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Recent results from optical synoptic observations of the solar atmosphere with ground-based instruments

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Abstract. This brief review summarizes three research topics recently addressed with synoptic observations carried out at the Ca II K line and other continuum spectral ranges and relating to solar variability occurring on time scales from a day to a few decades. Namely, the irradiance reconstructions from intensity images, the radiative emission of solar features in the Ca II K line, and the comparison of time series of Ca II K spectroheliograms.

Key words: Sun: activity – Sun: photosphere – Sun: chromosphere

1. Introduction

Since the first telescopic observations it was recognized that knowledge about the solar magnetism can be gained by regular long-term observations derived from synoptic programs. Outstanding examples are offered by the finding of the cyclic modulation of the sunspot number, which occurred more than two centuries after the beginning of the telescopic observations of the solar disk, as well as by the discovery of the butterfly diagram and the latitude drift of sunspots, from the analysis of hand-plotted charts of data collected in many years.

Various observatories around the globe started regular full-disk imaging of the solar atmosphere in the early decades of the 20th century. These historic observations were made in white light and various spectral bands, often in the Ca II K and Hα lines, mostly using spectroheliographs. Among the several synoptic programs carried out before 1950 (for a list of these programs, see Mouradian and Garcia, 2007), we acknowledge the ones at the Coimbra, Kodaikanal, Meudon, and Mt. Wilson Observatories which still go on. Besides, in mid 1970s, daily observations of the Sun's global magnetic field began at the Mt. Wilson, Wilcox and Kitt Peak Solar Observatories. These historical investigations have evolved over time into the synoptic programs carried out with new generation ground-based instruments at various sites. Among these instruments, we mention the CFDT2 at the San Fernando Observatory (Chapman *et al.*, 2004), the PSPT at the Monte Porzio Catone and Mauna Loa Observatories (Ermolli *et al.*, 1998, Rast *et al.*, 1999), the SOLIS at the Kitt Peak National Solar Observatory (Keller *et al.* 2003), and various instruments setting up the multi-station networks for Hα (Steinegger *et al.*, 2000; Ueno *et al.*, 2010) and helioseismology (BISON, Miller *et al.*, 2004; GONG, Harvey *et al.*, 1996) observations.

In the past, synoptic observations played a major role in advancing our understanding of the Sun as a large-scale, time varying system. In the course of time, these observations have continued to provide fundamental knowledge about the physical processes responsible for solar activity, but also served the purpose to monitor solar activity, so as to forecast future active events. As we still do not have a clear picture of the nature of the solar activity cycle, future synoptic observations shall be used for the same purposes of past observations, but they shall also play a considerable role in disclosing the properties of solar variability on ever longer time-scales.

This brief review describes three research topics recently addressed with synoptic observations carried out at the Ca II K line and other continuum spectral ranges and relating to solar variability on time scales from a day to a few decades.

2. PSPT observations

The PSPT is a 15-cm, low-scattered-light, refracting telescope designed for synoptic solar observations characterized by 0.1 % pixel-to-pixel relative photometric precision (Coulter and Kuhn, 1994). Two such telescopes, which differ only in minor hardware characteristics and operational strategies, are operated at Mauna Loa (MLSO-PSPT) and Monte Porzio Catone (Rome-PSPT) Observatories by the High Altitude Observatory (Rast *et al.*, 1999) and Osservatorio Astronomico di Roma (Ermolli *et al.*, 1998; 2007), respectively. The Rome-PSPT has been acquiring daily full-disk observations since July 1996, but with the final instrument only since 1997. Observations with the MLSO-PSPT started in 1998, but regular data have been available since 2005. The PSPT telescopes typically acquire full-disk solar images on 2048×2048 CCD arrays with narrow-band interference filters centered on the blue continuum (409.20 FWHM 0.25 nm), red continuum (607.1 FWHM 0.5 nm), and Ca II K (393.3 FWHM 0.25 nm). The installation of additional filters on both telescopes has also allowed the acquisition of images at other spectral ranges. In particular, two interference filters sampling the G-band (430.6 FWHM 1.2 nm) and the Ca II K line center (393.38 FWHM 0.10 nm) were added to the Rome telescope in March 2007, while two such filters sampling the Ca II K line center (393.38 FWHM 0.10 nm) and the Ca II K line wing (393.63 FWHM 0.11 nm) were installed at the MLSO telescope in June 2007. The PSPT observations are carried out with various filters within a few minutes from each other, so as to show the solar photosphere and chromosphere almost simultaneously. All the observations are routinely processed in order to apply the instrumental calibration, as described in Ermolli *et al.* (2003) and Rast *et al.* (2008). The Rome and MLSO observing day generally run from 08:00 UT to 12:00 UT and from 16:50 UT to 02:00 UT, respectively. As a general

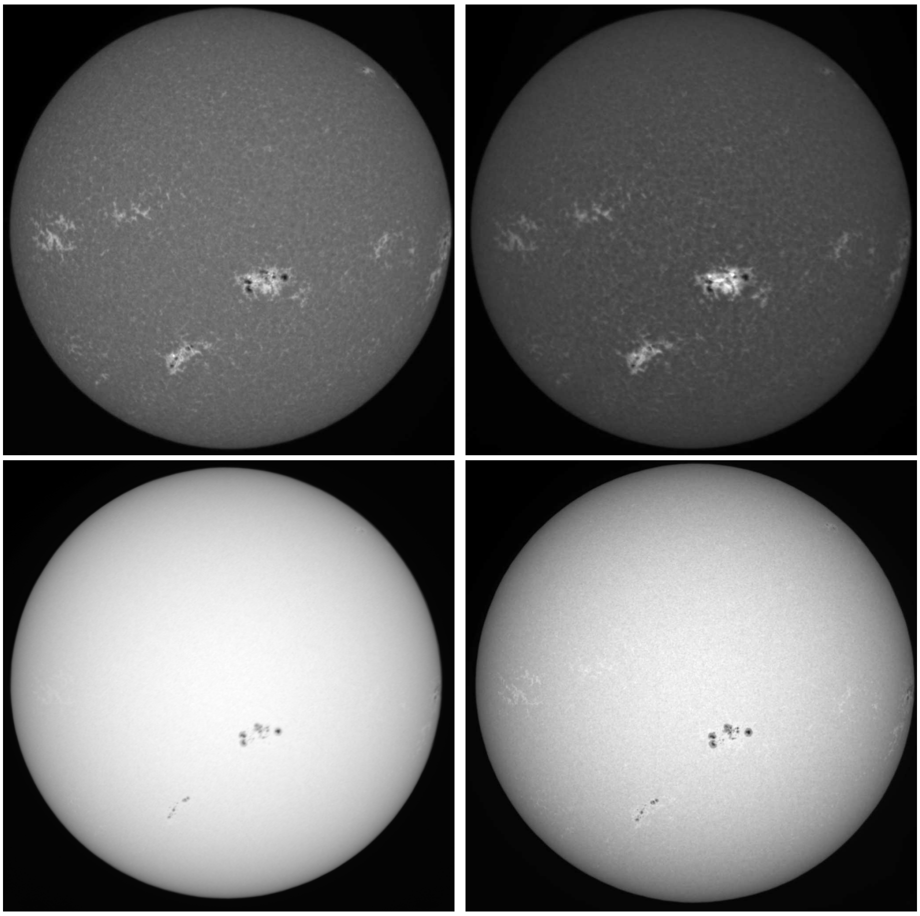

Figure 1. Examples of the full-disk images obtained with the Rome-PSPT on March 9th, 2011; top left: Ca II K (bandwidth 0.25 nm), top right: Ca II K (bandwidth 0.10 nm), bottom left: red continuum, bottom right: G-band images.

rule, the best seeing conditions at the two sites occur between 09:00 UT and 11:00 UT and 16:00 UT to 19:00 UT, respectively.

Fig. 1 shows examples of recent Rome-PSPT observations. Calibrated images from the two PSPTs are available on-line at `http://www.oa-roma.inaf.it/solare` and `http://lasp.colorado.edu/pspt_access/`.

3. Irradiance reconstructions from intensity images

Over the last thirty years, the Total Solar Irradiance (TSI) has been measured by numerous instruments on-board of consecutive space missions (Fröhlich, 2010). The TSI measurements show variations on time scales from minutes to decades. Variations measured on time scales of a day to the solar-cycle length have been attributed to changes of internal structure of the Sun, subsurface fields or changes of the magnetic field on the solar surface. The third explanation has found growing support until the recent minimum of solar activity. Indeed, various models based on either solar activity proxies or outcomes of the spectral synthesis, in combination with results derived from imaging observations and measurements of the photospheric magnetic field, have shown that at least 90 % of the measured TSI variability can be explained by the radiative effects of the magnetic features seen in the solar photosphere (for a review, see Domingo *et al.*, 2009). Nevertheless, an unusual behavior of the TSI (Fröhlich, 2009) and unexpected trends of the spectral variations (Harder *et al.*, 2009) measured over the declining phase of the last activity cycle have been interpreted as new evidence against the leading role of surface magnetism (Steinhilber, 2010). On the other hand, recent studies hint at problems on measurements, as an explanation of the unexpected variations reported for solar irradiance (Krivova, Solanki and Schmutz, 2011; Ball *et al.*, 2011).

The regular full-disk observations carried out with the PSPT telescopes, although suffering from degradation due to variable seeing, constitute a particularly interesting data set for the investigation of the mechanisms leading to irradiance variations on time scales of the activity cycle and longer. In fact, these observations allow to model irradiance measurements and investigate the contribution to the measured TSI variations due to the different solar features resolved by the observations.

Fig. 2 (top) shows the annual mean values of the fractional disk area covered by solar features identified on Rome-PSPT observations, taken from September 1997 to December 2010. With the purpose of this application, all the Rome-PSPT observations were processed for instrument calibration, re-sizing and alignment of the solar disk, and then segmented for the identification of the features seen on the solar disk, as described by Ermolli *et al.* (2010). Briefly, the segmentation is made through a threshold scheme derived from the partitioning of intensity histograms constructed from the images as a function of heliocentric angle. The code applied for these results assumes seven classes of disk features, which are coded by the letters B, D, F, H, P, S, and R, to follow the scheme and reference atmosphere models proposed by Fontenla *et al.* (2009). These features localize average median quiet Sun (internetwork, quiet Sun hereafter), network, enhanced network, plage, bright plage, umbral and penumbral regions, respectively.

Following other irradiance models presented in the literature, we estimate the irradiance associated with the solar features observed at a given time, by

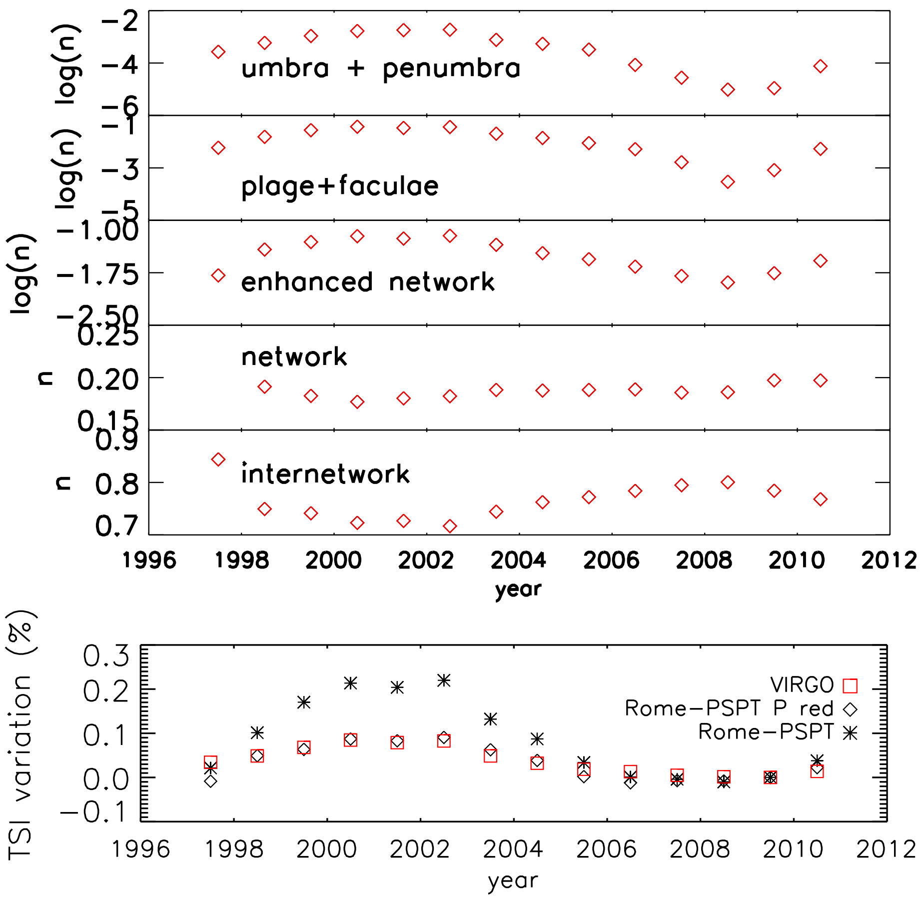

Figure 2. Top: Annual mean values of the fractional disk area (n) covered by the solar features identified on the full-disk Rome-PSPT observations carried out from September 1997 to December 2010. Bottom: Comparison between annual averaged values of the TSI variation measured by SoHO VIRGO (red symbols) from September 1997 to December 2010, and those obtained with the irradiance modeling based on Rome-PSPT observations as described in the text (black symbols). Details are given in the text.

combining the time-dependent information on the fractional area covered by the features identified on Rome-PSPT observations with the time-independent results of the spectral synthesis carried out on atmosphere models representative of the various identified features. This estimate is based on the assumption that the solar irradiance is given by the sum of the fluxes emerging from all the features identified in the solar atmosphere.

Fig. 2 (bottom) compares the annual mean values of TSI variation obtained with our estimates (black symbols) with the ones derived from the measurements provided by the VIRGO team (composite−d41−62−1102, red symbols). This comparison covers most of Solar Cycle 23, from September 1997 to December 2010. These irradiance estimates account for the seven features identified on observations and the corresponding brightness spectrum. The latter was computed on the semi-empirical atmosphere models of Fontenla *et al.* (2009) through the RH synthesis code (Uitenbroek, 2002) by assuming LTE. The bolometric flux evaluated for a given feature was obtained by integrating the spectral fluxes computed over the range of synthesized wavelengths from 200 nm to 2423 nm. Fig. 2 shows the results derived from two computations carried out by assuming the results of spectral synthesis unaltered (Rome-PSPT, black asterisks) and the ones obtained by reducing the bolometric flux emerging from a bright plage by 7 % (Rome-PSPT P red, black diamonds), in order to roughly account for the overestimation of their UV emission by our LTE calculations (Unruh, Solanki and Fligge, 1999; Krivova, Solanki and Floyd, 2006).

It is worth noting that these model reconstructions are obtained by assuming a fixed number of components and a fixed set of model atmospheres. The number of components used, the details of the image decomposition applied and some parameters of the model atmospheres are all important ingredients of the model, and can be varied to some extent in order to improve the quality of the agreement with observed irradiance variations.

4. Radiative emission of solar features in the Ca II K line

The intensity of the Ca II K resonance line observed with spectrographs and Lyot-type filters has been for a long time a diagnostic of the solar chromosphere and an indicator of magnetic activity. However, except for the quiet Sun, the literature contains a relative lack of photometric measurements of solar features observed at this spectral range. An analysis of PSPT observations has recently filled this gap. Ermolli *et al.* (2010) studied the radiative emission of different types of solar features, such as quiet Sun, enhanced network, plage, and bright plage regions identified on full-disk observations carried out with the MLSO-PSPT. The data were taken in the summer of 2007 by using three interference filters that sample the Ca II K line with different band-passes.

The study depicted the dependence of the radiative emission measured on different solar features on the filter band-pass. The results obtained from observations were also compared with those derived from a non-local thermal equilibrium (NLTE) spectral synthesis over the band pass of the MLSO-PSPT filters. The synthesis was carried out by utilizing the RH code (Uitenbroek, 2002), by adopting a partial frequency redistribution (PRD) and the most recent set of semi-empirical atmosphere models presented in the literature (Fontenla *et al.*, 2009), as well as the earlier similar models. Since some of these models were constructed with radiative transfer codes using the complete redistribution ap-

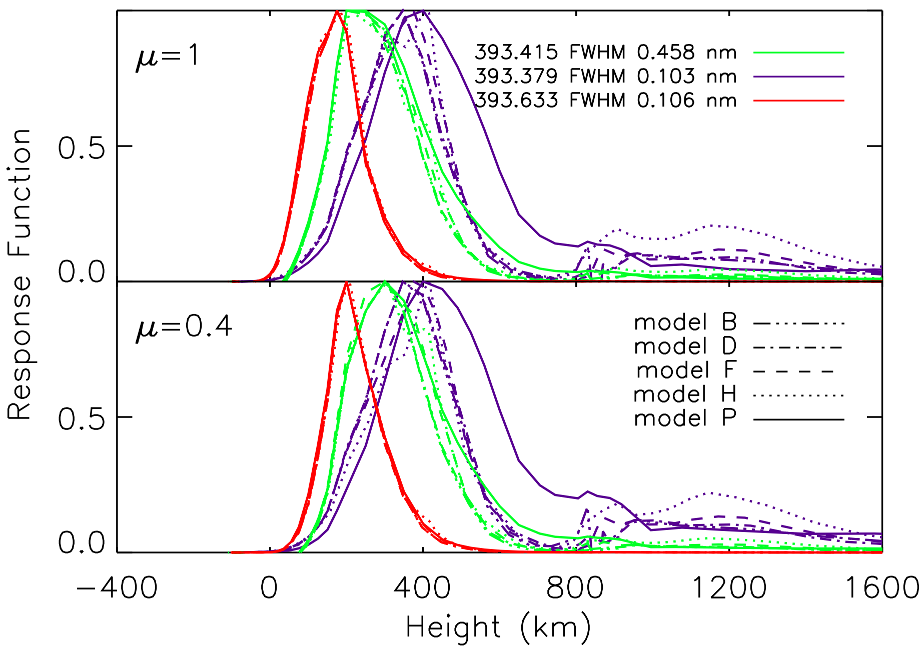

Figure 3. Intensity response functions to perturbations of temperature for the PSPT filters computed at the disk positions $\mu = 1$ (top) and $\mu = 0.4$ (bottom). The functions derived for the different filters are specified in the legend on top and atmosphere models are indicated by various colors and lines, as described by Ermolli et al. (2010). Details on the different filter transmission profiles and atmosphere models are given in the legend on top and bottom panels, respectively. Each function is normalized to its maximum.

proximation (CRD), which is also an option of RH, the synthesis of the Ca II K line profiles was performed with both PRD and CRD formalisms, in order to evaluate the sensitivity of results to code approximations.

Fig. 3 shows the intensity response functions to perturbations of temperature for the MLSO-PSPT filters. The results obtained indicate that the MLSO-PSPT filters sample quite a wide range of atmospheric heights, and that the radiative signals measured with these filters are dominated by the wings of the Ca II K line, which form at the height below 500 km. The average and FWHM of the response heights of the computed functions proved to be only slightly sensitive to the choice of atmosphere models and filter profiles. It is worth noting that even for the narrowest MLSO-PSPT filter analyzed (FWHM 0.10 nm), which has a band-pass similar to that of the Ca II K high-resolution observations from the Swedish Solar Telescope, 58-82 % of the contribution at the disk center is from atmospheric heights below 500 km, with the fraction being lower for brighter features. The same quantity evaluated for the wider MLSO-PSPT filter analyzed (FWHM 0.27 nm), which has a bandwidth close to that of the SOT/BFI Ca II H filter on-board the Hinode spacecraft, is 84-94 %. Therefore, while these observations are commonly considered to depict chromospheric patterns, they turned out to be heavily affected by photospheric conditions.

As to the comparison between the emission measured on various solar features and the one derived from the synthesis performed on various atmosphere models, the study pointed out that CRD calculations derived by using the most recent quiet Sun model, on average, reproduce the measured values of the quiet Sun regions slightly more accurately than PRD computations with the same model. This may reflect that the utilized atmospheric model was computed by assuming CRD. Calculations with PRD on earlier quiet Sun model atmospheres reproduced measured quantities with an accuracy similar to that achieved here by applying CRD to the recent model. Besides, the intensity center-to-limb variation of the quiet Sun measured on the observations taken with the narrowest filter turned out to be in close agreement with the results published in the literature from data taken with spectrographs at the Ca II K line core. On the other hand, the median contrast values measured for most of the identified bright features, disk positions, and filter band-passes resulted, on average, in a factor of ≈ 1.9 lower than those derived from PRD simulations performed by using the recent bright feature models. The discrepancy between measured and modeled values decreased by $\approx 12\,\%$ after taking into account stray-light effects on PSPT images. When moving towards the limb, PRD computations showed better agreement with the data than performed in CRD. Finally, PRD computations on either the most recent or the earlier atmosphere models of bright features reproduced measurements from plage and bright plage regions with a similar accuracy.

5. Comparison of Ca II K spectroheliogram time-series

Among the historic series of synoptic observations, those including Ca II K images have the greatest potential of providing information about solar magnetism. Motivated by the potential value of these observations for studies focusing on time scales longer than the solar cycle, Ermolli *et al.* (2009) analyzed the image quality and contents of three Ca II K spectroheliogram time-series, specifically those obtained by the digitization of the Arcetri (Ar), Kodaikanal (Ko), and Mt. Wilson (MW) photographic archives. The study, based on the processing of more than 72 000 observations stored between 1907 and 1999, focused on the quality of historical data and their comparison with present-day Ca II K observations taken with the Meudon spectroheliograph and the Rome-PSPT.

The study showed that historic data suffer from stronger geometrical distortions and photometric uncertainties than similar modern observations. The latter uncertainties mostly originate from the photographic calibration of the original data and from stray-light effects. The analysis also showed that the

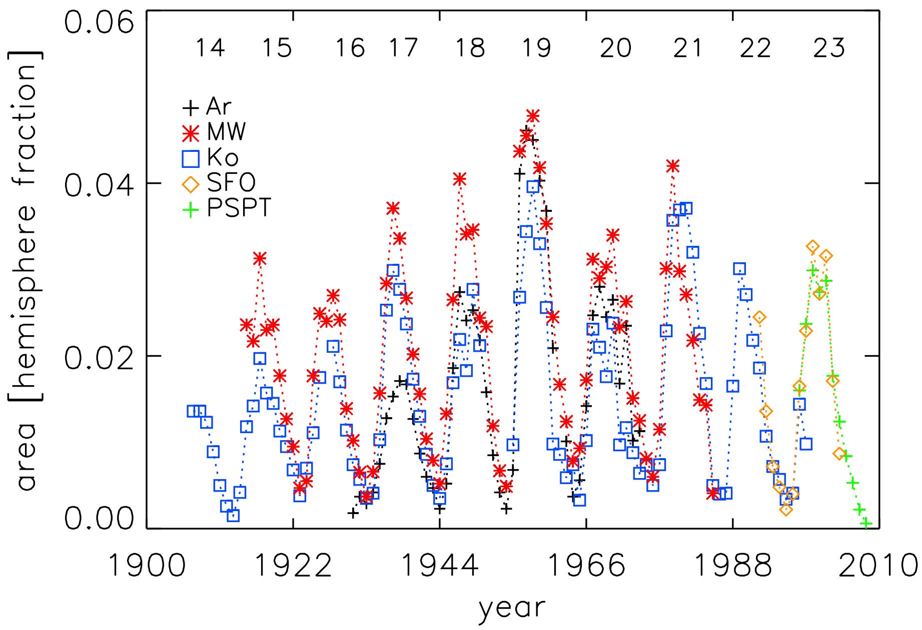

Figure 4. Temporal variation of the annual median values of the plage coverage measured from Arcetri (Ar), Kodaikanal (Ko), and Mt. Wilson (MW) series, as well as those obtained from the analysis of present-day Ca II K observations carried out with the Rome-PSPT (PSPT) and the synoptic telescope of the San Fernando Observatory (SFO). Details for the results derived from historical observations are given in Ermolli *et al.* (2009). Cycle numbers are given at the top of each cycle.

image contents of the three analyzed series vary in time. These variations are probably due to instrument changes and aging of the spectrographs, as well as changes of the observing programs. Some of the image problems affecting historical observation, *e.g.*, the image eccentricity, can be fixed through application of an appropriate image processing technique. Other problems, such as the photometric uncertainties associated with photographic calibration, stray-light, and variation in time of image contents (*e.g.*, produced by shifts in the wavelength of the observation) are more difficult to account for with image processing. In particular, the temporal variations of the image contents due to instrumental changes can be separated from solar temporal variations only through the intercomparison of the data from different archives. In this respect, the series of Kodaikanal spectroheliograms turned out to be both the most homogeneous and the longest among those analyzed.

The study also showed that the segmentation technique applied on both historical and present-day observations provides reasonably consistent results. Fig. 4 shows the temporal variation of annual median values of the fraction of the solar hemisphere covered by plage regions identified on the Ar, Ko, and MW series, and on similar present-day observations. The values of plage coverage obtained from the three historical datasets agree within 40 %. The Pearson correlation coefficients are 0.87, 0.85, 0.93 for the pairs of Ko-MW, Ar-Ko, and Ar-MW, respectively. The mean of these values is 0.88. However, the values derived from the three series differ considerably for cycles 15, 17, and 19, probably because of the instrumental inhomogeneities affecting the three data-sets. The relative difference between the median values obtained for the three series is up to 140 % in these cycles. Nevertheless, the results obtained from the study are highly connected with other recent measurements of Ca II K plage indexes by Bertello *et al.* (2010) and with measurements of activity proxies, such as the Mg II index and flux measured at 10.7 cm.

The time-interval covered by the three historical time-series is extended in Fig. 4 with plage measurements derived from the two samples of present-day Ca II K full-disk observations carried out with the telescope at the San Fernando Observatory (SFO) and with the Rome-PSPT (PSPT). This composite time-series suggests that the solar magnetism depicted by these plage measurements had slight variations during periods of minimum solar activity of the last 100 years. In particular, it increased from 1900 to mid 1970s, and it has systematically decreased since then.

6. Conclusions

Undoubtedly, the analysis of past synoptic observations helped to advance our understanding of the solar magnetism and activity cycle. In recent years, the advent of the high-resolution ground- and space-based experiments has greatly improved the resolution of measurements carried out by increasing our knowledge of the physical processes in the solar atmosphere. Nevertheless, precise synoptic observations of the solar atmosphere shall continue to contribute to advance our understanding of the solar magnetism and its variability, especially as to variations occurring on time-scales longer than the activity cycle. Indeed, the distinctive role of synoptic observations in solar physics has been recently recognized by two leading projects. In 2008, although small-size facilities providing synoptic observations were not part of the large infrastructures addressed by the project, the ASTRONET Roadmap recognized that some scientific challenges of the future concerning the Sun-Earth system and longer-term space-climate issues shall be accomplished with the analysis of data derived from global networks of ground-based, synoptic instruments which continuously monitor magnetic and velocity fields, and the spectrally resolved radiative output of the solar disk with adequate spatial resolution. Besides, the synoptic observations turned out to be important also to support the space environment modeling significant for the space exploration and for the Space Situational Awareness (SSA) project of the ESA.

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