# NSO/AFRL/Sac Peak K-line Monitoring Program

Stephen L. Keil
*Air Force Research Laboratory, Sunspot, NM 88349*

Timothy W. Henry[1]
*National Solar Observatory, Sunspot NM 88349*

Bernard Fleck
*ESA Space Science Department, NASA/GSFC Mailcode 682.3, Greenbelt, MD 20771*

**Abstract.** We summarize the National Solar Observatory/Air Force Research Lab/Sacramento Peak synoptic Calcium K-line monitoring program that was initiated in November of 1976. We observe the disk-integrated solar Ca II K-line using the Evans Coronal Facility at NSO/SP. Several K-line parameters, including the emission index and various measures of asymmetry are computed from the calibrated line profiles. We discuss the cyclic variation of these K-line parameters and their correlation with a several other solar variability indicators.

## 1. Introduction

Precise measurements of the disc integrated solar Ca II K-line ($\lambda$ 3933 Å ) flux are important not only for a better understanding of the long-term variability of the solar chromospheric energy output, but they should also give insight into solar-terrestrial relationships as well as the solar-stellar connection.

The National Solar Observatory (NSO) has a long-term program to monitor the Ca II K-line in integrated solar light which now spans more than two solar cycles. Measurements are made with the Fourier Transform Spectrometer at the McMath Telescope on Kitt Peak on four consecutive days each month (White & Livingston 1978, 1981; White et al. 1998) and with the Littrow Spectrograph at Sacramento Peak on a daily basis (Keil & Worden 1984, hereafter call KW). White, Livingston & Keil (1992) have compared the two data sets and derived regression relationships for combining them.

The combined data has been used for comparison with activity cycles in solar-type stars (White, Livingston & Keil 1992, White et al. 1992) and for comparison with thermospheric properties measured by the UARS satellite (White et al. 1994) The higher cadence Sacramento Peak data has been used by Donahue & Keil (1995) to measure solar differential rotation in integrated sunlight with

[1]Supported by Funding from the Air Force Office of Scientific Research

the goal of showing such measurements are feasible for other stars. Donahue, Restaino & Keil (1994) used it to measure chromospheric contrast and active region filling factors and to discuss the feasibility of similar measurements for solar-like stars using the solar data as a calibration.

This paper describes the current data set from Sacramento Peak, describes how it varies over the two previous solar cycles and how it correlates with other indicators of solar activity. Further information and results from the combined NSO/SP and NSO/KP data can be found in White et al. (1998).

## 2. Observations and Reduction

KW describe the observational procedures in detail so we give only a brief summary.

The observations are made with the coleostat and the horizontal Littrow spectrograph of the Evans Coronal Facility at Sacramento Peak. A 5 mm focal length cylindrical lens focuses the solar image on the entrance slit of the spectrograph. This lens forms a one dimensional image of the sun which is slightly smaller in height than the spectrograph slit. A decker slit behind the cylindrical lens blocks out excess light. The Littrow is used in double pass to further reduce scattered light. All of the light from the grating is imaged onto a photomultiplier tube. The spectrum is scanned from 3898 to 3954 Å in 5.5 mÅ steps. The entrance slit is closed to measure noise and the intermediate slit is closed to measure scattered light.

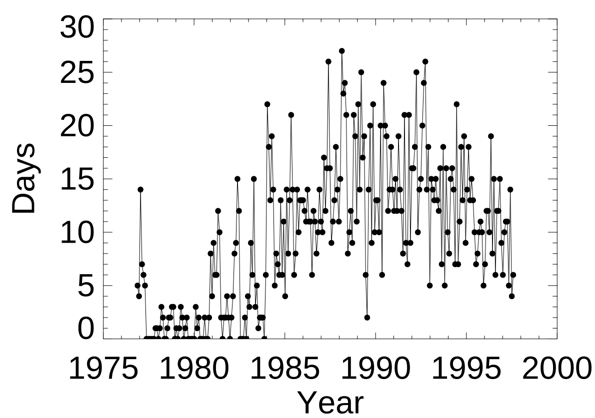


Figure 1. Number of Days Observed per 30 Day Interval

On most days we make from 50-150 spectral scans. These are averaged, after removing scattered light, dark current, and sky transparency variations to form a daily mean profile. We attempt to observe every day near noon, but telescope scheduling and weather limit our coverage. From 1976-1983 data was obtained on 10% of all days, while from 1984-present data is obtained on about 45% of all days. Fig. 1 shows the number of days on which observations have

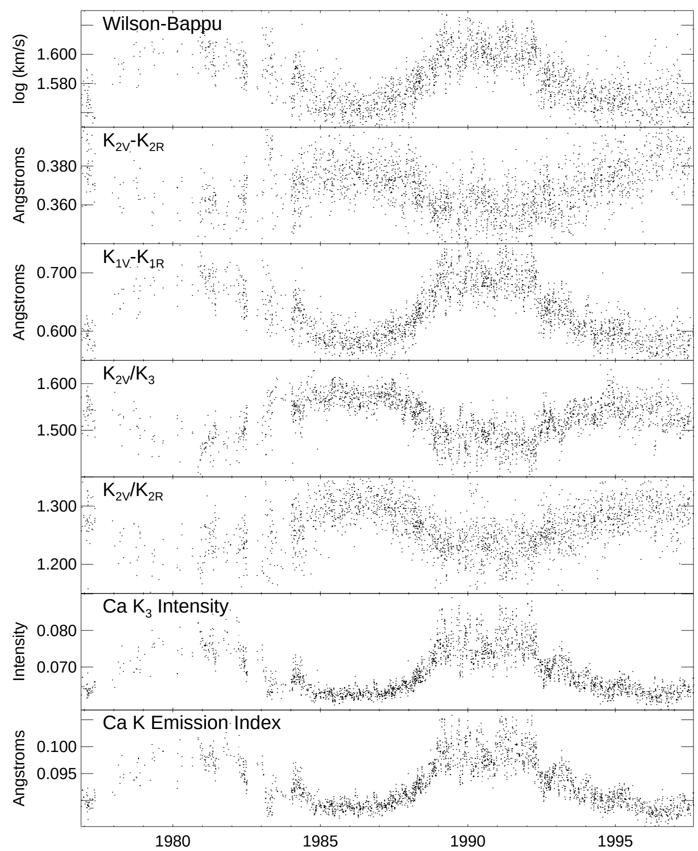


Figure 2. Solar Cycle dependence for the Ca II K-line Parameters given in Table 2.

been obtained during 30 day intervals. The decrease beginning in 1993 resulted from decreases in the operational budget of NSO/SP.

Since we do not have an absolute calibration of the instrument we determine a gain and offset for each profile by correlating 400 points in a window several angstroms away from the K-line core in the red wing point by point with a reference profile. We then average the intensity in a 0.528 Å window in the red wing 1.187 Å away form the K line core, and set this average to an intensity of 0.162 of the local continuum. The daily averaged spectra are high frequency filter to remove residual noise.

Seven parameters, described in Table 1, are deduced from the calibrated line profiles and used to measure changes in the K-line over the solar cycle and to perform correlations with other data sets.

Table 1. Measured Parameters

| | | |
|---|---|---|
| EM | $\int_{\lambda_0-\frac{1}{2}\mathring{A}}^{\lambda_0+\frac{1}{2}\mathring{A}}(I_\lambda/I_c)d\lambda$ | Emission Index, Equivalent width in 1 Å band centered on $K_3$ |
| $K_3$ | $I(K_3)/I_C$ | Intensity in the core |
| $K_{2V}/K_3$ | $I(K_{2V})/I(K_3)$ | Relative strength of the blue $K_2$ emission peak wrt the $K_3$ intensity |
| $K_{2V}$-$K_{2R}$ | $\lambda_{K_{2R}} - \lambda_{K_{2V}}$ | Separation of the two emission maxima |
| $K_{1V}$-$K_{1R}$ | $\lambda_{K_{1R}} - \lambda_{K_{1V}}$ | Separation of blue and red $K_1$ minima |
| $K_{2V}/K_{2R}$ | $\frac{(I(K_{2V})-I(K_3))}{(I(K_{2R})-I(K_3))}$ | The line asymmetry, which is the ratio of the blue and red emission maxima |
| WB | $log_{10}\{76.28(\lambda_R - \lambda_V)\}$ | Wilson-Babbu parameter, width between outer edges of $K_2$ peaks |

## 3. Variations with the Solar Cycle

Fig. 2 displays the cyclic behavior of the seven Ca K-line parameters given in Table 1. The most salient feature is the strong modulation with the 11 year solar cycle. Solar rotation and the appearance and disappearance of ephemeral active regions causes most of the scatter in EM and $K_3$. This also explains the high scatter at solar maximum compared with solar minimum. This cyclic dependence of the scatter is weaker in the other parameters implying higher intrinsic noise levels. Discontinuities in the data, such as that in mid-1993, are real and have been shown to correlate with discontinuities in other indicators of solar activity. White et al. (1994) showed that these discontinuities correlate with levels of thermospheric heating in the Earth's atmosphere and with the orbital decay rate of the UARS satellite.

Table 2 summarizes the variation between solar maximum and solar minimum for EM, $K_3$ and $K_{2V}/K_3$ for cycles 21 and 22. The last column of Table 3 gives the percentage variation for just the chromospheric component of EM based on the arguments presented by KW that approximately 60% of EM at solar minimum is due to a non-chromospheric component while the $K_3$ intensity requires little correction for non-chromospheric components. We note that the

Table 2. Chromospheric Heating: Values of EM, $K_3$, and $K_{2V}/K_3$ are compared at solar max and min for cycles 21 and 22. The final two columns give the total observed change and for EM the change in the chromospheric component after removing a photospheric contribution.

| | Cycle | Solar Max Peak (Ave) | Solar Min Peak (Ave) | $\delta_{total}$(%) Peak (Ave) | $\delta_{Chromo}$(%) Peak (Ave) |
|---|---|---|---|---|---|
| EM (Å) | 21 | 0.104 (0.097) | 0.087 (0.089) | 20 (10) | 45 (21) |
| EM (Å) | 22 | 0.107 (0.099) | 0.085 (0.088) | 25 (25) | 56 (26) |
| $K_3$ | 21 | 0.086 (0.075) | 0.060 (0.063) | 44 (20) | |
| $K_3$ | 22 | 0.090 (0.077) | 0.058 (0.063) | 55 (22) | |
| $K_{2V}/K_3$ | 21 | 1.315 (1.481) | 1.616 (1.572) | -19 (-6) | |
| $K_{2V}/K_3$ | 22 | 1.376 (1.481) | 1.642 (1.535) | -16 (-4) | - |

corrected variation in EM is similar to the observed variation in $K_3$ supporting the claim by KW that the radiation loss rate over the solar cycle is not localized to higher chromospheric levels.

The $K_{2V}/K_3$ ratio measures the relative strength of emission between the lower and upper chromosphere. Skumanich (1967) remarks that this ratio is proportional to the square root of the chromospheric optical depth. The numerical calculations of Restaino (1990) verify that such an approximate relationship is valid in the chromosphere. Fig. 2 shows that this ratio decreases as activity levels increase. The mean value of the ratio decreases by about 4–6% between solar minimum and maximum, while the maximum observed variation is approximately 16–19%. However, while the ratio changes, the absolute intensity increase in $K_{2V}$ and $K_3$ are nearly identical, both show a maximum increase of 0.029 and an average increase of 0.015 of the local continuum. This suggests that heating is occuring uniformly over the chromosphere in agreement with our findings for $K_3$ and EM. Caution is needed in interpreting the relative increase in the emission peaks and $K_3$, since line formation in such a heterogeneous structure as the solar chromosphere during activity maximum is too complex a phenomena to allow over simplified studies. However, the K-line profiles synthesized by Restaino (1990) from the VAL models for the quiet and active chromosphere do show similar behavior, i.e. almost equal increase in $K_3$ and the $K_2$ emission peaks.

The differences between cycle 21 and 22 may not be significant. Our sampling during the maximum of cycle 21 is very coarse. It the NSO/Kitt Peak data is used to fill in some of the gaps, the differences between solar maximum and minimum in cycle 21 are nearly the same as cycle 22 (White et al., 1998).

## 4. Correlations

Table 3 shows the correlation between EM and several other quantities often used as indicators of solar activity levels. These include: the He 10830 Å equivalent width (He EQW) which is measured daily at NSO/KP (Harvey, 1984); the corrected disk-integrated absolute value of the magnetic flux which is also measured daily at NSO/KP; the Ly-$\alpha$ flux obtained by the Solar Mesosphere Explorer (SME) of the University of Colorado, Boulder obtained from the National Geophysical Data Center (NGDC) in Boulder; the 10.7 cm radio flux (F10.7, the Penticton 2800 MHz full disk flux) obtained from NGDC; the sunspot number obtained from NGDC; and the composite Mg II core to wing ratio (Mg II c/w) from the unresolved Mg II h & k lines at 2800 Å measured by combining data from Nimbus 7, NOAA-9, and NOAA-11 (Deland & Cebula, 1993) obtained from NGDC.

All of the parameters are strongly modulated by the solar cycle and by solar rotation. Thus we also show the correlation coefficients computed after removal of the solar cycle and after removal of both the cycle and solar rotation. In addition we show the correlations computed at several epochs, solar minimum (Nov 1984 - Jan 1987), solar maximum (Mar 1989 - Mar 1992), a rising phase of activity (Jan 1987 - Mar 1989), and a falling phase (Apr 1992 - Jan 1996) after the removal of the solar cycle variation. Removal of rotation modulation causes the largest decrease in the correlations. This results because most active region are fairly long lived and they modulate most of the parameters in a similar fashion over a solar rotation. However, the day to day variations contain both noise and real events. By studying the individual data sets, we found many discontinuities in the K-line that are also apparent in F10.7, the Mg II c/w, He 10830 Å and the magnetic field. On the other hand, we also find many events in one parameter that are not reflected in the others.

Table 3. Ca Emission Index vs Other Activity Indices: The correlation between EM and the parameter listed in column 1 is given for various epochs. The columns labeled A1, A2 and A3 use all overlapping data, A1 uses the raw data, A2 the data with the solar cycle variation removed, and A3 has both the solar cycle and rotational variations removed. The other columns give correlations for specific epochs (given in the text) using data which has had the solar cyclic variation removed.

| | A1 | A2 | A3 | MIN | MAX | RISE | FALL |
|---|---|---|---|---|---|---|---|
| He EQW | 0.93 | 0.68 | 0.12 | 0.68 | 0.82 | 0.65 | 0.55 |
| B Corr | 0.90 | 0.61 | 0.09 | 0.48 | 0.74 | 0.49 | 0.52 |
| Ly $\alpha$ | 0.86 | 0.54 | 0.04 | 0.44 | - | 0.56 | - |
| F10.7 | 0.93 | 0.63 | 0.14 | 0.53 | 0.74 | 0.59 | 0.57 |
| Sunspot # | 0.89 | 0.57 | 0.14 | 0.48 | 0.68 | 0.50 | 0.53 |
| Mg II c/w | 0.93 | 0.67 | 0.15 | 0.58 | 0.78 | 0.47 | 0.53 |

One reason for looking at these correlations is to develop ground-based proxies for solar emissions in the UV and EUV. For example, properties of the Mg II absorption at 2800 Å are used with scale factors to estimate irradiance from 1700 - 4000 Å (Health and Schesinger 1986; Cepula et al. 1992; Deland

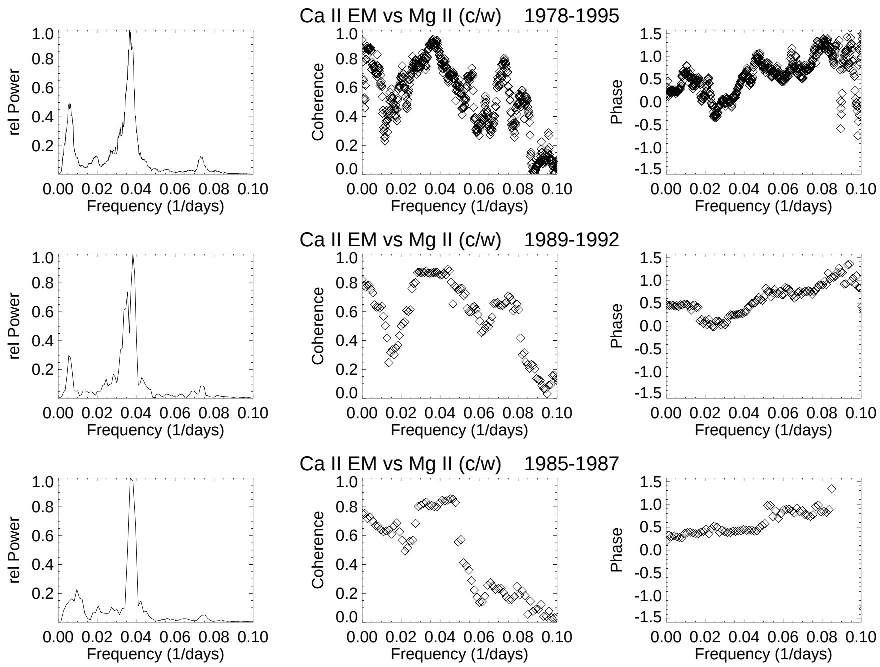


Figure 3. Ca II EM vs Mg II c/w for all overlapping data (1978-1995), for maximum of Cycle 22 (1989-1992) and for minimum of Cycle 21 (1985-1987).

& Cebula 1993), and the F10.7 flux is used as a proxy for the EUV input to terrestrial models (Donnelly et al. 1992). Thus, we have computed the cross-power, coherence and phase between the Ca II parameters and the other activity indicators to better understand their temporal behavior. In addition, we have started investigating how well the K-line measurements can predict some of the other parameters. As examples, Figs. 3 and 4 present the results of comparing EM to Mg II c/w.

In Fig. 3 we plot the relative cross-power, coherence and phase between the Ca II EM and the Mg II c/w for all overlapping data, for a period of high activity (1989-1992) and a period of low activity (1985-1987). The strongest coherence occurs around the 27 day rotational period. The two data sets appear to be in phase at the solar rotation period. However, at shorter periods there is evidence that the phase increases linearly, implying a lag between the two sets, with the Ca II emission leading the Mg II emission by about 3-4 days. The coherence associated with periods shorter than 27 days is much higher (even when the apparent harmonic at 13.5 days is excluded) when activity levels are high. This increase in coherence could result from the appearance of ephemeral regions that affect both the Ca II emission and the Mg II profiles in a similar manner, but with an apparent lag of a few days.

Fig. 4 shows the measured Mg II c/w (upper right), the regression relationship between EM and Mg II c/w (upper left), the value of Mg II c/w one

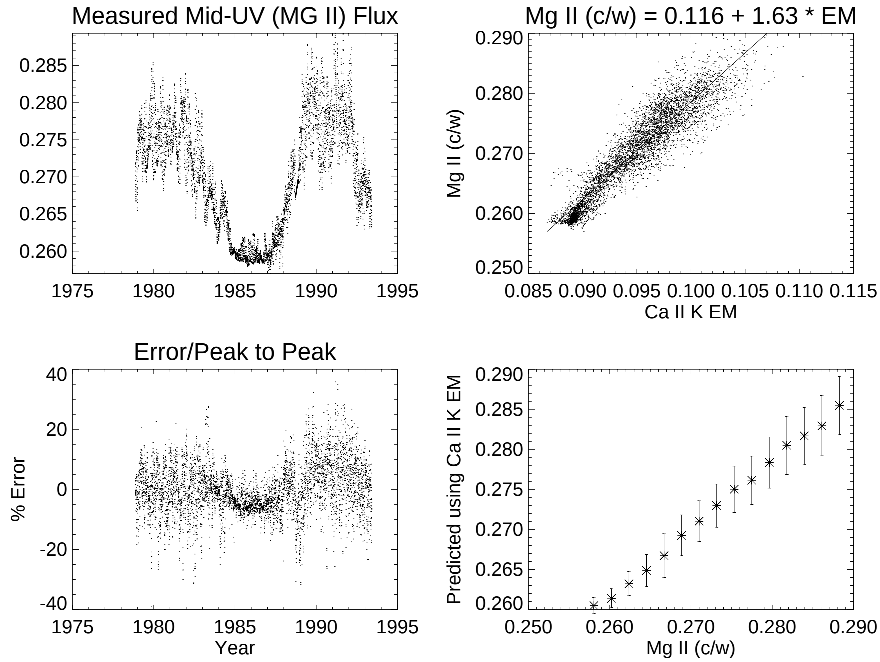


Figure 4. Using the Ca II Emission Index to predict the Mg II c/w. The difference between the predicted value and the observed value of Mg II c/w has been divided by the observed total variation in the observed value over the solar cycle to obtain the lower right plot.

would predict using the EM regression where the error bars show the standard deviation of the predicted values (lower right). and the difference between the predicted value of Mg II c/w and the observed value divided by the maximum observed variation between solar minimum and solar maximum (lower left). While EM accurately predicts the mean level of MG II c/w over the solar cycle, the error in the day to day prediction varies from 5-10 % of the peak to peak Mg II c/w variation at solar minimum to 10-20 % of the variation at solar maximum.

## 5. Conclusion

The Ca II K-line monitoring program at NSO/SP now spans almost two solar cycles. The data is available over the WEB at the NGDC site or by e-mailing a request to skeil@sunspot.noao.edu. We plan to expand the analysis using the K-line as a predictor to other parts of the EUV spectra. We are investigating replacement of our current detector which is a photomultiplier that must be scanned across the Ca II spectrum with a linear diode. This would decrease the time required to obtain our daily sample and thus increase the number of observing days.

**Acknowledgments.** Our thanks to the observing staff at NSO/SP for their continuing efforts to obtain the data, with special thanks to Lou Gilliam, Brian

Armstrong, and Joe Elrod who have born the brunt of the effort. NSO/Kitt Peak magnetic data used here are produced cooperatively by NSF/NOAO, NASA/GSFC and NOAA/SEC. This work is support by the Air Force Office of Scientific research under Task 2311G3.

## References

Cebula, R. P., DeLand, M. T., and Schlesinger, B. M. 1992, Journal of Geophysical Research, 97, 11613-11620

Deland, M. T. and Cebula, R. P. 1993, Journal of Geophysical Research 98, 12809-12823

Donahue, R. A., Restaino, S. R., and Keil, S. L. 1994, Solar Phys. 149, 257-265

Donahue, R. A., and Keil, S. L. 1995, Solar Phys. 159, 53-62

Donahue, R. A., Dobson, A. K., and Baliunas, S. L. 1997, Solar Phys. 171, 191-209

Donnelly, R. F., Hudson, H., Pap, J. and Willson, R. 1992, in Proceedings of the Workshop on the solar Electromagnetic Radiation Study for Solar Cycle 22, ed. R. F. Donnelly, NOAA ERL SEL, Boulder, CO 80303, pp. 275-285, July 1992

Harvey, J. W. 1984, in Solar Irradiance Variations on Active Region Time Scales, eds. B. J. Labonte, G. A. Chapman and H. S. Hudson, NASA Conf. Publ. 2310, pg 197

Heath, D. F., Schlesinger, B. M. 1986, Journal of Geophysical Research 91, 8672-8682

Keil, S. L., and Worden, S. P. 1984, Astrophysical. J. 276, 766-781

Restaino, S. R. 1990, private communication

Skumanich, A. 1967, Astrophysical Journal 72, 828

White, O. R. and Livingston 1978, Astrophysical Journal 226, 279

White, O. R. and Livingston 1981, Astrophysical Journal 249, 798

White, O. R., Skumanich, A., Lean, J., Livingston, W. C., Keil, S. L. 1992 Publication of the Astron. Soc. of the Pacific 104, 1139-1143

White, O.R., Livingston, W. C., and Keil, S. L. 1992, in Proceedings of the Workshop on the Solar Electromagnetic Radiation Study for Solar Cycle 22, Richard F. Donnelly (ed.), page 160-165

White, O. R., Rottman, G. J., Woods, T. N., Knapp, B. G., Keil, S. L., Livingston, W. C., Tapping, K. F., Donnelly, R. F., and Puga, L. C. 1994, Journal of Geophysical Research, 99, No. A1, 369-372

White, O. R., Livingston, W. C., Keil, S. L. and Henry, T. W. 1998, these Proceedings