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How do the magnetic field strengths and intensities of sunspots vary over the solar cycle?

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Abstract. Many efforts have been made to determine if sunspot umbrae continuum intensities and magnetic field strengths are different at sunspot maximum than at sunspot minimum. The results are inconsistent, probably due to differences in sample size and analysis methodology. However, five out of six studies reviewed in this paper agree that sunspots are darker and stronger at sunspot maximum than later in the same cycle, i.e. sunspots brighten during the declining phase of the sunspot cycle. The trend during the rising phase is not agreed upon. Better statistics during the rising phase is crucial to determine if umbrae exhibit a cyclical or linear brightness trend over the cycle. We further this work by analyzing the intensities of 179 sunspots observed with the Helioseismic Magnetic Imager (HMI) for the rising phase of Sunspot Cycle 24. We find no significant trend in the brightness of sunspot umbrae in HMI data during Carrington Rotations 2097-2129 in either hemisphere. Future studies should place limits on sunspots included in the data sample, i.e. use only the leading sunspot in a bipolar active region after most of the flux has emerged but prior to sunspot decay, hopefully separating the effects of surface conditions from those of the interior where the magnetic flux is generated.

1. Introduction

The strength of a sunspot cycle can be defined by the number and area of sunspots generated during the cycle. Although the number of sunspots differ greatly from one cycle to the next, indicating an inherent variability in the process that generates sunspots, it has been difficult to identify trends in the average properties of individual sunspots during a sunspot cycle or between successive sunspot cycles. For example, a strong cycle may produce sunspots that are on average stronger, darker and larger than those from a weaker cycle. Within a cycle, we might also expect stronger, larger sunspots to appear more frequently at maximum than during the rising or declining phase of the cycle.

Sunspot umbrae, in particular the dark nuclei that evolve the least during sunspot formation and dissipation [1] may prove to be a diagnostic of the dynamo mechanism. This should be true if the flux formation and eruption process determines the peak magnetic field strength of sunspots. One of the reasons the intensity of sunspots is interesting is that the brightness ratios (BR), the ratio of the continuum intensity in the darkest part of umbra to the average surrounding continuum intensity of the photosphere, is a very good proxy for magnetic field strength.

$$BR = \frac{minimum(I_c\ umbra)}{average(I_c\ photosphere)} \tag{1}$$

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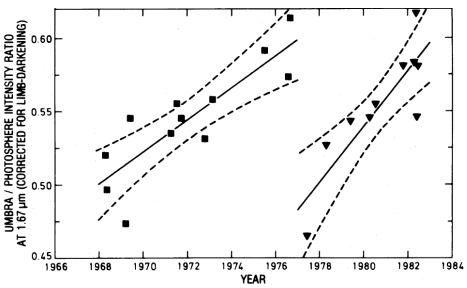

Figure 1. LINEAR FIT: BR of 22 sunspots observed in Cycle 20 & 21 by Maltby *et al* [6].

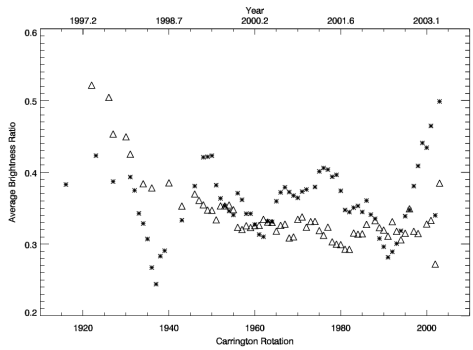

Figure 2. CYCLICAL: Norton & Gilman plot binned BRs of 650 sunspots observed with MDI separated by hemisphere for Cycle 23 [7].

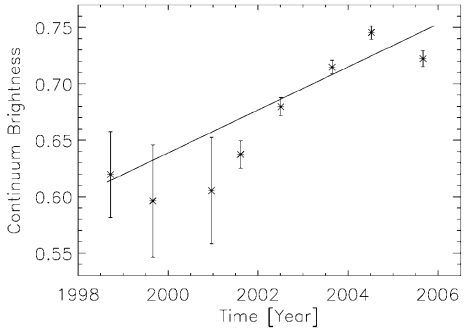

Figure 3. LINEAR FIT: Average annual BRs of over 900 umbrae observed by Penn & Livingston [11] for Cycle 23 with the Fe I 1564.8 nm line at NSO McMath Pierce.

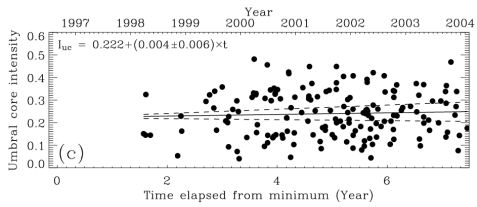

Figure 4. NO TREND: Mathew *et al* [13] studied 160 sunspots from 1998−2004 in Cycle 23 using MDI data.

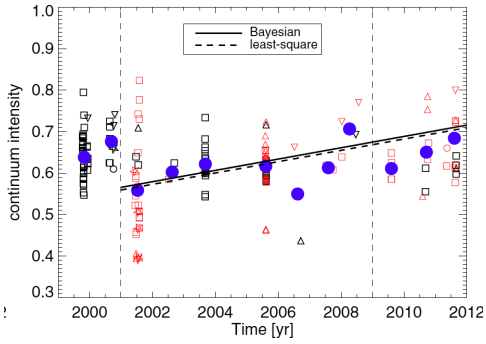

Figure 5. LINEAR FIT: Rezaei *et al*[14] plot the binned BRs from 183 sunspots observed during 1999−2011 (Cycle 23−24) with TIP.

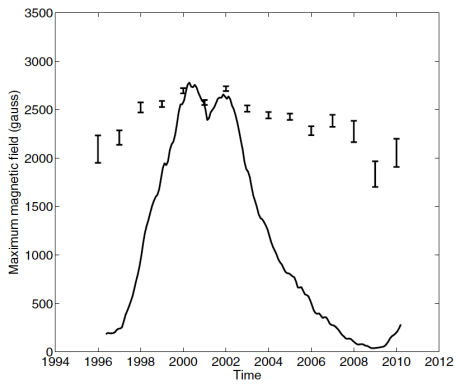

Figure 6. CYCLICAL: Maximum magnetic fields in Cycle 23 from over 30000 umbrae in MDI data as studied by Watson *et al* [17].

The BR is free from many problems experienced in the inversion of Stokes profiles to determine field strength and therefore is useful in inferring field strengths over several solar cycles using

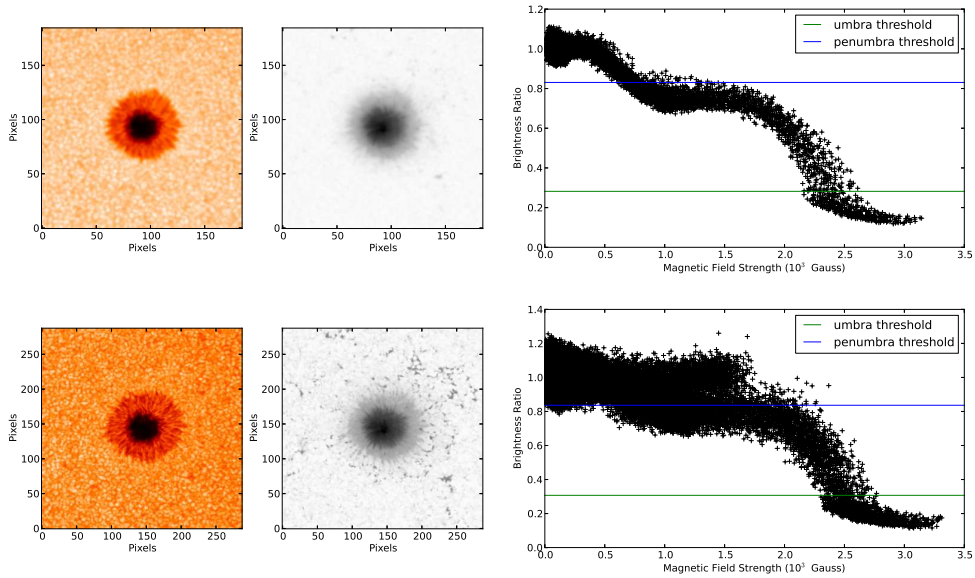

Figure 7. Continuum image (left), Magnetogram (center), and Brightness Ratio vs. Magnetic Field Strength (right) for Active Region 11084, as seen by SDO HMI (top) and Hinode SOT-SP (bottom).

different telescopes with varied spectral lines. The BR does not experience saturation effects due to large wavelength shift from Zeeman splitting or spacecraft velocity [2]. Martínez Pillet & Vázquez [3] studied the distribution of continuum intensity and magnetic field in eight umbrae and demonstrated that the smaller continuum intensities corresponded to larger field strengths. This relationship can be understood in terms of the sunspot response to a horizontal force balance. Stronger umbral magnetic fields (higher magnetic pressure) need less plasma (lower gas pressure) to balance the external forces. The local relationship between temperature and magnetic field in sunspot umbrae dictates that the darker, cooler umbrae contain stronger magnetic fields.

Sunspot cycles are not symmetric in time [4-5]; the cycle rises quickly from sunspot minimum to maximum then declines slowly from maximum to minimum. The Solar International Data Centre (SIDC) monthly smoothed sunpot numbers show Cycle 23 spent 47 months rising (May 1996 - Apr 2000) and 97 months declining (Apr 2000 - Dec 2008). Cycle 22 spent 34 months rising (Sep 1986 - July 1989) and 82 months declining (July 1989 - May 1996). The declining phase is approximately twice as long as the rising phase. Consequently, any trend in sunspot BR field strength is poorly sampled in the rising phase as compared to the declining phase. Perhaps this fact contributed to the difficulty in determining trends in the rising phase of the cycle. A brief literature review of intensity trends observed in sunspots follows.

2. Survey of Six Previous Studies on Umbral Brightness Trends

Maltby *et al.* [6] observed twenty-two sunspots from 1968−1983 including data from sunspot cycles 20−21, see Figure 1. They limited the data sample to large sunspots with the criteria that umbrae radii be $>5''$, and concluded that sunspots become linearly brighter and hotter, corresponding to weaker magnetic fields, throughout an individual sunspot cycle. Mid to late cycle sunspots were modeled as 190 K and 380 Kelvin hotter than early cycle sunspots, respectively. (Early, middle and late sunspots were defined as 0.1, 0.5 and 0.9 percentage of time into the cycle.) A strength of this analysis was that multiple wavelengths were used

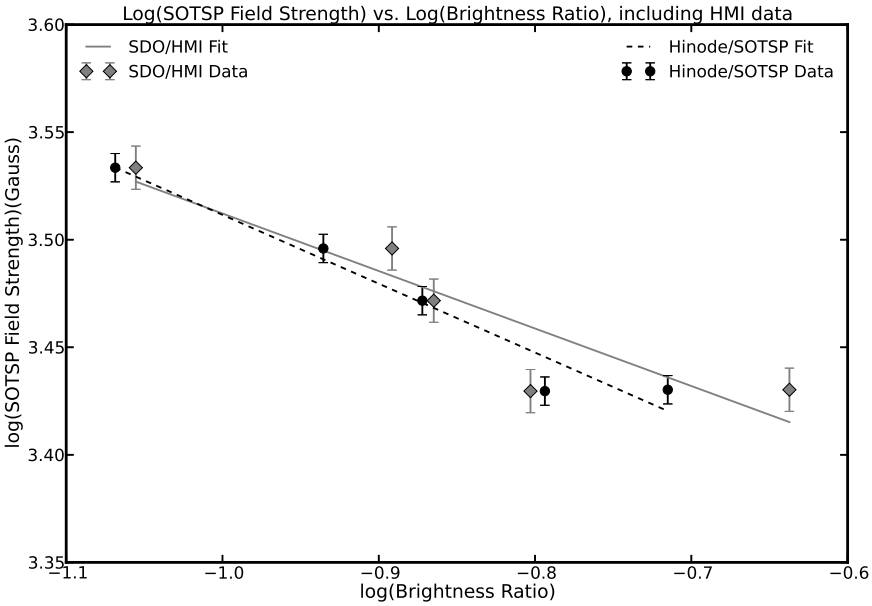

Figure 8. A log plot of SOT-SP field strength versus SOT-SP and HMI brightness ratio, with best-fit lines for each instrument showing extremely good correlation between the two. Error bars represent the standard deviation between the observed magnetic field strength and the value expected from the best-fit of the data. The standard deviation values are 62 and 41 Gauss for HMI and SOT, respectively.

and that the model umbral atmospheres developed from this work are the standard Maltby-E, Maltby-M and Maltby-L models. A weakness is the very small sample size: twenty-two sunspots over sixteen years.

Norton & Gilman [7] studied the sunspot cycle trends from 1998−2003 (Cycle 23) using over 650 sunspots observed with Michelson Doppler Imager (MDI) [8], see Figure 2. MDI BRs were compared to the BRs and field strengths obtained with the Advanced Stokes Polarimeter [9,10] for the same sunspots. Data were separated into N and S hemispheres. A decrease (not linear) in continuum intensity brightness was seen until sunspot maximum in the North, then sunspots began to brighten again. The late declining phase of Cycle 23 was not sampled as their data ended in 2003. A maximum difference of 650 K was found in the N hemisphere. The S hemisphere was disorganized. A weakness of this study was that no scattered light correction was applied.

Penn and Livingston [11] observed over 900 sunspot umbrae from 1998−2005 (Cycle 23) using the Fe I 1564.8 nm line at NSO McMath Pierce Telescope. They find that the maximum sunspot magnetic fields decreased at about 52 Gauss yr^{-1} and that the umbrae became linearly brighter with the normalized umbral intensity changing from 0.60 to 0.75 (corresponding to a rise of 550 Kelvin), see Figure 3. It could be argued that the trend is not linear in as much as it is cyclical with the brightness of spots decreasing until sunspot maximum and then increasing until the minimum that follows. As the rising phase of the sunspot cycle is shorter than the declining phase, the rising phase is not as well sampled. It is the trend of sunspots in the rising phase of the cycle which is controversial. A later study [12] includes data from Cycle 24 and reports the increasing trend in umbrae brightness continuing into Cycle 24 with sunspots in general being brighter and weaker in Cycle 24 as compared to sunspots early in Cycle 23. This results caused

Table 1. Active regions with associated observation dates, HMI and SOT-SP brightness ratios, magnetic field strengths, and μ values.

AR No.	Date	BR_{HMI}	BR_{SOT}	$B_{HMI}(Gauss)$	$B_{SOT}(Gauss)$	μ
11084	20100702	0.13	0.12	2910	3130	0.93
11064	20110301	0.16	0.16	2640	2690	0.71
11066	20110310	0.14	0.13	2680	2960	0.95
11076	20110326	0.23	0.19	2440	2690	0.78
11339	20111106	0.09	0.09	3440	3420	0.82

speculation that sunspots may disappear soon if this trend continues and the Sun enters another grand minimum.

Mathew *et al.* [13] studied 160 sunspots from 1998−2004 (Cycle 23) using MDI data. They reported no trend in umbral brightness, see Figure 4. They limited their data to sunspots with radii between 5−15″ and they corrected for stray light. They found a significant decrease in core brightness with increasing umbral radii. The slight decrease in umbral core intensity in the N hemisphere was attributed to a trend in sunspot radius in time during the cycle.

Rezaei, Beck and Schmidt [14] studied 183 sunspots from 1999−2011 (Cycle 23−24) with Tenerife Infrared Polarimeter [15,16]. They found a trend that sunspots in the late stage of cycle 23 are weaker than those at the start of the cycle, see Figure 5. The decrease in the field strength with time is about 94 Gauss yr^{-1}. In the same time interval, the continuum intensity of the umbra increases linearly with a rate of 1.3% of I_c yr^{-1} from maximum to the following minimum, while the umbral area does not show any trend. Sunspots in the new Cycle 24 show higher field strengths and lower continuum intensities than those at the end of cycle 23, interrupting the trend, and conflicting with [12].

Watson, Fletcher & Marshall [17] analyze over 30000 sunspot observations using MDI and find a cyclical trend that follows sunspot number (not linear) with sunspots having stronger maximum magnetic fields at sunspot maximum and weaker fields at sunspot minimum, see Figure 6. They focus on distribution of the sunspots, area and yearly average of maximum umbral strength. Unfortunately, they do not report on intensity or BR changes.

Why may there be a trend in umbral brightness during a sunspot cycle? Yoshimura [18] postulated that "the depths of the roots of the flux ropes decreases in time." Flux ropes rising from greater depths early in the cycle may be darker than those rising from shallower depths later. Alternatively, the surface or near-surface processes in which emerging flux coalesces into sunspot umbrae could vary with the solar cycle and emergent latitudes. For example, rates of mass removal from entrained U-loops may vary [19]. There could be a stronger convergence flow at depths below sunspots in the mid-latitudes of the sunspot belts resulting in the coalescence of more magnetic flux in the middle of the cycle. Another possibility is that there could simply be more flux or stronger flux emerging at sunspot maximum.

3. Sunspot Brightness of Cycle 24 Rising Phase Observed by HMI

We wish to contribute to the discussion of umbral brightness trend by studying the sunspots of Cycle 24 during the rising phase using HMI data. HMI is a filter-based instrument observing Stokes I, Q, U and V at six wavelength positions across the 6173 Å Fe-I line with 76 mÅ filter space sampling [20,21]. The HMI pipeline uses a Milne-Eddington inversion code named the Very Fast Inversion of the Stokes Vector (VFISV) [22,23] to detexcrmine the solar atmospheric parameters based on Stokes observations.

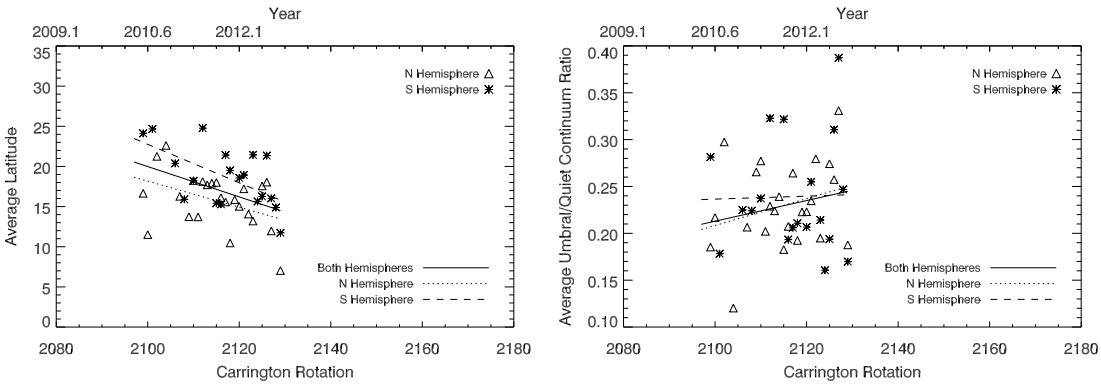

Figure 9. (Left) Cycle 24 sunspot latitude (left) and BR (right) as a function of time as observed by HMI. The data are separated into N and S hemispheric data and average of each CR are plotted. There is no smoothing. Some CRs did not have any sunspots and hence do not have a data point. The N and S hemispheric and total-Sun data are fit with a linear regression and overplotted as lines. The linear fits to the latitude data (left) have greater than a 3σ confidence level. The linear fits to the BR data (right) are not significant at even a 2σ level.

Norton et al. [7] used the Advanced Stokes Polarimeter (ASP) to verify that MDI BR data could be used to infer field strengths. In a similar manner, we use the Hinode Solar Optical Telescope Spectropolarimeter (SOT-SP), which uses a slit and a diffraction grating to sample Stokes I, Q, U and V with a 21.5 mÅ spectral resolution in the 6301.5 and 6302.5 Å Fe-I line pair, to verify that HMI BR data can be used to infer field strengths. We chose the active region NOAA 11804 to begin our analysis, as it was observed by Hinode SOT-SP and HMI on 2 Jul 2010 on 5:12:00 UT. HMI continuum and magnetic field strength products of VSIFV were obtained from Joint Science Operations Center (JSOC) at Stanford University for this date and time, while Hinode SOT-SP continuum and level2 MERLIN [24,25] magnetic field strength products were obtained from the Community Spectro-polarimetric Analysis Center (CSAC) hosted by HAO NCAR.

In Figure 7, the Active Region 11084 continuum intensity and field strength are shown as context plots as well as the scatter plot of intensity versus magnetic field strength as observed by Hinode SOT-SP and HMI respectively. Due to the difference in resolution between SOT-SP and HMI, data from SOT-SP was binned 2×2 and then interpolated to have the same resolution as HMI of $0.5''$. Much of the difference between Hinode SOT-SP results and HMI results are due to the fact that the HMI VFISV inversion code assumes the filling fraction of the pixel is one, meaning that all the plasma sampled within the pixel is magnetized and contributing to the Stokes polarization. No scattered light corrections are applied at this time since the appropriate point-spread function is still being developed.

To determine how well Hinode SOT-SP and HMI correlate, we calculate the BRs and peak magnetic field strengths of several simultaneously observed active regions. Thresholding in continuum intensity was used to determine the umbra in each region. Then the darkest pixel in the umbral continuum intensity was selected and the associated field strength recorded. Table 1 lists each active region, observation date, BR, peak magnetic field strength, and μ for SOT-SP and HMI. The uncertainties of the BR values are small. For example, active region 11804 was observed over a seven hour period with BRs determined at five equal time intervals, providing a mean BR of 0.128 ± 0.004, where the uncertainty is the standard deviation of the five measurements.

Figure 8 is a log plot of the umbral peak magnetic field strengths versus BRs for 5 sunspots

simultaneously observed in 2010-2012, with linear fits to HMI and SOT-SP BR data. In this plot, all field strengths are determined by Hinode SOT. We do not use HMI magnetic field data because the HMI algorithm can become saturated in the strongest part of the umbrae depending upon the spacecraft velocity [2]. Error bars are determined using the standard deviation between the observed magnetic field strength and the value expected from the best linear fit to the data. The standard deviation values are 62 and 41 Gauss for HMI and SOT, respectively. This is higher than the error determined for the BR of 11804 observed over the seven hour time period as reported above; the BR of 0.128 ± 0.004 is equivalent to a field strength of 3045 ± 25 Gauss when using the fit to the HMI BR to determine field strength. The large range of μ values for data shown in Figure 8, $0.71 - 0.95$, is not ideal, but was necessary to compare simultaneous data from SOT-SP and HMI.

For our analysis of BR trends observed with HMI, we use a continuum intensity Carrington rotation map from HMI that samples sunspots as they cross the central meridian. Thirty-three Carrington rotation maps are sampled, from CR 2097 - 2129. As most sunspots appear within 30° of the equator, BR data are in general determined from $cos(\theta) = 0.87$ or greater. Specifically, 90% of the sunspots have $\mu \geq 0.90$ with only 11 sunspots having $\mu < 0.90$. The HMI synoptic continuum intensity data is determined from observations taken every 720 seconds and a fifth order polynomial in $log(\mu)$ is used to remove limb-darkening. These maps are normalized so that faculae have values above 1.0 and the entire range of the data is from $0.3 - 1.2$.

For Figure 9, Carrington rotation synoptic intensity maps from HMI are used, corrected for limb darkening and flat fielded, but stray light has not been removed yet. Sunspots are hand-selected and include 179 sunspots in total with 101 (78) in the N (S) hemisphere, respectively. Their latitude, BR and peak field strength is recorded. The average latitudes and BRs of umbrae are plotted as a function of time for each hemisphere. We assume that Cycle 24 began in 2009 in CR 2083 and have adjusted the origin of the plot accordingly. We calculate a mean for all data in each CR. The left panel of Figure 9 shows the well-documented migration of the sunspot latitudes toward the equator. The right panel of Figure 9 plots the average BR for each CR that sunspots were present in the separate hemispheres. The linear fit to the BR data was not signifcant at the 2σ level for either the N and S hemisphere or the total-Sun average. We argue that there is always a need to separate data into N and S hemispheres in order to not blur mechanics that are operating slightly out-of-phase with each other.

4. Conclusions

A consensus is forming that sunspots are darker and stronger at sunspot maximum than at sunspot minimum. The observed intensity difference could represent a change of 300-600 Kelvin in average umbral temperatures. There are conflicting results, though, for the overall trend during the cycle since the trend during the rising phase is not agreed upon. The underlying question is whether there is

- a linear increase in brightness from the start of the cycle until the end,
- a cyclical change where brightness decreases in the rising phase until maximum, then increases again until the following minimum, or
- no significant change whatsoever.

The rising phase of the sunspot cycle is not as well-sampled as the declining phase; it is shorter and produces less sunspots. If the brightness of umbrae decrease during the rising phase, then the trend will be cyclical, as reported by [7, 17] and seen in Figures 2 and 6. Alternatively, if the umbrae in the rising phase increase in brightness on average, then the results of [6, 11, 14] will be confirmed as seen in Figures 1, 3 and 5. Another option is that after careful correction of stray light, no trend may be present as reported by [13] and seen in Figure 4. Understanding

the behavior of umbral brightness of field strengths during the rising phase of the sunspot cycle is key.

We find no significant intensity trend in either hemisphere in the HMI BR data for the rising phase of Cycle 24, as can be seen in the right panel of Figure 9, thereby confirming the results of [13]. If a linear fit is forced to the data, the total Sun and N hemisphere show an increasing brightness trend but the p-value for the linear regression is 0.19 and 0.20 respectively, much higher than the p=0.05 expected for a 3σ detection. Therefore, we must conclude that no trend is detected for BRs in HMI data. We need, however, to carefully apply a stray light correction to HMI data and re-evaluate the umbral brightness trends.

We stress that it is very important to separate the hemispheric data since the sunspot cycles may be out of phase and have slightly different amplitudes in the two hemispheres. Future studies should place limits on sunspots included in the data sample, i.e. separate the leading and following sunspot populations in bipolar active regions after most of the flux has emerged but prior to sunspot decay, hopefully separating the effects of surface conditions from those of the interior where the magnetic flux is generated. The leading and following sunspot asymmetry may be worth studying as a function of solar cycle to ascertain changes in the flux emergence process. Future studies could also determine if similar umbral trends are observed in BR, mean umbral strength, or parameters fit to the umbral distribution of strengths. The relationship between umbral radius (size) and BR is controversial. We argue that the mechanism which determines the maximum field strength of an umbra may be the same mechanism that determines the umbral size. Therefore, even if a clear relationship between radius and maximum umbral field strength were established, the trend during a sunspot cycle would still be interesting.

Comparing Cycle 23 to Cycle 24, we find the peak umbral field strength based on BRs was 2660 (MDI) [7] and 2690 Gauss (HMI) at a time of forty CRs (3 years) into each cycle. The average umbral latitude at a time of 40 CR into the cycle is 22° and 17° for Cycle 23 and 24 respectively. We do not observe a decrease in the peak field strengths of sunspots between Cycle 23 and 24.

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