Determining the Variations of Ca–K Index and Features Using Century-long Equal-contrast Images from Kodaikanal Observatory

Jagdev Singh, Muthu Priyal®, and B. Ravindra®

Indian Institute of Astrophysics, Koramangala, Bengaluru-560034, India; jsingh@iiap.res.in

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Abstract

In an earlier analysis of Ca–K spectroheliograms obtained at the Kodaikanal Observatory, the “Good” images were used to investigate variations in the chromosphere. However, the contrast of the images varied on a day-to-day basis. We have developed a new methodology to generate images to form a uniform time series. We adjusted each image’s contrast until the FWHM of the normalized intensity distribution attained a value between 0.10 and 0.11. This “equal-contrast technique” is expected to compensate for the change of emulsion, development, and contrast of the images due to centering of the Ca–K line on the exit slit and sky transparency. In addition, this procedure will correct variations in density-to-intensity conversion for different images. We find that the correlation between sunspot and Ca–K line data improves to a large extent. For example, the correlation coefficient (CC) between monthly averaged sunspots and Ca–K plage areas for the equal-contrast data reaches 0.9 compared to 0.75 for the “Good” data with unequal contrast. The CC for equal-contrast images improves to ∼0.78 from ∼0.46 for the “Okay” data with unequal contrast. Even the CC between the plage area and the daily sunspot number is 0.85 for 100 years of data. This methodology also permits us, for the first time, to study the variations in enhanced, active, and quiet networks with time with high accuracy over about a century. Further, this procedure can be used to combine data from different observatories to make a long time series.

Unified Astronomy Thesaurus concepts: Solar cycle (1487); Active sun (18); Quiet sun (1322)

1. Introduction

The long-term periodicity or quasi-periodicities of the Sun’s large- and small-scale magnetic fields can be investigated using long-term spectroscopic and imaging data. The Sun’s images in the Ca–K line can be used as a proxy to study the variations in magnetic fields as there is a strong spatial correlation between Ca–K and magnetic features such as plages and networks (Babcock & Babcock 1955; Howard 1959; Leighton 1959). At the Mount Wilson Observatory (MWO) and the Kodaikanal Observatory (KO), spectroheliograms were obtained in Ca–K and Hα wavelengths daily over about 100 years during the 20th century. These data sets provide a time series of solar images for study of the long-term variations of the solar magnetic field.

Earlier analysis of the digitized data of Ca–K images used density-to-intensity conversion using the theoretical equation or mean curve as step-wedge calibration was not recorded on all the images obtained during this long period (Foukal 1996; Worden et al. 1998; Ermolli et al. 2009; Tlatov et al. 2009; Bertello et al. 2010; Priyal et al. 2014, 2017; Chatterjee et al. 2016; Chatzistergos et al. 2019).

Several observatories have adapted their procedures to correct the images for limb-darkening and instrumental effects. After completing the task of making the quiet chromosphere of uniform nature, Priyal et al. (2019) displayed each image along with its intensity distribution curve on the computer screen. By visual inspection of these images and examining the corresponding intensity distribution curves, the images are classified as “Good” and “Okay” to generate two separate time series. Those two time series analyses showed very different results. The “Good” time series with uniform images indicated smooth variations of Ca–K plage areas and Ca–K index with solar cycle phase. In contrast, the time series of remaining “Okay” images showed a large amount of scatter in the Ca–K parameters. Further, an inspection of the “Good” images indicated that there are variations in contrast on a day-to-day basis as well as long term. The effect of contrast variations in Ca–K images still needs to be studied on small- and large-scale activities in the long term.

Livingston et al. (2007) found that the Ca–K line intensity at the center of the Sun does not vary with the solar cycle phase. This result implies that quiet chromosphere does not show solar cycle or long-term variations. But Priyal et al. (2017) found that the intensity of the quiet network varies with the solar cycle but with a very small amplitude. Therefore, it is reasonable to assume that the quiet chromosphere’s intensity distribution does not vary with time. Worden et al. (1998) showed that the contrast of active regions is beyond the intensity contrast of the quiet chromosphere. Priyal et al. (2019) found that in the normalized intensity distribution of the image, an intensity contrast greater than 1.30 represents plages and enhanced networks (ENs), that between 1.20 and 1.30 represents active networks (ANs), and that between 1.10 and 1.20 represents quiet networks (QNs). The remaining pixels, forming a large area of the Sun, with intensity contrast lying between about 0.9 and 1.10 values, approximately follow a Gaussian distribution, representing a quiet chromosphere. The extended tail of the intensity distribution of the image indicates the active area of the chromosphere.

The Gaussian part of the intensity distribution representing the background chromosphere is expected to remain the same irrespective of the solar cycle phase (Livingston et al. 2007). The area under the extended tail varies significantly with time and is expected to show solar cycle variations. Therefore, all the images obtained on a day-to-day basis are expected to show a similar intensity distribution for the quiet background chromosphere. This implies that the contrast in the images, and thus, full width at half maximum (FWHM) of the intensity distribution of all the images obtained during long periods,
should remain approximately the same. There might be a small change in the total area occupied by the quiet chromosphere over the solar cycle. However, the FWHM of the intensity distribution is likely to remain the same with minor variations, if any. But the FWHM of the intensity distribution was found to be related to the contrast of the images and much larger for high-contrast images than for those with very low contrast (Priyal et al. 2019). Therefore, by making the FWHM of the intensity distribution the same for all the images, it is possible to make the contrast of the long-time series data the same.

It may be noted that images need to be corrected for the limb-darkening and instrumental effects effectively before correcting for contrast so that the FWHM of the intensity distribution becomes uniform within the specified limits. In this paper, we describe the methodology adopted to make the contrast of all the images uniform and compare the results with those of earlier analyses obtained using data without correcting for the intensity contrast. The adopted methodology is somewhat similar to the approach used in MWO studies of Ca–K observations (Pevtsov et al. 2016; Bertello et al. 2020).

2. Data Preparation and Analysis

In our earlier paper (Priyal et al. 2019), we divided the data into two groups depending on the image quality and intensity distribution. Of these two, one forming a time series of uniform images was termed “Good” and the other as “Okay.” Some bad quality images were discarded. Even though we selected normal-contrast data to make the “Good” uniform time series, the contrast of the images still varied daily due to sky conditions, development of the photographic film, and variations in visually setting the center of the Ca–K line on the exit slit of the spectrograph (Priyal et al. 2014). The contrast also varied due to the emulsion change on a long-term basis. In the earlier analysis, we found that the FWHM of the intensity distribution varied systematically for the “Good” (hereafter “P-Good”) images. The average decrease in FWHM of the intensity distribution from 1907 to 1950 and subsequent increase indicated that the contrast varied with time, probably due to the change in emulsion and on a day-to-day basis due to sky conditions. In the “Okay” (hereafter “P-Okay”) series, the FWHM of the intensity distribution showed two branches due to the inclusion of very high and very low contrast images in this data set. These two series were analyzed separately. We have decided to analyze the two series of data separately to compare the earlier results with those of the new methodology. We occasionally refer to the “P-Good” and “P-Okay” images as “P-images” in general.

We have determined the FWHM of the Gaussian fit to the intensity distribution of each image of the “P-Good” and “P-Okay” time series. The upper panel of Figure 1 shows a histogram of a number of “P-Good” images per year whose FWHM of intensity distribution lies between 0.10 and 0.11 (shown in blue). The number of images per year with FWHM > 0.11 and FWHM < 0.10 is also shown in the same plot in red and yellow. The lower panel shows a histogram of the “P-Okay” time series. The “P-Good” histogram indicates that the number of high-contrast images is higher than that of low-contrast images from the beginning of observations until 1930. After 1930, this trend is reversed. The histogram for
“P-Okay” images shows a similar trend in general. It indicates that the number of high-contrast images is higher during the period 1975–1990. It may be noted that the number of images in the “P-Okay” data with FWHM in the range 0.10–0.11 is lower than that in the “P-Good” data.

In the present analysis, we studied the FWHM data for a large number of images selected in a random spread over several years. We noted that images with FWHM in the range 0.10–0.11 show chromospheric features very well. Therefore, it was decided to keep the FWHM of the intensity distribution between 0.10 and 0.11 for all the images by changing their contrast. We compute the intensities of the modified image using the relation

$$I_{ECI} = I_p^\gamma.$$  

Here, $I_{ECI}$ is the intensity of a pixel of new image (equal-contrast image), $I_p$ is the intensity of the pixel of the corrected image (Priyal et al. 2019), and $\gamma$ is the contrast of the image.

First, we assume $\gamma = 1.0$ and then compute the FWHM of the intensity distribution of the image. The images with FWHM less than 0.10 are low-contrast images. $\gamma$ was increased in steps of 0.025 until the FWHM was between 0.10 and 0.11. The step of 0.025 was chosen after doing several experiments with different step sizes on many images. For the images with FWHM larger than 0.11 (high-contrast images), $\gamma$ was decreased in steps 0.025 until the FWHM of the distribution was between 0.10 and 0.11. We term this methodology the “equal-contrast technique” and it can be used anywhere provided the images have been properly corrected for limb-darkening and instrumental effects. The new methodology was applied to both the “P-Good” and “P-Okay” time series. With their contrast changed, the new images are referred to hereafter as “ECI-Good” and “ECI-Okay” or “ECI-images” in general.

2.1. Comparison of “P-images” and “ECI-images” During the Quiet Phase

The left panel in the top row of Figure 2 shows a typical image belongs to the “P-Good” data set taken during the quiet phase of the solar cycle. The details of the image and FWHM of the intensity distribution greater than 0.11 shown on the right-side panel imply high contrast. The FWHM is large, and the peak value of the frequency distribution is about 1.6%. The extended tail beyond intensity contrast of 1.2 of the intensity distribution in the “P-image” indicates a significant existence of ENs and ANs even during the quiet phase of the Sun, which is contrary to expectation. The left panel in the bottom row of this figure shows the “ECI-image” after adjusting the contrast of the image so that the FWHM of the intensity distribution curve is between 0.10 and 0.11 (right-side panel). After changing the intensity contrast of the image, the tail of the intensity distribution curve reduces, indicating a lower number of ANs and an almost absence of ENs, as expected during the quiet phase of the Sun. By this procedure, the peak value of the frequency distribution increases to $\sim$2.5%.
In contrast, the top row of Figure 3 shows a low-contrast image (also selected from the “P-Good” time series) taken during the quiet period of the solar cycle. This image exhibits a small FWHM and a high peak value (∼3.8%) in the frequency distribution. In the plot, due to the low contrast of the image, the intensity distribution >1.10 indicates an insignificant existence of QNs. The bottom row shows the image after increasing the contrast such that FWHM lies between 0.10 and 0.11. After increasing the contrast of the image, the QN contribution becomes approximately 2–3 times more than that with the original low contrast image. After adjusting the contrast of the images, both the high- and low-contrast images (in the “P-Good” time series) acquire a similar intensity distribution, as seen in the bottom row panels of Figures 2 and 3. A similar intensity distribution of the two types of images from the “ECI-Good” time series with a peak value of ∼2.5% obtained during the quiet phase of the Sun confirms the methodology adopted works well in both cases. Hence, these two types of data can be used reliably for the study of short- and long-period variations in solar activity.

2.2. Comparison of “P-images” and “ECI-images” During the Active Phase

The four panels of Figure 4 shows the images of “P-Good” (top) and “ECI-Good” (bottom) and their intensity distributions for a typical high-contrast image obtained during the active phase of the solar cycle. The intensity contrast for part of the plage region exceeds 2, but we have plotted it up to 1.6 to clearly show the intensity distribution. The intensity distribution of the image after adjusting the contrast appears realistic, indicating the area of the quiet chromosphere and the plage and the EN regions’ existence. The peak value of the intensity distribution during the active phase appears to be lower by a very small amount than that during the quiet phase to account for plage and the EN regions’ existence. The area under the extended tail with an intensity contrast of more than 1.2 indicates the area occupied by the plages, EN, and AN networks. The four panels of Figure 5 show the “P-image” and “ECI-image” after adjusting the contrast of the image and their intensity distributions represent a low-contrast image obtained during the active phase of the solar cycle. The tail of the distribution curve for the “ECI-image” beyond 1.2 indicates the area of plages, ENs, and ANs.

A comparison of “P-images” in Figures 2–5 indicates that the FWHM of the intensity distribution for the low-contrast image is considerably less than that for high contrast, and also the peak value of the frequency distribution is about 2–2.5 times higher. In addition, the intensity distribution of the low-contrast “P-images” in Figures 3 and 5 shows a significantly smaller area under the extended tail representing plages, ENs, and ANs. However, a large number of plages are visible in the “P-image”. After adjusting the contrast of the “P-image”, the area under the extended tail increases for the “ECI-image”; thereby, the detected area of plages, ENs, and ANs increases. Similarly, after tuning the contrasts of high-contrast
“P-images”, intensity distributions of the “ECI-images” show the area of detected plages, ENs, and ANs decreasing. Thus, the values of the detected plages, ENs, and ANs become realistic in both cases. A comparison of all the intensity distributions of the images after fine-tuning contrast indicates that the peak values (2.5%) and FWHMs become similar. This suggests that the area occupied by a quiet chromosphere may vary only by a small percentage in all images. In contrast, the area under the extended tail varies significantly (percentage), showing variation in the active part of the Sun.

The results of the analysis of the images in the “P-Okay” time series agree well with those of the “P-Good” time series. Therefore, all the data can be combined and analyzed together to reduce the gaps in the long time series to study solar variations with time.

3. Results

To study the chromosphere’s long-term variations, we generally determine the Ca–K plage area, Ca–K index, and other such parameters with time. We also define the sum of plage, EN, AN and QN area as the “total active area” of the image. In other words, the “total active area” is the percentage area of an image occupied with intensity greater than 1.10 after normalizing the intensity of the image. It is also necessary to establish the correctness of the procedure adopted by comparing these derived parameters with the reliable other solar indices such as sunspots. First, we compare the recent measurements and similar data determined earlier with the sunspot data and then study the variations in other parameters of Ca–K line images such as networks.

3.1. Comparison of Daily Ca–K Parameters with Sunspot Data for Equal- and Non-equal-contrast Images

To assess the improvement in the results due to the equal-contrast technique on the historical data, we first compare the results of this analysis with some reliable works on earlier solar activity indices. Data on sunspot numbers and areas are available on a daily basis over the extended period for the comparison. The sunspot data obtained from various observatories were rescaled, combined, and formed a long daily time series with negligible gaps, if any. Thus, to compare the solar activity-related indices, the sunspot data are most reliable.

The left-side top panel of Figure 6 shows a scatter plot of the SILSO sunspot numbers (WDC-SILSO, Royal Observatory of Belgium, Brussels) versus identified plage areas using the “ECI-Good” time series, whereas the right panel shows the total active area on a daily basis. The middle two panels show the same for the “ECI-Good” and “ECI-Okay” images, and the bottom two panels show the same for the combined “P-images”.

In Table 1, we list the values of correlation coefficients between sunspot data and Ca–K parameters derived using the daily “ECI-images” and earlier analyzed daily images of Priyal et al. (2019). The table shows the values of correlation...
Figure 5. Analyzed Ca–K line “P-Good” image taken on 1937 March 1, during the active phase of the Sun at Kodaikanal Observatory, showing very low contrast along with a narrow intensity distribution curve in the top row. The bottom row shows the “ECI-Good” image after increasing the contrast such that the value of FWHM of the intensity distribution lies between 0.10 and 0.11.

Figure 6. Top row: scatter plot of sunspot number vs. plage area (left) and total active area (right) for the “ECI-Good” time series on a daily basis. The middle row shows the same for the total data consisting of “ECI-Good” and “ECI-Okay” time series on a daily basis. The bottom row shows the same for the total data of “P-Good” and “P-Okay” time series analyzed by Priyal et al. (2019).
Figure 7. Top row: scatter plots between monthly plage areas determined using “ECI-Good” images and sunspot numbers (left) and areas (right). Middle row: scatter plot between plage areas determined earlier using “P-images” and sunspot data. Bottom row: scatter plot of plage area (Foukal 1996) vs. sunspot number (left) and plage area (Tlatov et al. 2009) vs. sunspot area (right). The value of the correlation coefficient is indicated in each panel. It may be noted that the scale of plage area along the x-axis is different for the bottom row panels than the top and middle row panels.

Figure 8. Top row: scatter plots of monthly plage areas determined using the “ECI-Okay” images and sunspot numbers (left) and areas (right). Bottom row: scatter plot of plage areas determined earlier using the “P-Okay” images (Priyal et al. 2019) and sunspot data.
coefficients are larger for the “ECI-Good” time series than the others. The correlation coefficient for the sunspot number and plage area of the “ECI-Good” images are 0.85 and 0.80 for the total active area. Excellent values of correlation coefficient for the data on a daily basis are spread over about a 100 year period. The correlation coefficients for the combined “ECI-images” are marginally lower than those for the “ECI-Good” data but still have a confidence level of greater than 99%. The values of the correlation coefficients for the combined “P-images” are significantly lower than those for the ECI data. Also, there is a large scatter around the linear fit in scatter plots of the “P-images” as compared to the “ECI-images”. Further, in the case of the total active area, the correlation coefficient of the “P-images” is much less, 0.32 only as compared to 0.80 for the “ECI-images”. This indicates that the plage area can be determined to show the solar cycle variations with averages of the data over a long time, even with non-uniform images of the time series. The maximum value of the total active region reaches 50% in the case of the “P-images” but decreases to about 25% after tuning the contrast. The large value of the total active region may be due to high-contrast images. This implies that it is almost impossible to study the periodic variations in networks representing a small-scale magnetic field with non-uniform time series data.

### 3.2. Comparison of Monthly Averaged Ca–K Parameters with Sunspot Data

Monthly averaged plage areas determined using the MWO, KO, and some other data are available (Foukal 1996; Tlatov et al. 2009) for comparison for this period. We compare sunspot numbers and plage areas on a monthly average basis to determine the most accurate methodology to analyze the historical data. In the top row of Figure 7, we plot the monthly averaged plage areas determined using “ECI-Good” data versus WDC-SILSO sunspot number and Royal Greenwich Observatory (RGO) sunspot area for the period 1905–2004 (http://www.sdcbe/silso/datafiles).

The middle row of this figure shows the plage areas determined from the “P-images” before applying the equal-contrast technique versus sunspot number (left) and area (right). The number of data points in all four plots is the same. In the bottom row of Figure 7, we show a scatter plot of sunspot number versus plage area identified by Foukal (1996) using MWO data for the period 1915–1985 only, (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_CALCIUM/DATA/Mt_Wilson/) in the left-side panel and by Tlatov et al. (2009) using KO data in the right-side panel for the period 1907–1999. The values of the correlation coefficient are indicated in each panel. Similarly, the two panels in the top row of Figure 8 show scatter plots of the plage area determined from “ECI-Okay” images versus monthly average sunspot numbers (left) and areas (right). The two panels in the bottom row show the same the “P-Okay” images. The values of the correlation coefficient are indicated in the panels.

The plots in the middle row (Figure 7) of monthly averaged data (“P-Good”) show a large scatter with correlation coefficients around 0.75. But the plage area obtained from the “ECI-images” shows that the correlation coefficient improved significantly to a value of ~0.9. Similarly, the plots in Figure 8 for the “ECI-Okay” images indicate a decrease in the scatter and large improvement in the correlation between plage areas and sunspot parameter. The correlation coefficient improves from a value of ~0.45 (“P-Okay”) to ~0.8 (“ECI-Okay”). In Table 2, we show the values of correlation coefficients for MWO and KO data sets derived by different authors for easy comparison. The obtained values are significantly larger for “ECI-Good” and “ECI-combined” data sets compared to the others. It may be noted that the correlation coefficients are better for the “ECI-Good” data than those for the “ECI-Okay” data, even in the case of equal-contrast images. The scatter plots between sunspot data and the plage areas indicate a much better correlation after making all the image contrasts equal for the “P-Good” and the “P-Okay” data. From the scatter plots, we learn that it is possible to combine “ECI-Good” and “ECI-Okay” after applying the equal-contrast technique. This will reduce the data gaps in the time series. The good values of correlation coefficient between sunspot data and plage area obtained using “ECI-images” compared to the other procedures adopted earlier to analyze Ca–K images of the historical data (Foukal 1996; Tlatov et al. 2009; Priyal et al. 2019) indicate that the difference in correlation coefficients is likely due to a combination of the different techniques, spectral bandwidth, and spatial resolution between the two databases.

We have computed the average intensity (Ca–K index) over the whole of the disk image as done in our earlier paper (Priyal et al. 2019). In the top row of Figure 9, we show the scatter plot of the full-disc intensity of the “ECI-Good” images versus sunspot number (left panel) and sunspot area (right) for monthly averaged data . The bottom row shows a similar scatter plot for the “P-Good” images. The scatter plots between the monthly averaged sunspot data and the averaged intensity of the “ECI-Good” images indicate an excellent correlation, with a value of 0.85 and confidence level $>99\%$ compared to the correlation coefficient of 0.65 for the plots in the bottom row of the “P-Good” images. The plots pertaining to the recent study indicate less scatter in the data than earlier work.
We show the linear least-squares fits for all the plots. There appears a polynomial relation between sunspot number and average Ca–K intensity for the “ECI-images”. But a linear fit to the data points is more satisfactory as compared to second- and third-order polynomial fits. The plots between sunspot data and average intensity of the full-disk image for the “ECI-Okay” and “P-Okay” images indicate a similar behavior, as shown in Figure 10. The correlation coefficients of about 0.7
for “ECI-Okay” and 0.35 for “P-Okay” indicate more improvement in the correlation between monthly averaged Ca–K index and sunspot parameters in the present methodology. This is because many low- and high-contrast images in this data set have been converted to images of the same contrast. It may also be noted that the correlation between the monthly averaged Ca–K area index and sunspot data is better for the “Good” data as compared to the “Okay” data in both the cases with and without conversion of images to equal contrast.

### 3.3. Variation of Ca–K Area Index with Time Using “ECI-images”

In Priyal et al. (2019), the plage areas determined from the “P-Good,” and “P-Okay” data exhibit solar cycle variations, and their amplitude is in general agreement with the sunspot data used with a 12 month running average. The procedure adopted to analyze the historic data provided reliable results until 1984 only, and the amplitude of variation for a couple of solar cycles differed with those of sunspot cycles. Now, we have developed the equal-contrast technique to analyze those data further. We have shown that “ECI-Okay” data become comparable with the “ECI-Good” data. But to make a detailed comparison, we analyze these two series separately before combining all of the data.

After making all the images equal contrast, we again examined the intensity threshold values to identify the plages and network features. After several experiments, we found the earlier values of intensity threshold determined by Priyal et al. (2019) still hold good. This is because average values of FWHM of intensity distributions for the “P-Good” and “ECI-Good” data are similar. We have defined plages with intensity contrast >1.30 and consecutive area >1000 pixel$^2$, equivalent to about 0.2 arcmin$^2$. In addition, we define regions with intensity $>$1.30 and consecutive area $>$4 pixels as ENs, and with intensity $>$1.20 and $<$1.30 with consecutive area $>$4 pixels as ANs. Regions with intensity $>$1.1 and $<$1.2 with consecutive area $>$4 pixels are treated as quiet networks (QNs). To compare the Ca–K and sunspot data, we computed the sum of the percentage of plages, ENs, and ANs (hereafter called the Ca–K area index) from daily data. The difference between the total active area and Ca–K area index is that the former includes the QN area. We compare both the sum of plages, EN, and AN area variation (the Ca–K area index is mostly related with activity) and total active area (including QNs) with sunspot activity. The QNs may be related with the global characteristic of Sun rather than sunspot activity. In Figure 11, we plot the Ca–K area index represented by black dots, monthly averages of Ca–K area index indicated by the red curve, and monthly averages of sunspot areas shown in green for the “ECI-Good” time series for the period 1905–2004. The daily Ca–K area index shows that the scatter in the derived index is much lower than in similar plots by Priyal et al. (2019) and others. In our earlier paper (Priyal et al. 2019), we plotted the data for the period 1907–1984 as there was a large scatter in the determined values of plage areas because of varying sky conditions and change of photographic emulsion. But after the equal-contrast technique was applied to the images, it became possible to determine the plage areas reliably for 1985–2007 data also. The respective solar cycle numbers are also given in the figure. The plot indicates an excellent agreement between the maximum amplitudes of solar cycles in the Ca–K area index with sunspot areas except for solar cycle number 21 (around the year 1980). The difference may be due to the availability of a smaller number of images per year after 1980. Generally, the red curve amplitudes appear larger than those of
green curves due to the selected scales of the Ca–K area index and sunspot areas.

Figure 12 shows the daily Ca–K area index, monthly averages of the Ca–K area index, and the monthly averages of sunspot areas from 1905 to 2007 by black dots and red and green curves, respectively, for the “ECI-Okay” data. The period of “ECI-Good” and “ECI-Okay” data differs because there are no “P-Good” images available from 2005 to 2007. The derived values of the Ca–K area index appear more reliable as these show much less scatter as compared to earlier studies by Priyal et al. (2019) and others. Generally, the monthly average Ca–K area index shows good correlation with sunspot area values. But the amplitudes of monthly averages of the Ca–K area index for the “ECI-Okay” data differs from those for the “ECI-Good” data, especially for cycle numbers 18 and 19.

3.4. Variation of Ca–K Intensity Index with Time Using “ECI-images”

The black dots in the upper panel of Figure 13 show average intensity over the whole solar image on a daily basis, and the red curve the monthly average intensity for the period of 1905–2004 for the “ECI-Good” time series. We have also computed the average intensity of the active region with pixels having intensity contrast $>1.1$, shown in the lower panel. The full-disc intensity and active region intensity for the “ECI-Good” data show that the amplitude variation increases from solar cycle 14 to 19, similar to that for sunspot data shown in Figures 11 and 12. The determined intensities vary smoothly with the phase of the solar cycle. This confirms that by fine-tuning the contrast of the images, the data have become uniform in quality. We show the same parameters for the “ECI-Okay” images for the period 1905–2007 in the two panels of Figure 14, which indicate results similar to those of the “ECI-Good” data but with some scatter. This is probably due to the image quality (but not contrast), or some other reason.

3.5. Variation of Ca–K Networks Area and Total Active Area with Time Using “ECI-images”

The top panel of Figure 15 shows the time variation of the EN area, representing the decaying plage regions as a function of time on a daily basis shown by black dots and monthly averaged data displayed by the red curve for the “ECI-Good” time series. The monthly averages of sunspot numbers are over-plotted for comparison. The middle panel of the figure shows the variation of the AN area on a daily basis (black dots), monthly averages (red curve), and monthly averages of sunspot area (green curve). The bottom panel indicates the variation of the QN area on a daily basis (black dots) and monthly averages (red curve). The plots of EN and AN show that amplitudes of variations agree well with those of sunspot data, whereas the amplitude of variations for QN remains more or less the same throughout all the solar cycles, 14–23. The three panels of Figure 16 show variations of EN, AN, and QN on a daily and monthly average basis for the “ECI-Okay” data as a function of time. The plots indicate variations in “ECI-Okay” data similar to those for the “ECI-Good” data. It may be noted that there appears some scatter in the “ECI-Okay” data in addition to temporal variations.

We have also computed the total active area in the images with intensity contrast of pixels $>1.1$ and consecutive area $>4$ pixels (3 arcsec$^2$). The upper panel of Figure 17 shows the percentage of the total active area on a daily basis (black dots), monthly averages (red curve), monthly averages of sunspot numbers (blue), and monthly averages of sunspot area in green as a function of time for the “ECI-Good” data. The amplitudes of variations in all the parameters agree well with each other for
all solar cycles. The lower panel indicates the same parameters for the “ECI-Okay” data for the period 1905–2007. The plots show results similar to those for “ECI-Good” data but with some scatter due to the quality of some of the images in the “ECI-Okay” time series.

3.6. Variations with Combined “ECI-Good” and “ECI-Okay” Data

We have combined both the “ECI-Good” and “ECI-Okay” times series to study the variations due to all the Ca–K line images obtained at KO. In Figure 18, we show the Ca–K area index on a daily basis by black dots, monthly averages by the red curve, and monthly averages of sunspot areas by the green curve as a function of time for the period 1905–2007. The plots indicate a good correlation between the amplitudes of the Ca–K area index and sunspot areas for all solar cycles. It may be noted that the inclusion of “ECI-Okay” images has decreased the amplitude of the Ca–K area index for solar cycle numbers 18 and 19 as compared to those for the “ECI-Good” data.

The six panels of Figure 19 show scatter plots of the monthly average of sunspot numbers and monthly averages of Ca–K plages, ENs, ANs, total active area, average intensity of image, and active region intensity (average intensity of all areas with normalized intensity greater than 1.1). The plots for ANs and total active area appear to indicate polynomial relation but linear fits were found to be better than polynomial fits. Generally, it can be stated that there is a linear relation between numbers and areas of sunspots and Ca–K line parameters. An excellent correlation between the monthly averaged sunspot numbers and various features visible in Ca–K line images indicates that this methodology permits us to study the long-term systematic variations in small-scale activity as well as large-scale activity.

3.7. Periodic Behavior in the Ca–K Feature

We have performed a wavelet analysis of monthly averaged data of plages, EN, AN, and QN areas for the combined data of “ECI-Good” and “ECI-Okay” times series to investigate the periodicities in variation of the large- and small-scale activity on the Sun. The top two panels of Figure 20 show the relative variation in the plage areas as a function of time (left) and its power spectra (right). The bottom two panels show the wavelet power spectrum (left) and the global power spectrum (right). The color bar indicates the relative power in the wavelet power spectrum. The power spectrum and the global power spectrum indicate a strong periodicity around a 10.8 yr period and negligible power at periods >16 and <5 yr. The existence of some quasi-periods <4 yr and 11 yr was observed in the earlier
analysis. The wavelet analysis of the ENs and ANs indicates similar results as seen in Figures A1 and A2 in the Appendix. But the wavelet analysis QN area in Figure A3 (Appendix) shows some power at periods >16 and <4 yr along with large power around 11 yr. This data set is more uniform than earlier ones and will be subjected to more rigorous analysis to study the existence of quasi-periods.

4. Discussion

We have developed a new methodology to analyze Ca–K line images to investigate long-term variations in the chromosphere’s large- and small-scale activity. First, we made all the images of equal contrast. This is to compensate for the different photographic emulsions used for recording the images, different sky transparency and seeing conditions affecting the contrast of the images, changes in contrast due to centering of the Ca–K line on the exit slit of spectro-heliograph, different developing conditions, and chemicals used for developing photographs over long periods. This methodology has also overcome the difficulty of intensity calibration of the time series as a significant part of the data did not have step wedge calibration. Even the step wedge calibration has some uncertainty due to the non-uniformity of the light source used at edges of photographic plates (Priyal et al. 2014).

The variations in the parameters of Ca–K line features obtained from the analysis of each image represent variations on the Sun, free from the effects of the above-mentioned observational parameters and sky conditions. Most papers (Priyal et al. 2019; Chatzistergos et al. 2020 and references therein) have done 12 month averages or running averages of the data to show the correlation between sunspots and Ca–K plage areas. We have shown the correlation between plage areas and sunspot data on daily and monthly mean basis. The percentage of plage area vary with the solar cycle phase smoothly and their amplitude agrees well with that of sunspot data until 1975 for the data termed “ECI-Good.” After 1975 the amplitudes of plage areas differ from those of sunspots by a small amount, probably due to data available for fewer days per year. Apart from the study of variation of large-scale activity represented by plage areas, we have successfully investigated the variations in small-scale activity represented by ENs, ANs, and QNs for the first time for about 100 years. Only Worden et al. (1998) has defined the threshold values of intensity for ENs and ANs using some selected data from 1980 to 1996 to study their relationship with solar cycle phase. The amplitudes of solar cycle variations for ENs and ANs agree well with those of sunspot data. The amplitude of solar cycle variations for QNs remains almost the same irrespective of the amplitude of sunspot data. It may be noted that the values of average...
monthly intensity include the intensity of a quiet background chromosphere. These data will be very useful for making realistic models of solar cycle variations and will be made available to the interested researcher.

The Ca–K line images obtained at various observatories with different spatial resolution and passband lead to different contrasts. For combining the data of different observatories and types, one can compare the derived parameters with each other with large temporal averages and then up- or downscaled one of them (Bertello et al. 2016). But in this process, data on a day-to-day basis remain uncorrected. In the present methodology, we first adjust each image’s contrast and then identify the features, such as plages, ENs, ANs, and QNs. Thus, we make the correction on a day-to-day basis. Hence, this method is likely to work for different spatial resolution and with different passband images within certain limits and will help in combining the data to yield better results.

Most solar cycle variation models are based on the observed changes in large-scale magnetic activity. Some small-scale magnetic field measurements have been done and analyzed to study solar cycle variations (Scherrer & Spruit 2011). Using full-disk observations of solar magnetograms from the Michelson Doppler Imager (Scherrer et al. 1995) instrument, Jin & Wang (2012) have found two components of varying small-scale fields. One of the components whose magnetic flux is smaller than $32 \times 10^{19}$ Mx exhibits cyclic variation in anti-phase with the sunspot cycle. Another one with flux between $(4.3–38) \times 10^{19}$ Mx correlated with the solar cycle. It is possible to observe the magnetic fields at $0''1$ or better, but with a smaller field of view (Jin & Wang 2015). The measurement of the magnetic fields was also made with an accuracy better than 5 G. With the results obtained from the accurate analysis of 100 years of Ca–K images of the Sun, it will become possible to study and better understand the small-scale network and internetwork magnetic fields and their variations over the solar cycle.

5. Conclusion

We have developed a new methodology, the “equal-contrast technique” to uniformly analyze the Ca–K line’s photographic images for long periods under different environmental conditions. This procedure will help us to uniformly analyze similar data sets obtained at several observatories with different instruments, then combine all the data to form a long time series, with fewer gaps in the data, for further studies. This technique helps to determine variations in large-scale and small-scale activity with very high accuracy and reliability for high-quality data. It also helps to minimize errors in low-quality data. It will be possible to extend the study of large- and small-scale magnetic activity on the Sun back in time as the...
Figure 16. Same as for Figure 15 but for the “ECI-Okay” data.

Figure 17. Upper panel: percentage of the total active area of images on a daily basis shown as black dots and monthly averages shown in red for the “ECI-Good” data as a function of time. We have over-plotted monthly averages of sunspot numbers and areas for comparison. Lower panel: same for the “ECI-Okay” data.
Figure 18. Black dots: daily Ca–K area index as a function of time for all the “ECI-Good” and “ECI-Okay” time series data. The red curve indicates the monthly average of the Ca–K area index, and green the monthly average of sunspot area from 1905 to 2007. The cycle number is also indicated in the figure.

Figure 19. Top: scatter plots of sunspot numbers vs. percentage of Ca–K plage area (left) and percentage of ENs (right) considering all the “ECI-Good” and “E-Okay” time series data on a monthly average basis. Middle: scatter plot of sunspot number vs. percentage of ANs (left) and percentage of total active area (right). Bottom: average intensity (left) and total active intensity (right). The value of the correlation coefficient is indicated in each panel.
activity observed in the Ca–K line is related to the Sun’s magnetic field.

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The daily sunspot data used here were from the SILSO sunspot numbers (WDC-SILSO, Royal Observatory of Belgium, Brussels). The monthly sunspot data were taken from http://www.sidc.be/silso/datafiles. The monthly Ca–K index was downloaded from ftp://ftp.ngdc.noaa.gov/STP/SOLARDATA/SOLARCALCIUM/DATA/MtWilson/.

Appendix

Figures A1, A2, and A3 shows the wavelet analysis of the EN, AN, and QN areas as explained in Section 3.7.
Figure A1. Top left: relative variations in the monthly EN areas of the combined “ECI-images” for 1905–2007; top right: power spectrum. Bottom left: wavelet power spectrum; bottom right: global power spectrum of the data. The color bar at the bottom indicates the relative power in the power spectrum.

Figure A2. Same as Figure A1 but for the active network (AN) areas.
Figure A3. Same as Figure A1 but for the quiet network (QN) areas.

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