Sunspots may vanish by 2015.

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We have observed spectroscopic changes in temperature sensitive molecular lines, in the magnetic splitting of an Fe I line, and in the continuum brightness of over 1000 sunspot umbrae from 1990-2005. All three measurements show consistent trends in which the darkest parts of the sunspot umbra have become warmer (45K per year) and their magnetic field strengths have decreased (77 Gauss per year), independently of the normal 11-year sunspot cycle. A linear extrapolation of these trends suggests that few sunspots will be visible after 2015.

Sunspots are cool dark regions on the solar surface with strong magnetic fields. There have been few direct measurements of changes in the physical parameters of sunspots, but here we present a study which shows that sunspots are becoming warmer and have weaker magnetic fields. The number of sunspots visible on the Sun normally shows an 11-year periodicity, and the current sunspot cycle (cycle 23) had a maximum in 2001, and is entering a minimum phase with few sunspots currently visible. Our data show that there are additional changes occurring in sunspots, independent of the sunspot cycle, and these trends suggest that sunspots will disappear completely. Such an event would not be

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unprecedented, since during a famous episode from 1645-1715, known as the Maunder Minimum, the normal 11-year periodicity vanished and there were virtually no sunspots visible on the solar surface (*1*). Recent studies of the appearance rate and latitudinal drift of sunspots (*2*) and of the solar magnetic field (*3*) predict that the number of sunspots visible in future cycles will be significantly reduced. Finally the occurrence of prolonged periods with no sunspots is important to climate studies, since the Maunder Minimum was shown to correspond with the reduced average global temperatures on the Earth (*4*).

In 1990, a time of maximum sunspot activity in cycle 22 , S. Solanki and his students from Zurich, took advantage of new IR capability at the now McMath-Pierce Solar Telescope on Kitt Peak. They made observations of sunspots with the main spectrograph and a single element detector measuring the Fe λ1564.8 nm line (*5*). Mapping magnetic fields was their objective, but the observed spectral region also contained OH lines at λ1565.2 and λ1565.3 nm, so the observations were valuable in many ways. These observations continued through the minimum of cycle 22. In 1998 the observing runs were made more systematic by measuring all sunspots visible on the disk during the run, by always setting the spectrograph entrance slit on the darkest position in umbrae and by making a nearly simultaneous observation in the nearby quiet photosphere to allow measurements of the sunspot umbral brightness ratio. The work has continued through cycle 23 up to the present (2005) and the resulting archives now contain the measures of 1077 spots.

The Oslo observers P. Maltby and others (*6*), using a simple pinhole photometer with filters, discovered that umbral brightness varies with the activity cycle. Umbrae brighten from the minimum to maximum of the sunspot cycle. The variation increased with wavelength becoming the greatest somewhat long-ward of 1.5 μm. Their results prompted a detailed study of the data in our archive, which has the advantage of spectral resolution.

In Figure 1 sample spectra from 1991 and 2002 are compared. The lines of interest are Fe 1564.8 nm, which is magnetically split, and OH 1565.3 nm. In 1990 the OH had an average relative central depth of 0.41; in 2005 it was 0.16. Note that all the OH lines show decreasing line depth during this 15 year period. The CN molecule has been shown to be less sensitive to temperature changes inside sunspot umbrae (*7*). The OH lines disappear completely from the spectrum of the quiet solar disk as the molecule is dissociated at the higher temperature (6640K) found there. The changing line depth of all three molecular lines is consistent with an increase in the umbral gas temperature. In particular, by using the observed change in OH line depth relative to sunspot continuum brightness, and by assuming the continuum intensity is simply a black-body source, we compute that the OH line depth change corresponds to a gas temperature change from 4670K in 1990 to 5350K in 2005.

Figure 2 displays OH line depth relative to the continuum for individual spots from 1990-2005. For these OH line studies a subset (472 spots) of the entire dataset is selected by choosing spots with a maximum field strength greater than 2400G. Unlike Maltby's finding, there is no evident cycle modulation. A linear least-square fit gives a slope showing a time change equal to -.014 ± .0014 per year in the depth of the line. To enquire if the spot selection during the cycle 22 observations (where the largest spots on the disk were observed) was a factor, we fit the OH line depth for spots only with fields greater than 3000 G (in order to sample both cycles in the same way). The linear slope found from this subset of 58 spots is identical to the larger subset within the error, and this continuity between the early 1990-93 data and more recent data suggests there is no selection bias.

Sunspot umbral magnetic fields also show systematic temporal changes during the observing period as demonstrated by the sample spectra in Figure 1. The infrared Fe 1564.8 nm is a favorable field diagnostic since the line strength changes less than a factor of two between the photosphere and spot umbra and the magnetic Zeeman splitting is fully resolved for all sunspot umbrae. In a histogram plot of the distribution of the umbral magnetic fields that we observe, 1500 Gauss is the smallest value measured. Below this value photospheric magnetic fields do not produce perceptible darkening. Figure 3 presents the magnetic fields smoothed by a 12 point running mean from 1998 to 2005. The ordinate is chosen so that 1500 G is the minimum. A linear fit to the changing magnetic field produces a slope of 77 Gauss per year, and intercepts the abscissa at 2015. *If the present trend continues, this date is when sunspots will disappear from the solar surface*.

During our cycle 23 observations, measurements of the sunspot umbral continuum brightness ratio were taken by comparing with spectra of the nearby photosphere. To these values we apply a 12 point mean, and fit the data with a linear function. Figure 4 shows the fit and the smoothed data. The ordinate maximum is chosen to be 1.0 since this is where the spot brightness equals the quiet disk and spots become invisible. The linear intercept is 2014, only a year different from the magnetic prediction. As with the fits to the magnetic data, the fit results were not sensitive to the choice of binning as one-year bins produced the same fit coefficients.

From the work of Kopp and Rabin (*8*) and others there is a relationship within individual sunspots between the magnetic field strength and the plasma temperature, following from the pressure balance required to maintain a sunspot structure. The temporal changes that we observe over this 15 year period do not violate the relationships that are observed within single sunspots. So as the mean magnetic field strengths in sunspots are observed to weaken, the temperatures are observed to change in the expected manner. The same holds true for the observed changes in the OH line depths and continuum temperature. So it appears that the physics operating within sunspots is not changing, rather that sunspots with different magnetic field strengths are being formed on the Sun. We are not aware of any satisfactory physical basis for this change. Interesting recent work by Norton and Gilman (*9*) show that sunspot brightness is tied to the Sun's internal toroidal field. Unfortunately their model is coupled to the 11 year cycle and has the spots darkening with time, but certainly the temporal changes observed in our data hold important clues to the mechanisms at work in the solar magnetic dynamo. Finally, observations of this type during the onset of the next sunspot cycle will be critical in determining if the observed trends continue.

References and Notes

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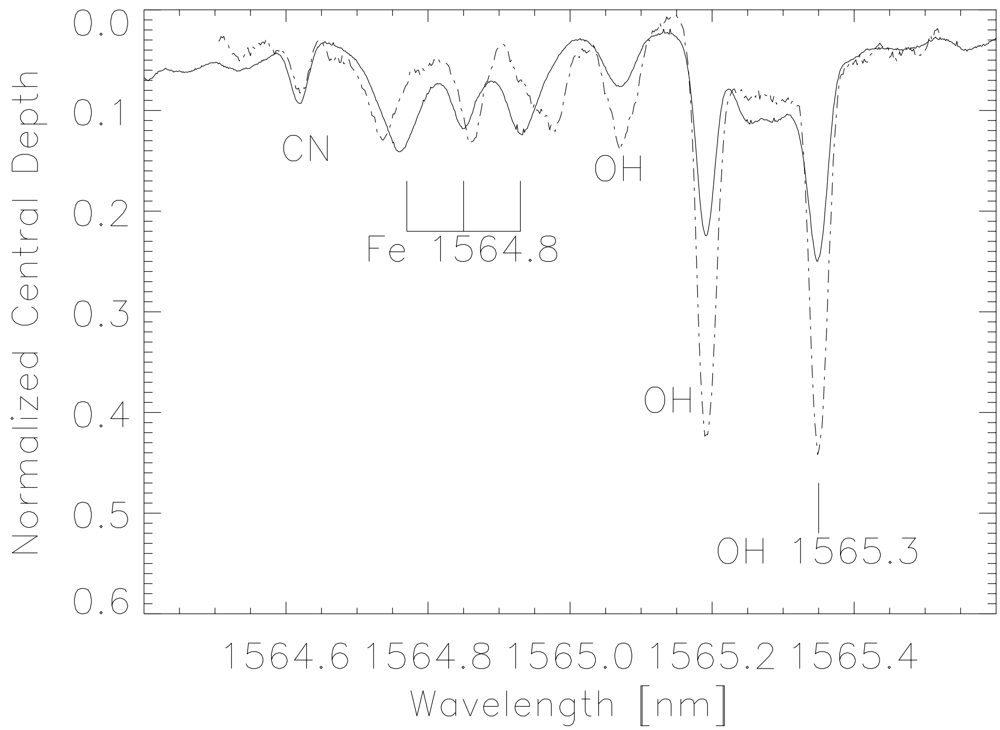

Figure – 1. Sample sunspot spectra from the data set. The dashed line is from a sunspot observed in June 1991, and the solid line was observed in January 2002. These provide examples of the trends seen in the data, where the OH molecular lines decrease in strength over time, and the magnetic splitting of the Fe line decreases over time. A magnetic splitting pattern for the January 2002 Fe line of 2466 Gauss is shown, while the June 1991 spectrum shows splitting from a 3183 Gauss field.

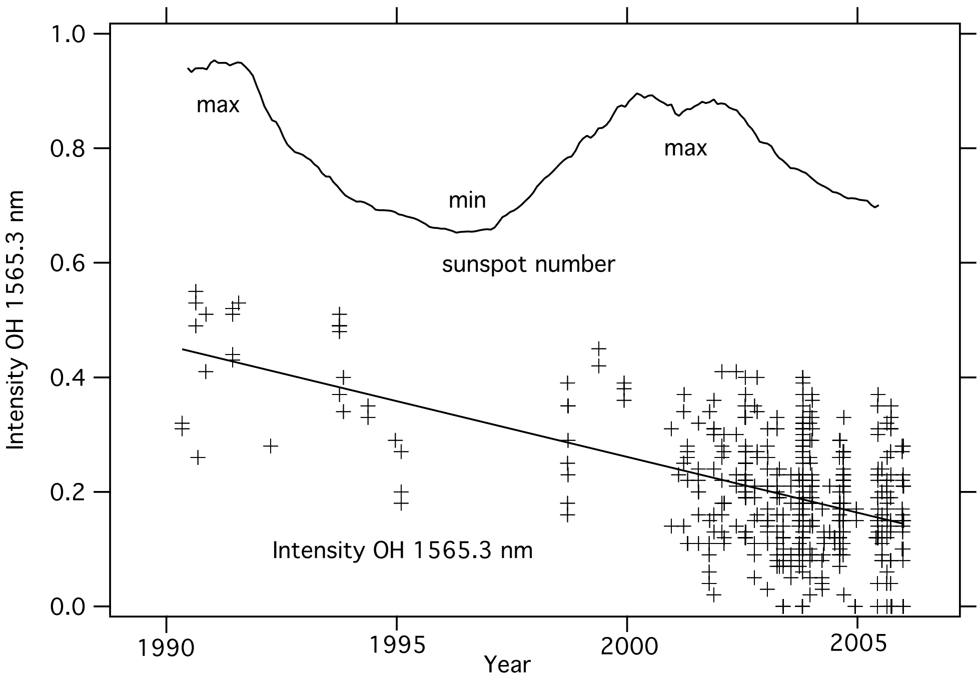

Figure 2. – The line depth of OH 1565.3 nm for individual spots. The upper trace is the smoothed sunspot number showing the past and current sunspot cycles; the OH line depth change seems to smoothly decrease independently of the sunspot cycle.

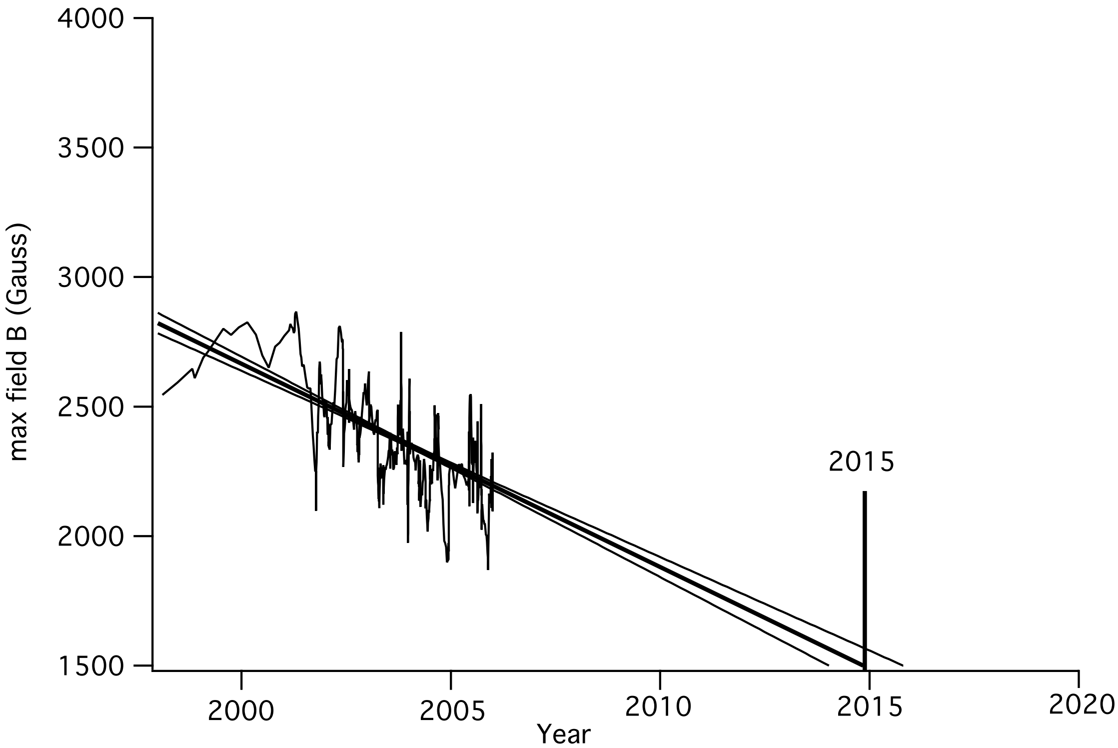

Figure 3. – A linear fit to observed magnetic fields extrapolated to the minimum value observed for umbral magnetic fields; below a field strength of 1500G as measured with the Fe I 1564.8nm line no photospheric darkening is observed.

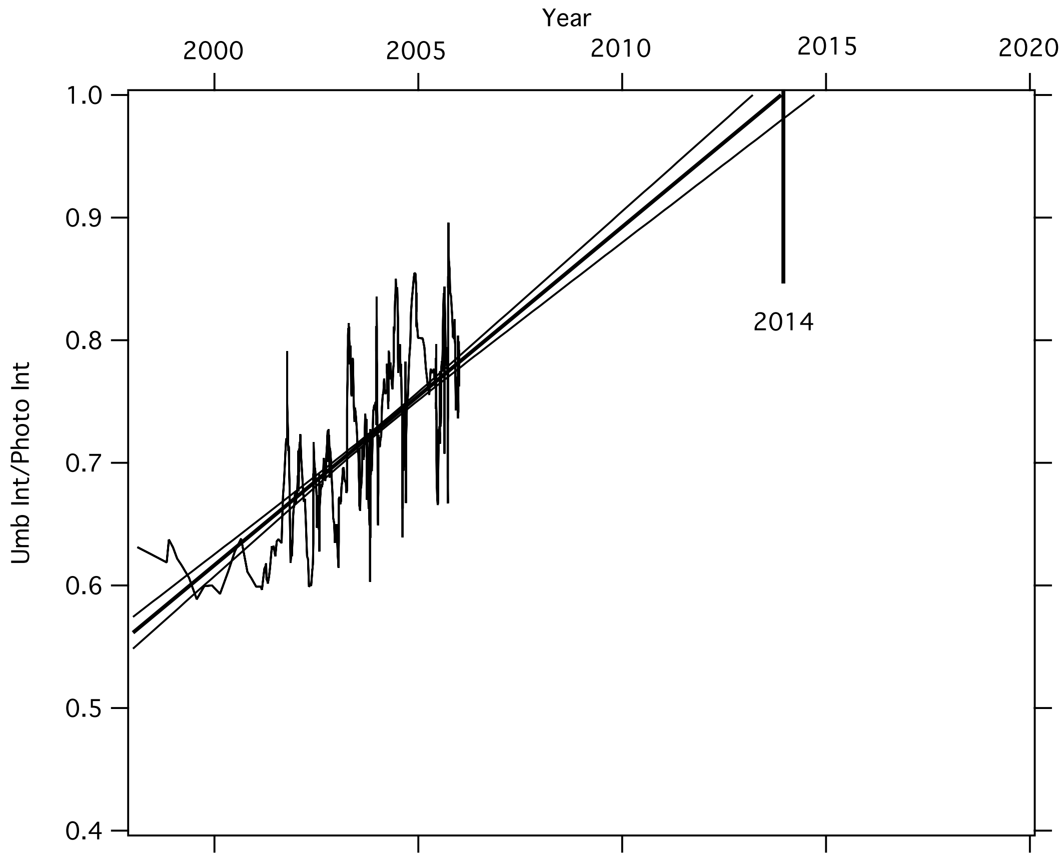

Figure 4 – A linear fit to the observed umbral contrast values, extrapolated to show that by 2014 the average umbrae would have the same brightness as the quiet Sun.