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TEMPORAL CHANGES IN SUNSPOT UMBRAL MAGNETIC FIELDS AND TEMPERATURES

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ABSTRACT

We have observed high-resolution intensity spectra near the Fe I 1564.8 nm line at a single umbral point corresponding to the darkest position in over 900 sunspots from 1998 through 2005. From these data we determine that the maximum sunspot magnetic fields have been decreasing at about 52 G yr^{-1}. The same data set shows a concurrent increase in the normalized umbral intensity from 0.60 to 0.75 (corresponding to a blackbody temperature rise from 5137 to 5719 K) and a decrease of more than 50% in the molecular OH line strength. The magnetic field and intensity changes observed over time in the sunspot umbrae from different spots behave in the same way as the magnetic field and intensity changes observed spatially across single sunspots.

Subject headings: Sun: activity — Sun: infrared — Sun: magnetic fields — sunspots

1. INTRODUCTION

The line of Fe I 1564.8 nm and its adjacent spectrum, which includes lines from the OH molecule, is a powerful diagnostic of sunspot conditions (Kopp & Rabin 1992). This wavelength corresponds to the opacity minimum, so it samples the lowest atmospheric levels. The Zeeman splitting of the Fe I line is always complete in spot umbrae because of the near-infrared wavelength and the fact that the line is a Landé $g = 3$ simple triplet. In the late 1990s one of us (W. L.) began to observe sunspots regularly in Fe 1564.8 nm when conditions were appropriate. The aim was to better define the intensity and magnetic field relation, which had been studied for only a few spots (Kopp & Rabin 1992; Martinez Pillet & Vazquez 1993 and others). The instrumental setup was easy and quick using the single-element InSb detector (Livingston 1991). The procedure was adopted of single observations per day at the darkest umbral position.

By means of a simple pinhole photometer and selected bandpass filters, Albregtsen & Maltby (1981) discovered a systematic brightening of sunspot umbrae over the solar cycle. An explanation was put forth by Adjabshirzadeh & Koutchmy (1983) that a solar cycle change in the number of umbral dots in the darkest section of the umbra could explain the cycle change, but later Maltby et al. (1986) showed that multiwavelength observations of the umbral changes were not consistent with a simple increase in the number of umbral dots. In contrast to these results, recently Norton & Gilman (2004) used umbral intensities from MDI (Michelson Doppler Imager) Carrington maps and found that sunspot umbrae in the northern solar hemisphere decreased in continuum contrast from 0.5 to 0.3 from 1997 to 2003, but that umbrae in the southern hemisphere showed a more complicated change during that period. Using an intensity–magnetic field relation among different sunspots, they deduce that the total magnetic field in sunspots changes as the spots appear at different latitudes, supporting the idea that on average, weaker magnetic fields rise through the convection zone farther from the solar equator.

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2. OBSERVATIONS

All data were acquired by Livingston with the National Solar Observatory 1.5 m McMath-Pierce (McM/P) telescope on Kitt Peak and its 13.5 m spectrometer. A 1 mm (2″.5 × 2″.5) Bowen-type image slicer serves as an entrance slit of 0.1 mm width. After the 0.20 mm exit slit of the spectrograph, a single InSb diode measures the intensity spectrum as the grating is scanned over an interval of about 1.2 nm (for more details see Livingston 1991). System noise is negligible (the spectral signal-to-noise ratio is $>10^3$), although seeing and image position are always a concern. An umbral observation consists of five averaged scans with each umbra observed only once on a given day. Each day's observation is treated independently of adjacent days; in general, we make no attempt to identify whether or not a given sunspot is recorded on multiple days.

Necessary conditions for observing are a clear sky and fair to good seeing. With the image under guider control, the umbra is searched for the darkest position by visually checking a brightness meter. One seeks out what has been called a void. This is the darkest place that shows the least intensity structure. The spectral scans are made at this position, and then the image is moved to the nearby quiet photosphere (same limb distance) for a comparison intensity scan. A white-light full-disk sunspot drawing is also made on the McM/P 0.9 m west auxiliary telescope. As the observations are taken the spot positions are marked on this sketch. This is used to identify the sunspot type (spot or pore) and the limb distance.

Figure 1 gives examples of spectra taken at 1565 nm. In the figure the umbral spectrum from 1998 September 18 is shown as the solid line. In this umbra the Fe I 1564.8 nm absorption line is seen completely resolved into Zeeman components, and a weak absorption line from the molecule CN is seen just to the blue of the Fe I at 1564.6 nm (Wallace & Livingston 1992). A second Fe I line is visible at 1565.3 nm, but it is blended with very strong absorption lines from the OH molecule at 1565.2 and 1565.4 nm. Weaker absorption lines from OH are also seen at 1565.1 and 1565.5 nm. The wavelength splitting of the two Zeeman σ-components of the Fe I 1564.8 nm line in this example implies a magnetic field strength of 2688 G, as indicated in the figure. Finally in this spectrum, the central π-component of the Fe I line is visible between the two σ-components, suggesting a component of the magnetic field transverse to the line of sight. Figure 1 also shows a spectrum from 2005 December 24 as a dashed line. In this spectrum

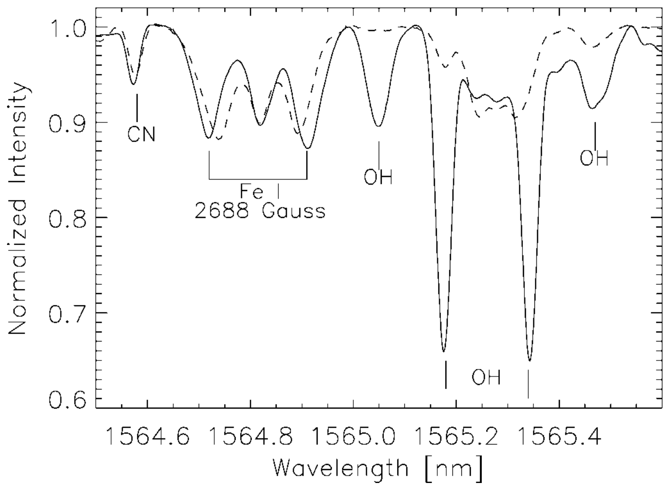

FIG. 1.—Sunspot umbral spectrum from 1998 September 18 (*solid line*) and one from 2005 December 27 (*dashed line*) are shown. Both are normalized to the same continuum intensity, although the 1998 spectrum was 0.55 times the nearby quiet-Sun brightness while the 2005 spectrum was 0.78 times the quiet-Sun brightness. The Zeeman splitting of the Fe I 1564.8 nm line is seen to decrease, and the OH 1565.2 nm absorption line weakens substantially. Note that a weak, Zeeman-split Fe line near 1565.2 nm contaminates the OH line when the OH absorption is weak, as in 2005. All of these changes are consistent with a lower magnetic field strength and a higher temperature between the two sunspot umbrae.

the Fe I 1564.8 nm line shows weaker splitting indicative of a 2180 G magnetic field strength. The OH lines are also much weaker than in the other spectrum; however, the CN line appears relatively unchanged. This different behavior of the two types of molecular lines is consistent with a higher umbral temperature (Penn et al. 2003). Although the two spectra are both normalized, the continuum brightness for the 2005 spectrum is 0.78 times the quiet-Sun brightness whereas the 1998 spectrum continuum is only 0.55 times the quiet-Sun brightness, again consistent with the 2005 umbra having a higher temperature. The spectra are reduced using the program DECOMP (Brault & White 1971). A least-squares fit of Voigt profile synthetic lines is made to the observed lines. We archive the continuum intensity, positions, depths, and half-widths of the Fe 1564.8 nm σ- and π-components, and the depths for OH lines at 1565.1, 1565.2, and 1565.3 nm. In the following analysis we discuss the time variations seen in these parameters from 1998 through 2005. These two spectra in Figure 1 are selected from the data since they have magnetic fields, continuum brightnesses, and OH line strengths very close to the values for the linear fits found in the time sequence analysis.

3. DISCUSSION

Since measurements of pores may be contaminated with scattered light, we removed pores from this study. Pores in the data set can be identified from the daily drawings. The magnetic field strengths in pores range from 1600 to 2600 G with a mean of 2100 G. Their sizes span 2″–5″, with occasional large pores of up to 10″ (Bray & Loughhead 1965). Our 2″.5 × 2″.5 aperture plus seeing results in the pore spectra being contaminated by photospheric light. Because the 1564.8 nm line is completely split at pore field strengths, the field measurement is less affected (neglecting subpore structure; Sütterlin et al. 1996) but the intensity measurements are likely compromised. Except where noted we exclude pores from the data analysis, and the resulting sunspot data set is confined to 906 spectra from well-resolved sunspot umbrae. Our observing periods were only 2–3 days per month, typically at the same time of the month. Since solar rotation has a period close to 1 month, our data set does not equally sample all Carrington longitudes and does not include all the sunspots of the solar cycle. There are only 14 spectra before the sunspot maximum in 2001, so most of the observations were made during the declining phase of solar cycle 23 from 2002 through 2005.

Stray light from the telescope at this wavelength is very low and has recently been measured to be $<10^{-3}$. Changes in this small amount of instrumental stray light should not be detectable in these data. Seeing-induced stray light, however, can exist on a much larger level than this. Stray light from the sunspot penumbra scattered by seeing into the umbra might effectively reduce the measured magnetic field strength, decrease the OH line strength, and increase the continuum brightness. The hypothesis that stray light can account for the temporal changes seen in this data involves two assumptions: first that scattered penumbral light added to an umbral spectrum can produce the observed changes in the Fe I and OH line profiles, and second that the seeing characteristics at the telescope have changed in a systematic way from 1998 to 2005 to increase the penumbral stray light. We now test these two assumptions.

First, several penumbral spectra are used and combined with the umbral spectrum from 1998 (see Fig. 1) to try to reproduce the observed umbral spectrum from 2005. The penumbra is a highly structured environment, and so several different penumbral spectra were used as contaminant sources. While some features of the Fe I profiles could be reproduced by adding penumbral stray light, it was not possible to produce the observed ratio of the Zeeman components. It was not possible to reproduce the Fe I profiles and the molecular CN and OH line strengths simultaneously, nor was it possible to produce reasonable fits to both the CN and OH lines simultaneously by adding penumbral stray light to the umbral spectrum.

Second, we test the assumption that the seeing characteristics changed in a systematic way during the observing period. For this test we use all (1045) sunspot and pore spectra. If we assume that the observations at the darkest point in the umbra are where the magnetic filling factor is exactly unity and that the magnetic field is vertical there, then for a spot at disk center the true Fe 1564.8 nm umbral line profile should show only two split σ-components and no central π-component. As the spot moves from the center of the disk toward the limb of the Sun, the component of the magnetic field perpendicular to the line of sight will increase, and so will the strength of the central π-component. The ratio of the strengths of the observed π- and σ-components should change with the projection of the line of sight on solar vertical, measured with μ. This relationship is seen in the data from values of about $0.7 < \mu < 1.0$, but from $0.0 < \mu < 0.7$ the ratio varies independently of μ. We conclude that for these umbral spectra near the limb, light scattered from the penumbra of the sunspot (where the magnetic field is often horizontal) into the umbra is the dominant source of the observed π-component in the Zeeman-split Fe I line. We can therefore test how the stray light in the observations changes during the observing period by examining the Zeeman component ratio for observations with $0.0 < \mu < 0.7$ and seek a time variation. Nonparametric correlation tests are very robust, and the Spearman rank-order correlation coefficient is a well-known nonparametric test (Press et al. 1992). The significance of such a test can be also be determined by shuffling the data many times and computing the Spearman coefficient for these

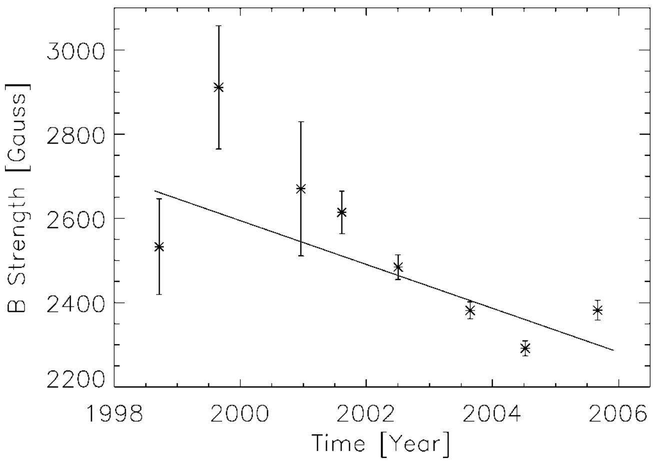

FIG. 2.—Magnetic field computed from the Zeeman splitting of the Fe I 1564.8 nm line, shown for umbral spectra observed from 1998 through 2005. While there is a large variation between different sunspots, nonparametric tests confirm that the data show a highly significant trend. The mean values for each calendar year are shown as data points, and the error bars show the standard error of the mean. The best-fit linear function (fit to the original 906 data points) reveals a decrease in the average magnetic field strength of 52 G yr^{-1}.

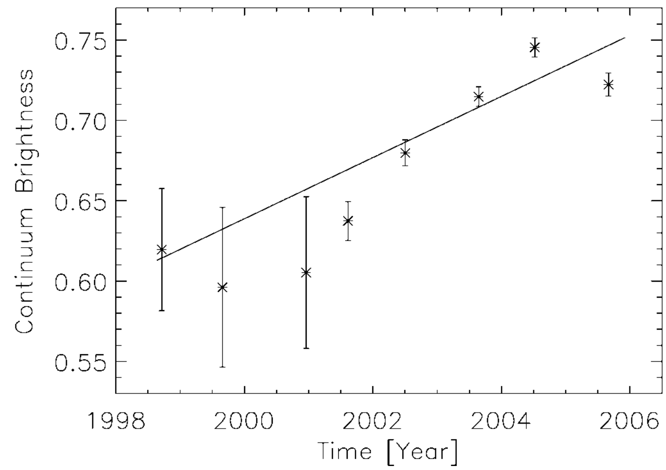

FIG. 3.—Continuum intensity of the umbral spectra, normalized to the intensity of the nearby quiet Sun, shown from 1998 through 2005. The points, error bars, and linear fit are computed as in Fig. 2. A linear fit to the data shows a temperature increase of about 73 K yr^{-1}.

random realizations (Bahcall et al. 1987). The Zeeman component ratio versus time has a low value for $r = 0.0255$ with a low significance (≈25%). More importantly, in 1000 random shufflings the Spearman coefficients showed a distribution of $\sigma_r = 0.0612$ so the computed Spearman coefficient is well inside the distribution of the random shufflings, and from this we must conclude that there is no systematic variation of the seeing-induced stray light during the 1998–2005 observing period.

So we conclude that both of these assumptions are poor: it is not possible to produce the observed umbral spectral changes by adding different amounts of stray penumbral light, and the seeing characteristics at McM/P have not systematically changed during the observing period. Stray light is not the source of the observed spectral changes.

In Figure 2 we plot the magnetic field strength measured from the Zeeman splitting of the σ-components of the Fe I 1564.8 nm line as a function of time for the observations. In all of the parameters that we measure, we see a large variation among different sunspots. Instead of showing all 906 umbral measurements, the data are binned according to calendar year, and the data points show the mean for each bin and the error bars represent the standard error of the mean. The linear fit shown in Figure 2 represents the least-squares fit to all the original data points, not to the binned points. To determine whether the apparent trend in the data was real, a Spearman rank-order coefficient was calculated and showed a high significance ($r = -0.17$, >99%). A shuffling test was done on the magnetic data and the distribution of the random data was 8 times smaller ($\sigma_r = 0.03$) than the computed coefficient, confirming a significant correlation. Then least-squares linear fitting to the data was done. In the first fit all the data were used, and we compute a decrease in the observed magnetic field strength of 52 G yr^{-1}. In the second fit only data from 2002 through 2005 were used and the resulting slope was 47 G yr^{-1}. Recent high-resolution magnetic field observations of sunspot umbral bright points show a reduction of the magnetic field strength in the bright points (Sankarasubramanian et al. 2004). It is possible that during the observing period the average number of umbral bright points increased and produced the magnetic field drop that we observe, although Maltby et al. (1986) shows that for thermal reasons the umbral intensity increase could not be explained by an increased number of umbral dots.

The normalized umbral intensity value is shown in Figure 3 for the spectra, and the graphed points, error bars, and linear fit are computed in the same manner as was done for Figure 2. These intensities are normalized by the quiet-Sun intensity at the same heliocentric angle, but no additional center-to-limb correction has been made to the data. Early studies of the center-to-limb intensity of sunspot umbrae at 1.6 μm showed no intensity variation with disk position (Albregtsen & Maltby 1981), but subsequent work (Albregtsen et al. 1984) did show a variation using 18 observations of six large sunspot umbrae. We examine the intensity of sunspot umbrae in our data with 297 measurements in umbrae with magnetic field strengths greater than 2500 G. Without making corrections for different continuum brightness among the different sunspots, we find only a very weak correlation of intensity with limb position.

The intensity data were analyzed with a Spearman test that again found a highly significant trend ($r = 0.22$, >99%, $\sigma_r = 0.04$), and so a least-squares fit was made. The computed slope shows an increase in brightness of about 1.9% yr^{-1} (or 1.8% if the pre-2001 data are removed). Assuming a blackbody function gives a temperature increase of about 73 K yr^{-1}. This rate of change is very close to the changes found by Albregtsen et al. (1984), who measured 1.2% yr^{-1} for cycle 20 and 1.9% yr^{-1} for cycle 21. Our infrared measurements only poorly sample the rising phase of the cycle, and so we cannot comment on the difference between the umbral darkening observed by Norton & Gilman (2004) and the umbral brightening that we report here. Current work is under way using another set of observations that also shows decreasing umbral brightness before 2001 and after 2005, but details of that analysis will be reported elsewhere. An analysis of the infrared data binned into low latitudes (within 10° of the solar equator) and high latitudes (more than 10° from the equator) revealed identical temporal trends, confirming that this behavior is not simply a dependence of umbral brightness on solar latitude.

Finally, Figure 4 shows the change in the molecular OH line depth from the 1565.2 nm OH line; again, the graphed points, error bars, and linear fit are computed in the same manner as was done for Figure 2. A significant Spearman rank-order co-

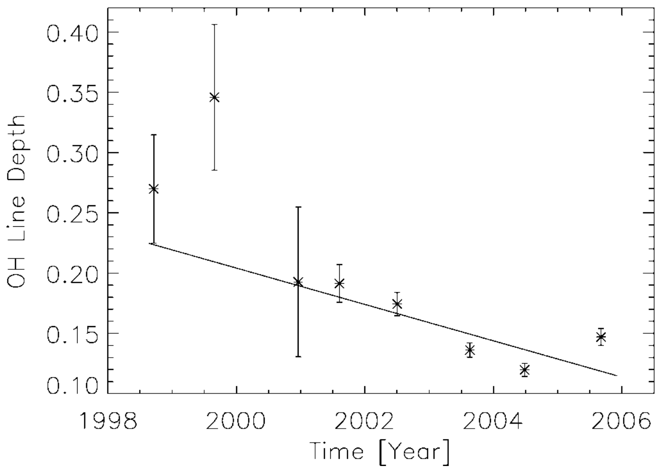

FIG. 4.—Line depth of the OH 1565.2 nm absorption, shown for the sunspot umbra measured in this study. The points, error bars, and linear fit are also computed as in Fig. 2. The line absorption decreases by just over 50% during the 8 years of observations. The weaker molecular absorption is consistent with an increased plasma temperature.

efficient inspired the linear least-squares fit to the data ($r = -0.14$, >99%, $\sigma_r = 0.04$). The line depth (in units of continuum brightness) decreases by 1.5% yr^{-1} (or 1.0% excluding pre-2001 data) in our spectra. This results in a dramatic reduction in the line depth by about 50%, on average, from the start of 1998 to the end of 2005. These OH absorption features are very sensitive to temperature; they increase from no absorption in the quiet-Sun spectra to a central depth of 0.4 times the continuum in our umbral spectra as the field strength increases and the gas temperature decreases. The decrease in the average line depth with time is a new measurement and provides a powerful confirmation of the temperature increase implied by the continuum observations.

It is important to note that the evolution we see of the intensity and the magnetic field strength in different sunspot umbrae roughly follows the relationship of the intensity and magnetic field strength seen in spatially resolved measurements of single spots. For example, Lites et al. (1993) make observations of the 630.2 nm Fe I line and plot the intensity and magnetic field seen in NOAA AR 7111 on 1992 March 25. The magnetic field is seen to decrease by about 250 G as the intensity increases by 0.1. The slopes determined from the temporal changes in our data suggest a decrease of 274 G as the intensity increases by 0.1. (More comparisons between these observations and other umbral spatial scans are shown in Penn et al. [2003].) Since both the magnetic field and molecular line strengths seem to vary with intensity over time in roughly the same way that they vary with intensity within individual sunspots, the temporal evolution that we observe does not reflect different physics, but instead suggests that the balance between magnetic and convective forces is constant during the time period. This is consistent with the idea that only the magnetic field of the sunspot umbra changes and that the continuum intensity and molecular line depths change in ways that reflect this different field strength.

A continuation of these trends would produce important changes for the next few solar cycles. The observed distribution of umbral magnetic fields runs from about 1500 through 3500 G, with a median value near 2400 G. If 1500 G represents a true minimum for spot magnetic fields and the field strengths continue to decrease at the rate of 52 G yr^{-1}, then the number of sunspots in the next solar cycle (cycle 24) would be reduced by roughly half, and there would be very few sunspots visible on the disk during cycle 25. It is with this in mind that we eagerly anticipate measurements of sunspot spectra in the next solar cycle.

Facilities: McMath-Pierce

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