THE SOLAR Ca II K INDEX AND THE Mg II 
CORE-TO-WING RATIO

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ABSTRACT. The 1 Å index of the solar Ca II K line is compared with the core-to-wing ratio of satellite measurements of the Mg II h and k lines. The correlation coefficient $r = 0.976$ for the Nimbus-7 Mg II ratio during solar cycle 21 and $r = 0.99$ for the NOAA9 Mg II ratio in cycle 22. Linear regression analysis for the full dynamic range of both data sets is used to combine the Nimbus-7 and NOAA9 Mg II data. These relations permit the ground-based Ca K index to estimate the solar UV flux.

1. Introduction

Satellite measurements of the core-to-wing ratio of the Mg II h and k lines ($R_{Mg}$) are important because of their long-term precision and their use in estimating solar UV flux temporal variations as a function of wavelength in the range important to the stratosphere and ozone layer (Heath and Schlesinger, 1986). The relation between $R_{Mg}$ and the Ca K 1 Å index is important because it aids in developing the relation between the time series of $R_{Mg}$ data from one satellite with those from a later satellite and because it allows the ground-based Ca K 1 Å index to be used to estimate solar UV flux variations. So what is the relation?

Fredga (1971) and Lemaire (1984) showed that the Mg k emission core intensity correlated highly with that for Ca K as a function of spatial position on the Sun. Since the increase or decrease in area and brightness of spatial features causes the temporal changes of full-disk fluxes, the high correlation of brightness as a function of spatial position implies that the temporal variations of the full-disk fluxes for the emission cores of these Mg II and Ca II lines should be highly correlated. Avrett’s (1992) theoretical modeling of the upper photosphere, chromosphere, transition region, and lower corona for a spherically stratified, average quiet Sun shows that the emission core of the Mg II k line originates from slightly higher but similar altitudes in the chromosphere than does the emission core of the Ca K line. Therefore, the Mg II and Ca K activity brightenings should involve essentially the same source regions, which supports the expectation that the temporal variations of the full-disk fluxes for the emission cores of the Mg II h and k lines and the Ca II K line should be highly correlated.

2. The Solar Ca K and Mg II h and k Line Profiles and Indices

The Ca K line near 393 nm, shown in Figure 1, consists of the strong absorption feature that produces the overall large V shape with two small emission peaks on either side of the cen-
ter of the line (the zero location on the relative wavelength scale). The Ca K emission peaks, which originate in the chromosphere, vary strongly with solar activity. The K index is simply the full-disk intensity integrated as a function of wavelength across the 1 Å interval centered on the core of the Ca K line (between the two vertical lines in Figure 1) and then divided by a measure of the solar continuum intensity per Å at two reference wavelengths near 4020 Å and 3875 Å (White and Livingston, 1981).

Figure 1 also shows a fine-wavelength-resolution observation of the Mg II h and k lines (Allen et al., 1978). The emission cores, labeled h and k, are so close together that the short-wavelength absorption wing of the h line overlaps with the long-wavelength wing of the k line to produce the interwing maximum near 280 nm. Most of the variation with solar activity occurs in the chromospheric emission cores and not in the photospheric wings or weak lines. The lower left part of Figure 1 shows the Mg II h and k lines seen with the broad bandwidth of the Nimbus-7 measurements from the Solar Backscatter UV (SBUV) experiment (Heath and Schlesinger, 1986), which are similar to the NOAA9 SBUV2 monitoring measurements. The h and k emission cores, the broad absorption wings, and all the fine structure from weak absorption lines are smoothed into one broad absorption feature. Strong changes in the emission cores produce small variations near the minimum of the unresolved lines.

Heath and Schlesinger (1986) defined the center-to-wing ratio for the Mg II h and k solar absorption lines for solar flux measurements made by the SBUV experiment aboard the Nimbus-7 satellite as follows:

$$R_{\text{Mg}}(t) = \frac{4[F(279 \ . \ 8 \ nm, t) + F(280 \ . \ 0 \ nm, t) + F(280 \ . \ 2 \ nm, t)]}{3[F(276 \ . \ 6, t) + F(276 \ . \ 8, t) + F(283 \ . \ 2, t) + F(283 \ . \ 4, t)]} \ .$$

(1)

$F(\lambda, t)$ is the measured solar flux at wavelength $\lambda$ and time $t$. The wavelengths in the numerator were selected to have a strong signal of solar variability from the large percentage variations of the h and k emission cores. The far-wing measurements in the denominator were selected to be close in wavelength to the core of the line but to have very weak solar signals. Consequently, the ratio has a strong solar signal while being insensitive to drifts in instrumentation throughput that are weak functions of wavelength over the range involved in equation (1).

The arrows in Figure 1 mark the approximate locations of the wavelengths involved in equation (1). There are two problems evident in this figure that illustrate the difficulty in comparing $R_{\text{Mg}}$ results from measurements made by two different instruments. The center wavelength of the three core wavelengths used by Nimbus-7 does not appear to line up with the minimum of the solid or dashed curves, yet the Nimbus-7 flux values for these three wavelengths indicate that the center one is close to the minimum. This is a consequence of a difference in the wavelength scales used for these two instruments. Secondly, the maximum in the short-wavelength wing of Hall and Anderson's (1988) balloon flight data is too low for $R_{\text{Mg}}$, derived from their data, to ever be low enough to agree with Heath and Schlesinger's (1986) results. This may result from the effect of the ozone layer on the balloon measurements being incompletely corrected. Other problems in comparing $R_{\text{Mg}}$ val-
Fig. 1. Wavelength dependence of the solar Ca K line (top right) and the Mg h and k lines with fine wavelength resolution (top left) and with the low wavelength resolution of the SBUV monitoring measurements (bottom left). The many narrow dips in the top two graphs are weak absorption lines that vary little with solar activity.

Values from different instruments involve differences in scattered light (the data in the top left frame of Figure 1 has a high level of scattered light) and differences in bandwidths or wavelength step sizes. Nevertheless, $R_M$ results from different instruments should have relative temporal variations that are linearly related.

3. Time Series of Ca K 1 Å Index and the Mg II Index

Figure 2 shows the Ca K 1Å index as a function of time from late 1974 through late 1990. All of solar cycle 21 and the rise and maximum of cycle 22 are included. The data recording rate of about 3 to 4 consecutive days each month samples the solar cycle or long-term variation very well, samples the intermediate-term variations (4–8 months) quite well, and provides a subsample of the short-term or day-to-day and week-to-week variations.

Figure 3 illustrates the Mg II index based on the research and data of Heath and Schlesinger (1986). These data start with the last part of the rise phase of solar cycle 21. They also include the entire peak phase and decline of solar cycle 21 and the minimum between cycles 21 and 22 in September 1986. Solar UV measurements were made by the Solar Backscatter Ultraviolet (SBUV) experiment aboard Nimbus 7, typically on three consecutive days and with the instrument turned off on the fourth day. So both Nimbus-7 data and
Fig. 2. Time series of the Ca K $1 \, \AA$ index.

Fig. 3. The Nimbus-7 core-to-wing ratio of the Mg II h and k lines.
the Ca K index were usually available on the same day for at least 2 days per month over an 8-year period.

Figure 4 presents the NOAA9 SBUV2 data for the solar Mg II index. These values differ from those in Figure 3 because a modified ratio is used for NOAA9. The output dynamic range for NOAA9 is covered by three overlapping ranges, each range having its own electronic system and digital telemetry output. Drifts have occurred in the relation between the strong signal output range and the medium signal range. To avoid these problems, the wing wavelengths used for the NOAA9 $R_{\text{Mg}}$ were moved to the sides of the absorption line walls; both the core measurements and these new “wing” measurements involved in the ratio can then use outputs from the same (medium) intensity range, thereby avoiding the range-to-range drift problems. Because the wing measurements are now on the steeper part of the line profile with respect to wavelength, this modified ratio requires very accurate wavelength repeatability, or low wavelength jitter, which has been successfully achieved in the “discrete-wavelength” mode data used here. One undesirable consequence is that the modified long-wavelength wing measurement includes a weak solar signal from the emission cores. The first-order effect of this is to linearly reduce the relative amplitude of the modified ratio’s solar variability; this is also reduced by the lower amplitude “wing” measurements, causing the average value of the ratio to be higher. These changes are all taken into account by using the linear regression relations described below to convert the modified ratios to equivalent Nimbus-7 values. (A very small but not negligible second-order nonlinear effect has not yet been corrected.) The modified core-to-wing
ratio for the Mg II h and k lines used for the discrete-wavelength mode of the NOAA9 SBUV2 measurements is given by the following:

\[ R_{\text{Mg,NOAA9}} = \frac{2 \frac{F(279 \cdot 92 \text{ nm}, t)}{F(278 \cdot 14, t) + F(281 \cdot 24, t)}}. \]  

(2)

The average daily values derived from (2) are presented in Figure 4. These data show the minimum between solar cycles 21 and 22 in September 1986, the rise of solar cycle 22, and the main peak of the cycle. These observations were interrupted in the fall of 1988 when the Sun was unexpectedly occulted by part of the satellite.

4. Linear Regression Analysis

Linear regression analysis was computed for the Nimbus-7 Mg II core-to-wing ratio as a function of the Ca K index for the same-day pairs (177 matched pairs) of the data shown in Figures 2 and 3. The best-fit linear equation is given by

\[ R_{\text{Mg,Nimbus7}} = 0.14391 + 1.3888 [\text{Ca K index}] \],

with the linear correlation coefficient \( r = 0.976 \). This means that about 5% of the variance is not explained by the linear relation with respect to the Ca K index. Some of that 5% is caused by both the Mg II and Ca K indices being based on daily samples over several minutes of the day where the samples are not taken at the same time of day for the two observing programs. Given \( R_{\text{Mg}} \), Heath and Schlesinger’s model allows one to estimate the solar UV flux as a function of wavelength and time in the 160–400 nm wavelength range. Equation (3) therefore lets one use the ground-based measurements of the Ca K index to compute the solar UV flux. Although the high correlations found above provide accurate conversions between the Nimbus-7 and NOAA9 Mg II ratios and the Ca K 1 Å index, the errors in the Heath and Schlesinger model are much larger than those in \( R_{\text{Mg}} \) and are also a function of wavelength.

Figure 5 shows the scatter diagram for the same-day pairs of Ca K index and the Nimbus-7 Mg II core-to-wing ratio. The straight line with the higher Ca K values in the upper right corner is that given in equation (3). The reverse relation for estimating the Ca K index from the Nimbus-7 Mg II index is also of interest; it is given by

\[ [\text{Ca K index}] = -0.09422 + 0.68577 R_{\text{Mg,Nimbus7}} \].

(4)

Equation (4) allows one to estimate the Ca K index for most of the days each month when Ca K is not measured. The second line shown in Figure 5, the one with lower Ca K values in the upper right corner, is given by (4). These two lines are nearly the same because these data are highly correlated. Figure 5 also presents a scatter diagram for 109 matched pairs of daily samples for the Ca K index and the NOAA9 modified Mg II ratio. The equation for the line is

\[ [\text{Ca K index}] = -0.10925 + 0.48468 R_{\text{Mg,NOAA9}} \].

(5)
Fig. 5. Scatter diagrams for same-day pairs of the Ca K index versus Nimbus-7 values of the Mg II ratio (left) and versus NOAA9 values of the modified MG II ratio.

Equation (5) allows one to estimate the Ca K 1 Å index from NOAA9 data. No second or reverse relation line is shown in this case because the correlation is so high \((r = 0.99)\) that the two lines are almost the same.

Substituting (5) into (3) provides estimates of equivalent Nimbus-7 values of \(R_{\text{Mg}}\) from the modified-ratio NOAA9 results, namely:

\[
R_{\text{Mg,Nimbus7}} = -0.007814 + 0.67313 \cdot R_{\text{Mg,NOAA9}}.
\]  

The advantages of converting the NOAA9 data to equivalent Nimbus-7 values through comparisons with the Ca K 1 Å index are the following: (1) the comparisons with Ca K involve very high correlations, in the high 0.9s; (2) the full dynamic range of the solar cycle is included; (3) several years of overlapping data are included (8 years for Nimbus 7 and over 3 years for NOAA9); and (4) short-term variations are included in the samples but do not highly dominate the comparisons as they would in direct comparisons of data from two satellites with an overlap period of the order of a year.

Figure 6 shows the results of applying equation (6) to the NOAA9 data shown in Figure 4 and then combining those results with the Nimbus-7 values in Figure 3. These observed and equivalent Nimbus-7 results can be used with Heath and Schlesinger’s (1986) wavelength scaling function to estimate solar UV flux variations in the 170–290 nm range.

5. Discussion

Ground-based measurements of the Ca K index and satellite measurements of the core-to-wing ratio \((R_{\text{Mg}})\) of the Mg II h and k lines are very highly correlated. Comparisons of NOAA9 data with the Ca K index, together with the regression analysis of the Nimbus-7...
$R_{\text{Mg}}$ as a function of the Ca K index, make it possible to derive equivalent Nimbus-7 values of $R_{\text{Mg}}$ from the NOAA9 data and thereby extend the Nimbus-7 results to later times. These $R_{\text{Mg}}$ values, together with the wavelength scaling function, provide estimates of the solar UV flux in the 170–290 nm range as a function of time since November 7, 1978, the start of Nimbus-7 measurements.

In effect, the Ca K data set the magnitude of solar cycle 22 $R_{\text{Mg}}$ data with respect to cycle 21 in Figure 6; the satellite measurements provide the cycle 21 results and the day-to-day variations in cycle 22. The high correlation of Nimbus-7 $R_{\text{Mg}}$ values with the Kitt Peak Ca K index, the regression relation in equation (3), and the wavelength scaling function also allow ground-based measurements of the Ca K index to be used to estimate the solar UV flux. Other observatories attempting to measure the Ca K 1 Å index should note the importance of keeping scattered light extremely low; the results must first be compared with the Kitt Peak measurements before they are applied to equation (3).

References