

## Molecule Formation and Magnetic Field Evolution in Sunspots

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**Abstract.** In a sunspot the magnetic field provides horizontal support to keep the warm, high pressure photosphere from intruding into the cool, low pressure sunspot atmosphere. In the very coolest regions of the umbra a rapid increase in magnetic field strength relative to temperature has been observed by many authors although its origins have remained unknown. In these regions the magnetic and gas pressure forces have found a different state which the current simplified theory of magnetohydrostatic equilibrium cannot quantitatively describe. It is well known that molecules form in sunspots. The formation of a large molecular fraction would alter the physical characteristic of the gas, providing a mechanism for concentrating the umbral magnetic field. The formation of molecules may be responsible for the observed rapid increase of the magnetic field strength observed in the coolest regions of the sunspots and may play a significant role in sunspot evolution. We investigate this problem with atmospheric models and present preliminary results from observations taken with the new Facility Infrared Spectropolarimeter on the Dunn Solar Telescope.

### 1. Introduction

Stable sunspots in non-flaring active regions can be considered to be in a magnetohydrostatic (MHS) equilibrium state. The magnetic field in a sunspot provides the horizontal support against the gas pressure of the hotter quiet sun photosphere. This implies a relation between the sunspot magnetic field and the interior and exterior gas pressures. For a sunspot with circular symmetry the equation of MHS equilibrium gives the following:

$$n_{qs}kT_{qs} - n_s kT_s(r) = \frac{1}{8\pi}(B_z^2(r) + F_c(r)) \quad (1)$$

where  $n_{qs}$  and  $n_s$  are the number densities of the gas in the quiet sun and in the spot, respectively.  $T_{qs}$  is the gas temperature in the quiet sun, and  $k$  is Boltzmann's constant. The radially dependent terms are  $T_s$ , the gas temperature in the sunspot;  $B_z$ , the vertical component of the magnetic field; and  $F_c$ , the magnetic tension or curvature force which is given by:

$$F_c(r) = \int_r^a B_z(r') \frac{\partial B_r(r')}{\partial z} dr' \quad (2)$$

where  $a$  is the maximum extent of the sunspot. In the first order approximation  $n_{qs}$  and  $n_s$  are assumed to be equal, the umbra magnetic field is mostly vertical so the curvature term  $F_c(r)$  can be neglected, and Equation 1 can be simplified to  $B^2 \propto T$ .

Many authors have investigated this linear relation between magnetic field pressure and temperature using spectropolarimetric measurements of magnetically sensitive photospheric lines. Early results were found to be at odds. Martínez Pillet & Vázquez (1993) showed a linear relation between  $B^2$  and  $T$ , while Kopp & Rabin (1993) found a clear three segment curve. Modern spectropolarimeters and inversion techniques have made this kind of measurement quite routine and it is obvious from more recent results that  $B^2$  is not a simple linear function of  $T$  (Gurman & House 1981; Balthasar & Schmidt 1993; Lites et al. 1993; Solanki et al. 1993; Stanchfield et al. 1997; Westendorp Plaza et al. 2001; Livingston 2002; Penn et al. 2002, 2003a,b; Mathew et al. 2004). It has been found that for larger sunspots the magnetic field in the very coolest regions of the umbra rises over the temperature more rapidly compared to other regions of the umbra. The mechanism for this intensification of  $B$  has not yet been established.

It is well known that molecules form in sunspots. In regions which are cool enough, free atoms can begin to combine into molecules, decreasing the number density and therefore the gas pressure as well. If the gas pressure decreases the sunspot will lose internal pressure support, and it must shrink a little, concentrating the magnetic field until equilibrium can be regained. If the magnetic field increases the convective energy transport will be further suppressed, resulting in additional cooling and the formation of more molecules. This runaway process would result in a steeper relation between  $B^2$  and  $T$  in regions where molecules are forming.

Atmospheric models of the sunspot umbra predict a molecular hydrogen population of up to 10%, peaking near the height of continuum formation (Maltby et al. 1986). Such a large molecular fraction will alter sunspot evolution and other consequences for sunspot physics are readily apparent. Molecules have internal degrees of freedom that do not contribute to the thermal signature of the gas. Because they have the ability to hide additional energy in rotational and vibrational modes they increase the heat capacity of sunspot atmosphere and may have an important effect on the local radiative output of the Sun. Therefore molecules are of critical importance to sunspot physics. To investigate the possible influence of molecule formation in sunspot umbrae we have been conducting a survey of sunspots of different sizes and at different stages of evolution to obtain a statistical sample. We present the preliminary results of this survey and essential atmospheric modeling in order to investigate the effect of the formation of  $H_2$  on the non-linear relationship between  $B^2$  and  $T$ .

## 2. Observations

This survey requires detailed characterization of the distribution of the vector magnetic field, temperature, and  $H_2$  abundance for every sunspot observed. Maps of the magnetic field and temperature derived from continuum intensity can be obtained from full-Stokes vector polarimetry of photospheric lines with high magnetic sensitivity (i.e. with large Landé  $g$ ) such as the Fe I 630.2 nm  $g=2.5$  or Fe I 1564.85 nm  $g=3$  lines. Direct measurement of the  $H_2$  abundance using the ro-vibrational transitions at near-IR wavelengths lies beyond the grasp of existing instruments. Florescent lines of  $H_2$  at wavelengths from 120 to 160 nm were observed initially from balloon-borne UV spectrographs (Jordan et al. 1978) and more recently with SUMER (Innes 2008), which

unfortunately is no longer in service. Nevertheless, with proper calibration the  $\text{H}_2$  abundance can be determined from more easily observed molecular species. Because of their similar dissociation energy the OH molecule is a very good proxy for  $\text{H}_2$  ( $\text{H}_2$ : 4.48 eV, OH: 4.39 eV). It also has strong lines conveniently located near the 1565 nm Fe I lines. We use the measurement of these lines to infer the  $\text{H}_2$  abundance in this study.

For each sunspot in this survey we have obtained spectropolarimetric observations of the Fe I 1564.85 nm  $g=3$  and Fe I 1565.29 nm  $g=1.67$  lines in the infrared. This bandpass includes a blend of two OH lines at 1565.08 nm and two lines on either side of the Fe I  $g=1.67$  line at 1565.19 and 1565.37 nm. Observations were taken with the Horizontal Spectrograph (HSG) (2001-2005) and during and after the commissioning of the new Facility Infrared Spectropolarimeter (FIRS) (2007-2010) on the Dunn Solar Telescope at the National Solar Observatory at Sacramento Peak, NM.

The HSG setup and data reduction techniques were the same as those used in Lin et al. (1998); Lin (1995). FIRS is a dual-beam spectropolarimeter in an off-axis Littrow configuration. Diffraction-limited performance is achieved using the High Order Adaptive Optics (HOAO) system (Rimmele et al. 2004). To improve system efficiency FIRS makes observations of four slit positions simultaneously at two wavelengths, 630.2 and 1083 nm or 630.2 and 1565 nm, using separate visible and infrared optics and detectors. A more detailed description of the instrument can be found in Jaeggli et al. (forthcoming). The FIRS spectra were reduced using the FIRS IDL reduction script which corrects for the detector non-linearity, subtracts darks, and demodulates the raw images to retrieve the Stokes vector. A flat field is applied to Stokes I to remove intensity variations due to the detector, slit, and narrow-band filter. The spectra from each slit are corrected for spectrograph curvature and drift, the orthogonally polarized beams are combined, and the spectra are stacked into a data cube in the proper order. The Stokes Q, U and V spectra are corrected for polarization cross-talk using the method of Kuhn et al. (1994). The reduced IR data were analyzed using a Milne-Eddington inversion code to retrieve the magnetic field vectors. A list of selected observations from HSG and FIRS is given in Table 1. The spots are ordered by maximum magnetic field strength in the sunspot umbra.

### 3. Model Atmospheres

Direct measurement of  $\text{H}_2$  is impossible with currently available instruments. Therefore, it is necessary to generate the diagnostics between  $\text{H}_2$  and the proxy measurement of the OH lines using spectra synthesized from model atmospheres. These models are also useful for conversion between the observed continuum intensity and temperature. We have used the Rybicky-Hummer (RH) radiative transfer and chemical equilibrium code developed by Han Uitenbroek for this calculation. The code was supplied with 1-D plane parallel model atmosphere grids of different effective temperatures with solar gravity and metallicity. We used the Kurucz model atmosphere grids ( $T_{eff}=4000-7000$  K, 250 K steps), and cooler models from the Phoenix model atmosphere grids ( $T_{eff}=2600-3900$  K, 100 K steps) were kindly provided by Peter Hauschildt. The RH code produces a synthetic spectrum of the 1565 nm range including the Fe I and OH lines for each atmospheric model. The logarithmic number densities of  $\text{H}_2$ , OH, CO, and CN molecules as a function of temperature and 1565 nm continuum intensity are shown in Figure 1. The OH abundance linearly tracks the increase of the  $\text{H}_2$  abundance

Table 1. Selected FIRS and HSG Data

No.	Target	Date	Max. B [Gauss]
1	NOAA 10743	2005-03-12	3200
2	NOAA 11035 L	2009-12-17	3200
3	NOAA 11035 F	2009-12-17	3000
4	NOAA 10953	2007-04-30	2900
5	NOAA 9429	2001-04-18	2900
6	NOAA 10999	2008-06-17	2900
7	NOAA 10742	2005-03-12	2800
8	NOAA 11024	2009-07-06	2800
9	NOAA 11072	2010-05-21	2700
10	NOAA 11072	2010-05-23	2600
11	NOAA 11035 F	2009-12-16	2600
12	NOAA 11049	2010-02-17	2600
13	NOAA 11046	2010-02-12	2500
14	Pores	2005-03-10	2400

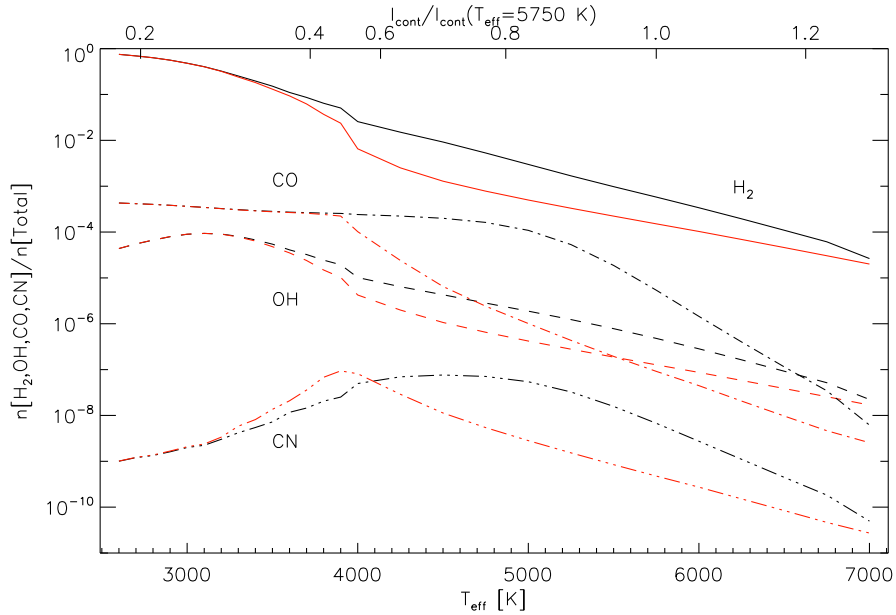


Figure 1. Semi-log plot of the modeled relative number density of  $H_2$ , CO, OH, and CN molecules as a function of effective temperature and 1565 nm continuum intensity.

from about 6500 to 3500 K. Below 3500 K the OH abundance decreases due to competition with CO for atomic oxygen. The equivalent width of the OH 1565.19 nm line ( $EqW_{OH}$ ) is used to infer the  $H_2$  abundance in the observed sunspots. Figure 2 shows the predicted  $EqW_{OH}$  as a function of temperature and continuum intensity, as well as the fractional number density of  $H_2$  in linear scale.

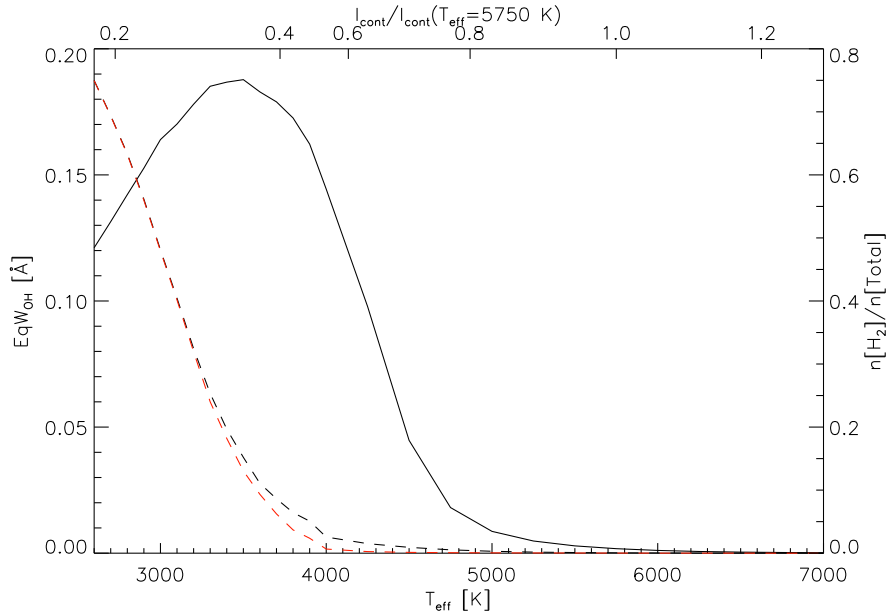


Figure 2. The equivalent width of the 1565.19 nm OH line plotted against continuum intensity and the atmospheric model effective temperature. The H<sub>2</sub> density fraction is included for reference.

#### 4. Discussion

The preliminary results from eight sunspots in the survey are shown in Figures 3 and 4 ordered by their maximum field strengths. The magnetic field pressure ( $B^2$ ) (black and yellow points) and  $\text{EqW}_{\text{OH}}$  (red points) are plotted against the effective temperature determined from the 1565 nm continuum intensity. Umbral (black) and penumbral (yellow) points in the sunspot are selected based on combined intensity and magnetic field thresholds. We calculate the equivalent width from the fit of the OH 1565.19 nm line (red dots). The theoretical  $\text{EqW}_{\text{OH}}$  (black line) and the H<sub>2</sub> number fraction (blue line) are included for reference. In the second panel we show a map of the sunspot's continuum intensity at 1565 nm for reference.

The larger spots in Figure 3 show a clear sharp increase in magnetic pressure against the effective temperature beyond 4500 K, which is also the temperature at which H<sub>2</sub> and OH start to form in significant numbers. These sunspots all have strong OH features and their measured  $\text{EqW}_{\text{OH}}$  approximately follows the theoretical curve. The discrepancy between the observed and predicted  $\text{EqW}_{\text{OH}}$ , in particular for FIRS data (obtained after 2005) may be due to changing scattered light and detector characteristics through different stages of development during the project. The inferred H<sub>2</sub> abundance of the spot with the highest maximum field strength exceeds 2%. For the smaller spots and pores shown in Figure 4 our data suggests that their temperatures were not low enough to allow for the formation of H<sub>2</sub> molecules.

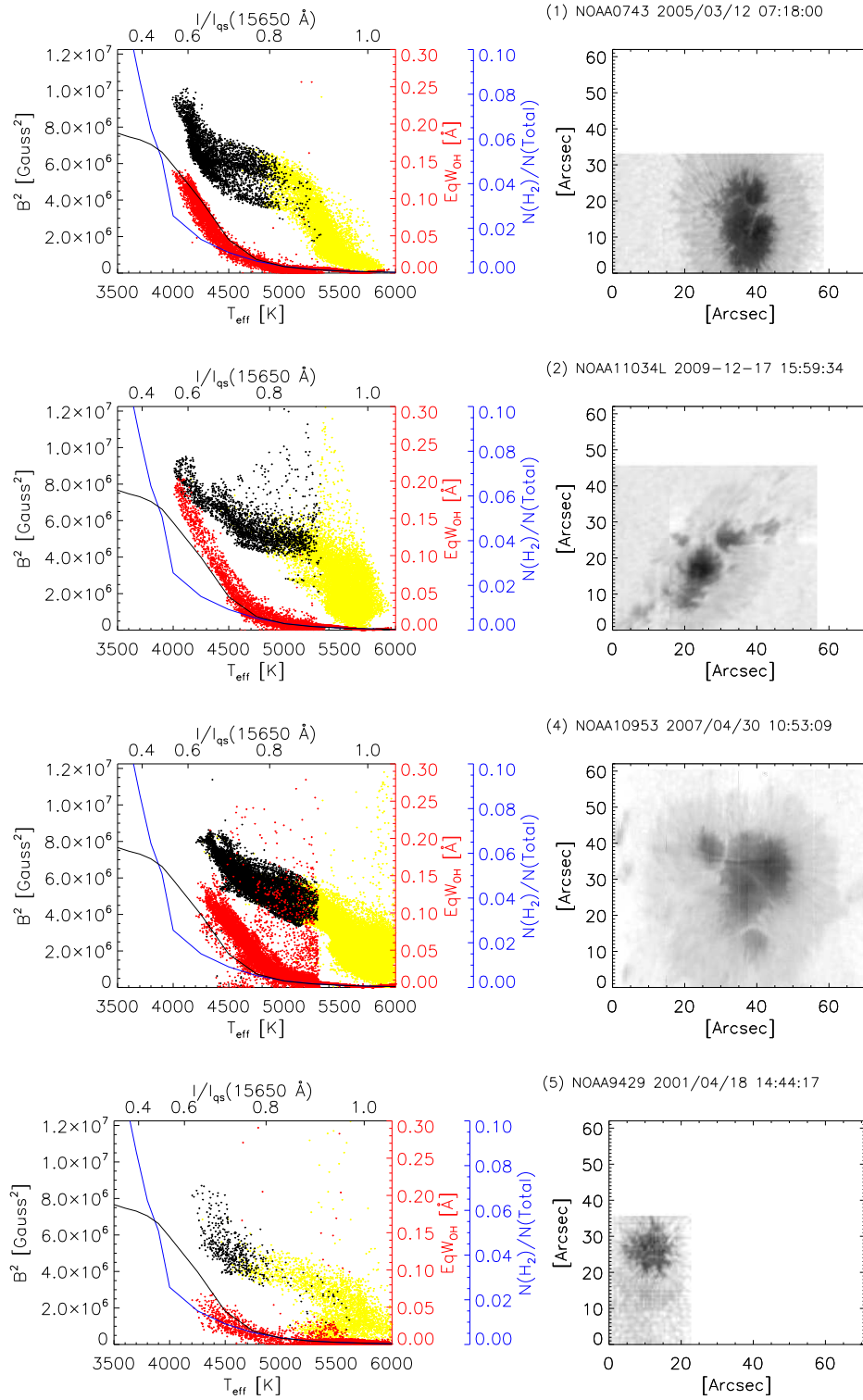


Figure 3. Spots 1, 2, 4, and 5.

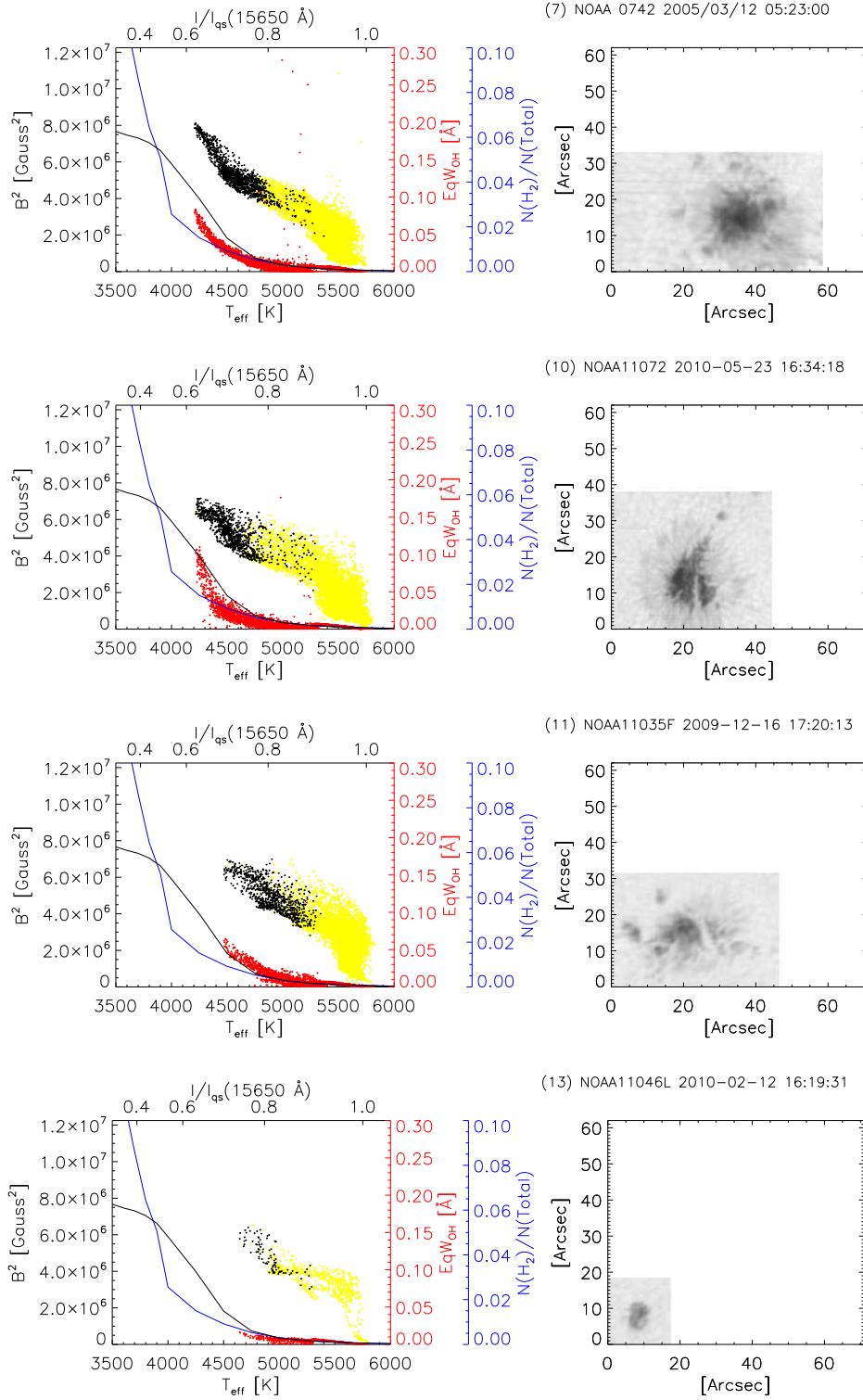


Figure 4. Spots 7, 10, 11, and 13.

## 5. Conclusions

Our survey and preliminary analysis provide observational evidence that significant H<sub>2</sub> molecule formation is present in sunspot umbrae. Measurements of the OH equivalent width are consistent with predictions from atmospheric models and imply a H<sub>2</sub> fraction of a few percent. We suggest that the formation of the H<sub>2</sub> molecules in the sunspot umbrae causes a rapid intensification of the magnetic fields without significant temperature decrease. This can have a stabilization effect of the sunspot core in its formative phase. Consequently, modeling of the MHS equilibrium condition of sunspots in the form of Equation 1 must include a multiple-component atmospheric model with the proper equation of state to account for the variation of the gas density due to the formation of H<sub>2</sub>.

Our sample was obtained sporadically through the minimum phase of solar cycle 23 and does not contain very large sunspots with very high magnetic field strengths. We will continue this observational effort. This will become a very illuminating study when larger sunspots with higher maximum field strengths and darker umbrae start to appear as solar cycle 24 enters its maximum phase.

The FIRS project was funded by the National Science Foundation Major Research Instrument program, grant number ATM-0421582.

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