1), and 655.87 nm (Hα). The spectral bandwidth for the observations in the Ca II K line was set at 0.015 nm, significantly narrower than what was used for the Kodaikanal measurements. In 2007, after the installation of the CCD camera, changes have been made to the original program. Currently, measurements are taken also at 656.28 nm (red continuum) and the bandwidth of the Ca II K observations has been slightly increased to 0.016 nm. Typical images have size of 1000×1000 pixels with a plate scale of 2.2 arcseconds/pixel. As reported in [23], between January 1, 1926 and July 31, 2010 17,770 observations were taken in the core of the Ca II K line. During the first 40 years, the number of these observations per year was relatively constant and around 200. This number dropped dramatically during the relocation of the instrument to the new and current location but eventually reach the previous value around 1980. Since then this number has slight increased over the years to reach a value of about 300 observations per year at the end of 2010.

All photographic material has been scanned and stored as 16-bit FITS and 8-bit JPEG files at http://tangerine.mat.uc.pt/novo/obsevatorio/site/index.html and at http://bass2000.obspm.fr/home.php.

2.6 Other Ca K line image archives

In mid-20th century, several other observatories conducted synoptic observations of the Sun in Ca II K line. Thus, for example, beginning early 1960, the daily spectroheliograms were taken at Evans Solar Facility at NSO/Sacramento Peak observatory in New Mexico, USA. The on and off band spectroheliograms were observed with a 0.0514 nm spectral bandpass centered at Ca II K line (λ393.367 nm). In addition, a smaller number of off band images were taken with on offset of 0.038 nm to the red wing of the Ca II K line. The Ca II K line core spectroheliograms from 1985–1999 period were digitized at 512-pixel, 8-bit resolution. Initially, four images per month (spaced as evenly as the data enabled) in the period 1985–1999 were digitized at 512-pixel, 8-bit resolution. A complete digitization of the entire collection of 7171 plates (6033 plates in the line core, and 1138 with red-wing offset) was carried out later with 1500-pixel, 16-bit resolution (see, [14]). The spatial resolution of NSO/SP data from this (second) digitization is about 1.2 arcseconds per pixel, so the radius of the solar disk on NSO/SP images is about 750 pixels. The digitized Ca II K line spectroheliograms can be accessed via NSO Digital Library at http://diglib.nso.edu/ftp.html.

Observations in the chromospheric Ca II K line have been taken also at the Kislovodsk Mountain Astronomical Station of the Pulkovo observatory since July 1952. During the first four years of this program measurements were recorded on film, and then on photographic plates until August 2002 when they were replaced by a CCD-array. Data from this archive can be retrieved from http://en.solarstation.ru/sun-service/chromosphere. In 1917 the National Astronomical Observatory of Japan (NAOJ) began taking observations in Ca II K with a Grubb 30-cm sidelostat and a Toepfer double-prism spectroheliograph. Daily observations were taken until the program was terminated in 1974. In total, more than 8585 images were recorded and digitized.

The daily full-disk, photometric images of the Sun in Ca II K line (393.4 nm) wavelengths are also taken at the San Fernando Observatory (USA) since 1988 [24], the Baikal Astrophysical Observatory of the Institute of Solar-Terrestrial Physics, Russian Federation (1995–present, http://en.iszf.irk.ru/KCaII-telescope), and the Mees Observatory of University of Hawaii (1995–1998, http://www.solar.ifa.hawaii.edu/KLine/index.shtml).

3 Sun-as-a-star measurements

In addition to the disk-resolved spectroheliograms described in the previous section, several long-term Ca II K programs have been monitoring the properties of the Sun-as-a-star. Beginning in November

1976 and until September 2015, observations of the disk-integrated solar Ca II K-line were made using the Evans Coronal Facility at the National Solar Observatory/Sacramento Peak (USA, [25, 26]). The light from a coelostat was feed the the horizontal Littrow spectrograph and the spectrum from 3898-3954 Å was recorded by rotating the spectrograph grating. The optical setup employed cylindrical lenses to compress the image of the entire solar disk prior to the spectrograph slit. A photomultiplier was used as a light detector. On a typical observing day, the observer would take between 50 and 150 spectral scans. These were averaged, after removing scattered light and dark current, to form a daily mean profile. The shot noise level of individual scans is about 10% of the observed signal in the core of the Ca II K line. The random noise of daily averaged profiles estimated from the standard deviation of mean (50-100 individual profiles) is about 3-5% in the 1 Å emission index derived from these data (S Keil, 2016, personal communication). Since the spectral scanning did not extend far into a pseudo-continuum, the flux calibration was done using observed intensity at a fixed wavelength offset relative to K-line code (i.e, average intensity in a 0.528 Å window centered at 1.187 Å in red wing of Ca II K line was set to 0.162 of the continuum intensity). The normalized line profiles were used to calculate several parameters such as the 1Å emission index (the equivalent width of a 1 Å band centered on the K line core), the K3 (the core) intensity, the relative strength of the blue K2 emission peak with respect to the K3 intensity (K2V/K3), the separation of the two emission peaks (K2V–K2R), the line asymmetry which is the ratio of the blue and red K2 emission maxima (K2V/K2R), the separation of the blue and red K1 minima (K1V–K2R), and the Wilson-Bappu parameter which is the line width measured between the outer edges of the K2 emission peaks. These parameters are available from the NSO web site at http://nsosp.nso.edu/node/15. Ca II K-Line Monitoring Program at NSO/Sac Peak had a duty cycle of 10% during 1976–1983 and about 45% between 1984 and 2015. On October 1, 2015, the NSO/Sac Peak Ca II K-Line Monitoring Program was stopped. The Ca K-line Sun-as-a-star time series is now continued using SOLIS/ISS observations. These new observations are discussed in more detail in the next sub-section.

The sun-as-a-star spectra in several photospheric and chromospheric wavelength spectral bands were recorded also at the Kitt Peak Vacuum Telescope (KPVT, [27]). In particular, the Ca II K line profiles were recorded from late 1974 till early 2013. The details of the initial instrument setup can be found in [28], but observations during different periods were taken with different instrument setups. Prior to 1992, the observations were taken with the spectrograph grating that did not sample the full solar disk completely (see, [28] for a discussion of possible effects on data). The cadence varies between 2-13 observations per year (1974–1976) to a maximum of 87 observations per year in 2009. The 1 Å emission index derived from these data can be access via ftp://solis.nso.edu/kpvt/CaK Indicies/K-line stats.dat.

In 1969, M.K.V. Bappu started the monitor program of the Sun-as-a-star Ca II K line at the Kodaikanal Observatory to study the Sun's long term variations [29]. The observations made at the KPVT and the KKL have similar spectral resolution but data from the KPVT has better photometric accuracy because of the electronic and photographic film adopted. The data obtained at Sac peak has less spectral resolution as compared to KPVT and KKL but has more coverage round the year. Their initial investigation found that several parameters of the Ca II K line profile varied with solar activity and the Ca II K index varied by about 20% over the solar cycle phase whereas the central intensity at K3 increased by about 30% during the maximum phase as compared to that at minimum phase of solar cycle. Following these observations, Skumanich *et al* [30] proposed a three component model of cell, network and plage to explain the observed changes in Ca-K line profile, using the extant laws of limb darkening. They were able to fit the model profile with the observed one by considering the contribution of two components, namely cell and network during the minimum phase. But during the maximum phase the contribution due to plage component alone was found to be insufficient to explain the observed profile. Therefore, they suggested an additional contribution due to 'active network component' to achieve a good agreement between the model and observed Ca II K line profiles. This assumption explained the existence of extra emission during the maximum phase. However, measurements made at the center of the solar disk over a region of 1-3 degrees showed no variation with the phase of the solar cycle ([31], [28]), suggesting that the extra emission originates from higher latitudes.

To further investigate the findings by Skumanich *et al* [30], in 1986 a new program of solar observations was started to study the dependency of the Ca II K emission with latitude [32]. Spectra are taken by using the following methodology: (1) A portion of the Sun's image is allowed to pass through the slit of the spectrograph; (2) While the Sun's image is moved with uniform speed from East end to the West end on the slit of the spectrograph at a particular latitude, the spectra in Ca II K wavelength is obtained; (3) The procedure is repeated for each 10-degree latitude belt but the spectra are integrated over the longitude belt.

The analysis of Ca-K line spectra as a function of solar latitude and integrated over longitudes taken during the period of 1989-2011 indicates that the K1 width reaches maximum amplitude at various latitude belts at different phases of the solar cycle [33]. The FWHM of the K1 distribution at different latitudes shows that its width varies by about 30% for the equatorial belt (< 30°) and 11% for the polar region (> 70°) latitudes. Interestingly, the K1 width varies by about 6% around 60° latitude during the solar cycle. The analysis of cross-correlation coefficients of the K1 width between the 35° latitude and other latitude belts as a function of phase differences indicates that the activity representing toroidal field shifted at a uniform rate of about 5.1 m/s in the northern hemisphere from mid-latitudes toward the equator. In the southern hemisphere, activity shifted at a faster rate, about 14 m/s, in the beginning of the cycle and the speed decreased with time, yielding an average speed of 7.5 m/s toward the equator. The shift of activity in the higher latitude belts showed complex behavior, indicating pole ward and equator ward migration. These findings, especially the fewer variations in mid-latitude belts as compared to polar regions, asymmetry in the speed of the shift in the activity in both hemispheres, and complex variation in the direction of the shift in the activity representing poloidal fields in mid-latitude belts, will have an important implication on the modeling of solar dynamos.

In 1994, a Solar-Stellar Spectrograph (SSS) project started at the Lowell Observatory. The SSS project provides regular observations of solar spectral lines in a broad wavelength range including Ca II K and H lines [34, 35]. Additional details about SSS project can be found in Pevtsov *et al* [36] and the referenced therein.

3.1 SOLIS/ISS Ca II K observations

Beginning December 2006, Sun-as-a-star spectra are recorded on a daily basis by the Integrated Sunlight Spectrometer (ISS), one of three instruments comprising the Synoptic Optical Long-term Investigations of the Sun (SOLIS) facility. ISS takes high spectral resolution (R 300,000) observations in nine different spectral bands, covering a broad range of wavelengths (350 nm - 1100 nm), including the Ca II K band. Observations with the ISS are accomplished through the use of a fiber optic feed. A small optical system (a lens of 8-mm diameter) installed on the side of main mount of SOLIS/VSM focuses a 400 micron diameter image of the Sun on the input face of a 600 μ 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. The output beam from the fiber consists of sunlight scrambled in both angle and position so that any output angle from any position on the exit face is well-integrated. A prism pre-disperser isolates the desired wavelength band. The spectrograph employs a 316 g/mm grating blazed at 63.5 degrees and a movable, back-illuminated 512 × 1024 CCD as the focal plane detector ([37] and reference therein).

Figure 6 shows a typical observation in the Ca II K band. The observed spectral range also includes a number of photospheric lines (shown in the figure) that are used for wavelength calibration. In general, ISS spectra show a slight gradient in intensity in the wavelength direction. For spectral bands that include a continuum, this gradient is removed by a linear fit to the continuum and the spectra are scaled by the fit. However, the Ca II K spectral band does not include a continuum. In this case the normalization of the spectrum is achieved by using the intensities at two narrow spectral bands situated in the blue (393.147-

393.153 nm) and red (393.480-393.500 nm) wings of the line. Mean intensities in these two bands are then scaled to match the spectral line profile taken by the NSO Fourier Transform Spectrometer [38].

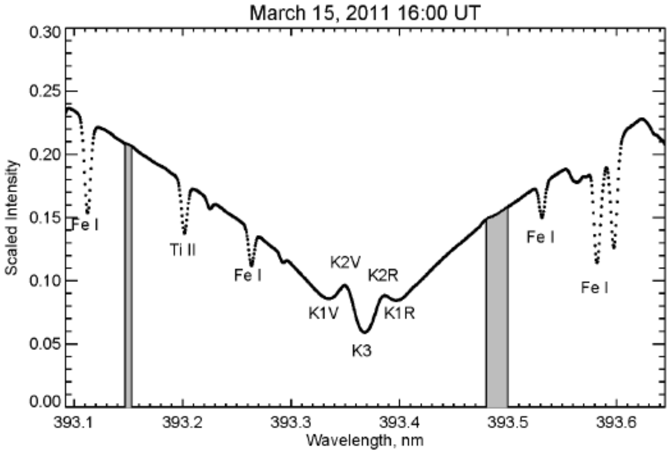

Fig 6. A typical ISS Ca II K profile. The five labeled photospheric spectral lines included in the observed spectral band are used mostly for wavelength calibration purposes. Significant sections of the Ca II K line profile, near the core and the emission components, are also labeled according to the standard convention. R indicates red portion of the profile, and V indicates the violet (blue) side of it. Highlighted in gray are the two narrow spectral bands used to normalize the profile (see text).

Nine different parameters are derived from the ISS Ca II K spectra, including those derived as part of K-line monitoring program at NSO/Sacramento Peak. Details about the observations and data reduction of those spectra can be found in [39] and [36]. ISS spectral data and the parameter files can be accessed via SOLIS web site at http://solis.nso.edu/0/iss/.

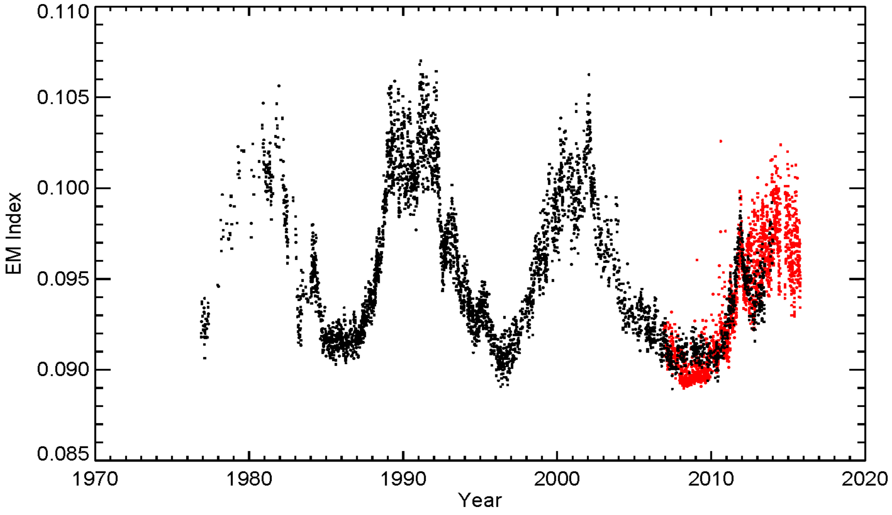

Fig 7. Daily disk-integrated Ca II K 1 Å emission index measurements from Sacramento Peak Observatory (black) and SOLIS/ISS (red) after adjusting the Sacramento Peak data.

Although the two instruments are similar in concept, the sensitivity of the ISS observations is much higher than the Sacramento Peak measurements. Due to shot noise in the photomultiplier, individual scans taken with the Sacramento Peak instrument are noisy (noise level is about 10% of the observed signal in the K-line core). Computing the daily mean decreases this noise level to a few percent of the signal for the mean spectral scan. Since each daily measurement of the Ca II K emission index is obtained by averaging 50-100 individual profiles, the random error can be determined from the standard deviation of the profiles and is approximately 3%-5% for the emission index measurements. In the case of the ISS these errors are much smaller, less than 0.1%, but the contamination from scattered light is likely to increase this value quite significantly. Except for a scaling factor, time series of the Ca II K emission index derived from these two sets of observations agree quite well, as shown in Fig 7.

The high quality of the parameter time series derived from the Ca II K profiles obtained by the ISS instrument will open the possibility for a variety of solar-stellar research related studies. In a recent paper by Bertello *et al* [40], the analysis of the temporal variations of Ca II K line profiles observed by the ISS instrument during the declining phase of Cycle 23 and the rising phase of Cycle 24 has shown that it is possible to detect the signature of solar surface differential rotation from disk-integrated measurements. This has important implications for the study of differential rotation and dynamo processes in other stars.

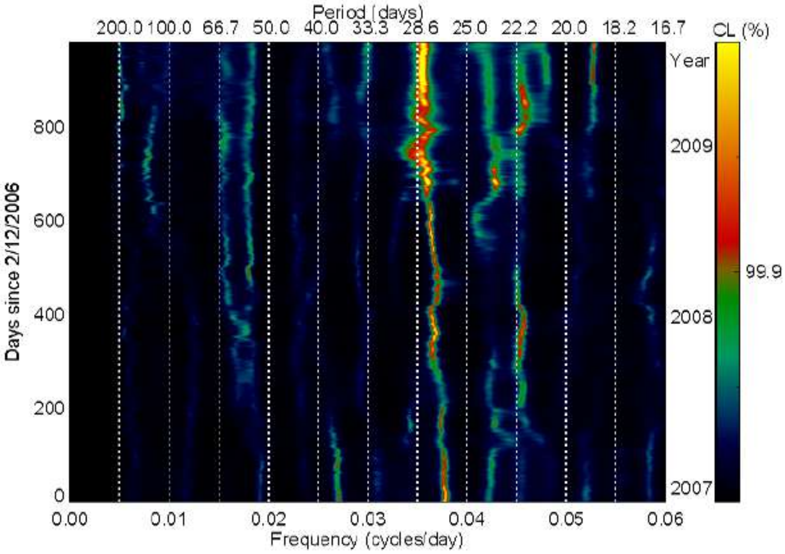

Fig 8. ISS Ca II K3 core intensity time-frequency distribution from observations taken during the period 12/2/2006-1/27/2012. A 900-day sliding time window was used, with a difference between consecutive segments of 1 day. The beginning of each segment, in days since 2/12/2006, is indicated on the left y-axis with the year shown on the right y-axis. The power spectral density above/below the 99.9% confidence level (CL) is indicated by the color bar (Fig 6 in Ref [40], reproduced by permission).

Figure 8 shows one of the results discussed Bertello *et al* [40]. A time-frequency analysis was applied to the ISS Ca II K3 core intensity time series to investigate the time evolution of the individual components of the power spectra. The time series was subdivided in overlapping segments of 900 days, with a 1-day time shift between consecutive segments. For each of these segments, the power spectrum was estimated using a maximum entropy spectral estimator (MEM). This choice is well suited for the analysis of these data because of its high spectral resolution capability. The choice of a 900-day sliding window provides the best compromise between time and frequency resolution. The signature of solar differential rotation is clearly visible in this figure: most of the contribution to the power spectral density of the signal is concentrated into a narrow frequency band, whose central value varies in time in the range 0.035 to 0.038 cycles/day (period range from 28.6 to 26.3 days). This change in period over time is consistent with the migration of activity from latitudes bands at ∼ 35 degrees to the equator. To large degree, this curve is remarkably continuous and smooth at all times. Figure 8 also shows some additional power distribution over different time-frequency regions. A possible interpretation is that this power is the result of sunspot and facular evolution.

4 Combining different Ca II K observations

In the previous sections we have briefly described some of the most important archives of Ca II K observations. While some of these programs have been terminated after decades of measurements, others have replaced them. Altogether, these programs provide a unique resource for detailed studies of long-term variations in solar chromospheric activity. Although different techniques/instruments have been used to collect those data, there is enough overlap among these sets of observations to allow for their cross-calibration. Ideally, a unique and homogeneous time series derived from combining these observations together will provide a fundamental tool to study the complex hierarchical structures of the solar magnetic field and its evolution on a wide range of different spatial and temporal scales (e.g. [41, 42], and references therein).

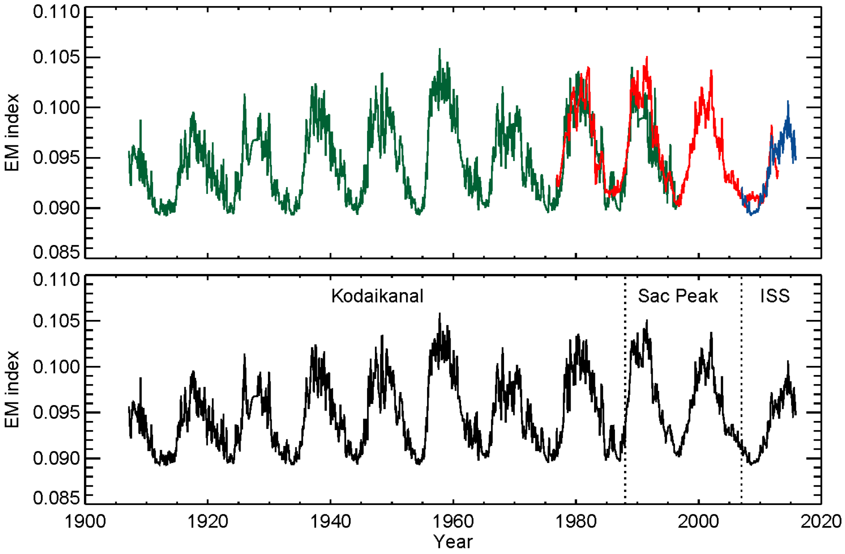

Fig 9. Top: Monthly disk-integrated Ca II K emission (EM) index derived from Kodaikanal (green), Sacramento Peak (red) and ISS observations (blue). Bottom: Final composite obtained by merging the three time series together. The vertical dotted lines indicate the transition from one time series to another. the Kodaikanal data were used until the end of 1987, followed by the Sacramento Peak time series until December 31st , 2006. The ongoing ISS data are then used starting January 1st, 2007.

In a very recent study (Bertello *et al* 2016, submitted to Solar Physics), time series of the Ca II K emission index from three major databases were combined together to create a unique composite spanning more than 100 years of observations, or about 11 solar activity cycles. As shown in the top panel of Fig 9, data from the Kodaikanal Observatory, NSO/Sacramento Peak Observatory (sun-as-a-star measurements), and ISS were used for this purpose. The first two time series were rescaled into the ISS measurements. The resulting composite is plotted in the bottom panel of Fig 9. The continuity between the various time series is well preserved at the transition points, which are indicated by the two vertical dotted lines. One can notice that at the sunspot minima, between cycles 21-22 and cycle 23-24, Sacramento Peak Ca II K data appear overestimating the level of the chromospheric activity as compared with Kodaikanal and ISS observations.

5 Conclusions

The Sun's variable magnetic fields constitute a rich source for processes that influence the heliosphere, and the Earth's upper atmosphere. The complex dynamo processes leading to the solar cycle of activity are believed to arise from the boundary layer just below the solar convection zone known as the tachocline [43, 44]. In turn, this cycle of activity drives the morphology of the solar surface magnetic field that influences the solar irradiance energy budget. Due to the Earth's atmospheric absorption it was not until long-duration measurements from space were available that changes in total and spectral solar irradiance were accurately measured. Those measurements began with the launch of the Nimbus 7 satellite in November 1978. Ca II K measurements, however, can be used as a proxy to reconstruct the past history of solar irradiance over much longer periods of time [8, 5]. The collection of historical Ca II K observations briefly discussed here constitute a unique resource for a variety of retrospective analyzes of the state of the solar magnetism and provide a temporal baseline of about 100 years for many solar properties.

These observations continue today through several different programs, preserving the continuity of this database. Although different instruments and methodologies have been employed during the many decades covered by these measurements, there is enough overlap among these observations to cross-calibrate the various time series. The major difficulty in achieving this task is to account for the non-uniformity of the images taken by long-term programs established at a particular observatory or by programs running at different locations. Differences in the width of the spectrograph slit, optical vignetting function, artifacts, and lack of calibration wedges are some of the factors that play a critical role in affecting the uniformity of these images. A detailed analysis of these differences and the development of a homogenous archive of well calibrated Ca II K data is a primary goal of our future investigations.

Although not discussed here, synoptic programs observing the Sun in white-light and Hα also began during the first two decades of the 20th century. These programs, together with the ensemble of Ca II K observations described in this paper, provide an an important insight into the behavior of the solar cycle of activity. The only set of direct observations of the solar atmosphere that covers a much longer timeline is the visual sunspot counts that dates back to the second half of the 18th century. However, the combination of Ca II K, white- light, and Hα measurements can better capture the complex hierarchical structures of the solar magnetic field and its evolution on a wider range of different spatial and temporal scales.

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