UMBRAL DYNAMICS IN THE NEAR-INFRARED CONTINUUM

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ABSTRACT

We detected peaks of oscillatory power at 3 and \( \sim 6.5 \) minutes in the umbra of the central sunspot of the active region NOAA AR 10707 in data obtained in the near-infrared (NIR) continuum at 1565.7 nm. The NIR data set captured umbral dynamics around 50 km below the \( \tau_{500} = 1 \) level. The umbra does not oscillate as a whole, but rather in distinct parts that are distributed over the umbral surface. The most powerful oscillations, close to a period of \( \sim 6.5 \), do not propagate upward. We noted a plethora of large umbral dots (UDs) that persisted for \( \geq 30 \) minutes and stayed in the same locations. The peaks of oscillatory power above the detected UDs are located at 3 and 5 minute oscillations, but are very weak in comparison with the oscillations of \( \sim 6.5 \) minutes.

Key words: sunspots – Sun: oscillations

1. INTRODUCTION

The umbra, the darkest part of a sunspot, has complex dynamics. The umbral oscillations, part of the umbral dynamics, have been the subject of many research studies. At chromospheric levels, researchers have observed velocity oscillations with periods close to 3 minutes and velocity amplitudes of about 6 km s\(^{-1}\) (Balthasar & Wiehr 1984; Soltau & Wiehr 1984; Tsiroupolia et al. 2000). At the photospheric level, umbral oscillations have periods closer to 5 minutes, with velocity amplitudes of about 75 m s\(^{-1}\) (Lites 1992).

From a theoretical standpoint, there are two postulated mechanisms for the generation of umbral oscillations. One is that they are generated on sub-photospheric levels by a common extended source (Rouppe van der Voort et al. 2003; Bogdan & Judge 2006) and propagate upward along the magnetic field lines (López Arístre et al. 2001). The other postulate suggests that umbral oscillations are generated when slow mode waves are trapped within a cavity in the umbra’s chromosphere. Broadband acoustic noise from the convection zone excites the trapped waves (Zhugzhda et al. 1983). Lites (1986) found that the 5 minute photospheric oscillations do not drive the 3 minute chromospheric umbral oscillations.

The umbra does not oscillate as the whole, but in distinct areas within the umbra (Socas-Navarro et al. 2009). Socas-Navarro et al. (2009) noted that the umbra is tremendously dynamic and requires a time cadence faster than 20 s to resolve the apparent motions of the emission source.

Umbral dots (UDs), small-scale structures distributed across the umbra, are part of umbral dynamics. Schüssler & Vögler (2006) showed that the appearance of UDs is a natural consequence of magnetoverconvection under the influence of a strong magnetic field. This was confirmed by Cheung et al. (2010) and Bharti et al. (2010). Heinemann et al. (2007) stated that UDs are caused by overturning convection.

Balthasar & Wiehr (1984) stated that the lifetime of UDs is on the order of 20 minutes. Rimmele (2008), Riehmüller et al. (2008), and Ortiz et al. (2010) observed the signature of UDs dynamics, as described by the model of Schüssler & Vögler (2006). Rimmele (2008) noted that UDs have a lifetime close to 30 minutes, as predicted by the model of Schüssler & Vögler (2006). Bharti et al. (2010) similarly predicted that the average UDU’s lifetime is between 25 and 28 minutes. On the other hand, Hamedivafa (2008) stated that the average lifetime of the UDs is between 7 and 10 minutes, while Watanabe et al. (2009) measured the average lifetime as 7.3 minutes.

Socas-Navarro et al. (2009) detected a movement of the bright umbral elements. They registered horizontal propagation speeds of 30 km s\(^{-1}\) and stated that their cadence of 20 s is not enough to resolve the fast lateral motion of the oscillatory sources in the umbra.

In this work, we present observations of UDs and umbral oscillations at a level of 50 km below the \( \tau_{500} = 1 \). The NIR continuum provides easier seeing correction with adaptive optics (AOs), and much lower scattered light, both instrumental and atmospheric. Hence we were able to observe structures near the telescope’s diffraction limit for this wavelength even without image reconstruction.

2. OBSERVATIONS AND DATA ANALYSIS

High-resolution photometric observations of the solar active region NOAA AR10707 were obtained simultaneously in the G band and the near-infrared (NIR) continuum near 1.6 \( \mu m \) with the Dunn Solar Telescope (DST) at the National Solar Observatory/Sacramento Peak on 2004 December 1. Benefiting from a high-order AO system, the spatial resolution was close to the diffraction limit of the 76 cm aperture DST in the NIR continuum, but significantly poorer for the G band.

To probe the deepest layer of the solar atmosphere, exploiting the Sun’s opacity minimum at 1.6 \( \mu m \), NIR photometry was employed, which consists of a tuneable NIR birefringent Lyot filter developed by the Center for Solar-Terrestrial Research/NJIT (Cao et al. 2006), an interference filter with a 5 nm bandpass, and an NIR camera. The Lyot filter has a very narrow bandpass of 0.25 nm and was tuned to the line-free continuum at 1565.7 nm. The NIR camera (Cao et al. 2005) is based on a 1024 \( \times \) 1024 HgCdTe/Al2O3 CMOS focal plane array with a liquid nitrogen cooling system. The pixel size is 18 \( \mu m \times 18 \mu m \). The output signal is digitalized into 14 bits with a dynamic range better than 70 dB.

The field of view was 122" \( \times \) 122" and 105" \( \times \) 105" for the NIR and the G band, respectively. Ten NIR frames were obtained every second, and the best frame was selected. The G-band data set had a cadence of 0.5 s. All images were dark-
flat-field corrected and selected according to the highest root-mean-square (rms) contrast. The observational run started on 16:54 UT and produced data sets 30 minutes long.

To equalize the time cadence of both data sets, we took every second image from the G-band data set, achieving a 1 s cadence. Thus in both data sets we acquired a Nyquist period of 2 s.

The data were co-aligned using a Fourier co-aligning routine, which uses cross-correlation techniques and squared mean absolute deviations to provide sub-pixel co-alignment precision. However, we did not implement sub-pixel image shifting to avoid substantial interpolation errors that sometimes accompany the use of this technique. The reference image for co-aligning routine was the floating mean; we made a mean image for each interval of 30 data images, shifting the interval by one image over the time series. De-stretching of the images was performed to eliminate the influence of seeing distortions. The de-stretching routine uses bilinear interpolation. The reference image for co-aligning the UDs stayed in the same locations (Figure 2).

We observed and analyzed 70 easily resolved UDs. The UDs shift in the horizontal plane was performed with the nonlinear affine velocity estimator (NAVE) method (Chae & Sakurai 2008), which tracked the detected structures through the data set.

The areas surrounding the umbra were masked out with a binary mask. We made an average frame over the time series and normalized it to the maximum. Then, we multiplied all pixels with brightness $\geq 0.75$ by 0 and darker pixels by 1, masking out in such way everything but umbra.

For the phase analysis of the oscillations two methods were applied. One is wavelet phase analysis between NIR and G-band data sets. This phase analysis is similar to the Fourier phase analysis, only it provides time and frequency localization. This localization is provided by the use of wave packets by wavelet analysis instead of the infinite wave train of Fourier analysis. The difference in cyclic phase $\Delta \phi$ can be determined for each frequency component, $v$, using the phase information contained within the complex wavelet transform. The quality of the values is represented by phase coherence. A time series in this work is extracted from the same $(x, y)$ pixel location in both data sets. The signals are separated in the direction normal to the solar surface. Therefore, the phase differences can be interpreted as delays caused by the finite propagation speed of waves traveling between the optical formation heights. The automated method used is described in detail in Bloomfield et al. (2004).

The second method was combining the Fourier and Hilbert transforms on a single data set (White & Cha 1973). In short, the signal is a complex function. The real part is the original signal and imaginary part is the quadrature of the original signal. Since a real function and its quadrature are Hilbert transform pairs, the Hilbert transform converts one into another. The resulting transform describes the amplitude and phase of a variable in complex plane. The signal is transformed into the Fourier space then transformed back using the Hilbert transform (Stebbins & Goode 1987).

The phase angle spectrum is formed in such way that an upward propagating wave has a positive phase angle. The phase angles are presented in a weighted diagram, where weighting is applied per sample by cross-power amplitude $\sqrt{P_1/P_2}$ to produce gray-scale phase, $\Delta \phi$ (Lites & Chipman 1979).

3. RESULTS

The target of our analysis, the umbra of the central spot of AR 10707 (Figure 1(a)), was full of UDs.

We observed and analyzed 70 easily resolved UDs. The UDs were long-lived; 80% of them existed during our entire time series of $\sim$30 minutes. During our time series, those 80% of the UDs stayed in the same locations (Figure 2).

The average size of UDs detected in this data set is 0$''$.86, double the Dawes’ limit for the Dunn telescope in NIR continuum. Since we analyze objects that are close to each other, the Dawes’ resolution limit is appropriate for our data set. All the sizes of the values below Dawes’ limit were ignored.

We analyzed the NIR continuum data set and G-band data set with wavelet analysis. The signal-to-noise ratio (S/N) of our G-band data was poor since the seeing was not good during our observational run. Hence, we used the G-band data only as test data for analysis methods. The data sets were 30 minute long, making the highest credible period in this data set 12 minutes. With the limitation to the period of 12 minutes we avoided the spurious oscillations that rise in the COI due to the finite nature of our time series. To avoid noise induced detections near the Nyquist frequency, we ignored oscillations that did not
contain at least 23 points in a single period. Thus we analyzed oscillations in the period range of 0.75–12 minutes.

The NIR continuum shows two strong peaks of oscillatory power at 3 and ~6.5 minutes (Figure 3, solid line). The G-band data set (Figure 3, dashed line) shows previously reported peaks at 3 and 5 minutes (Balthasar & Wiehr 1984; Lites 1992; Tsiroupolou et al. 2000) but no significant power at ~6.5 minutes.

The oscillations were separately calculated for UDs. The NAVE method also provides, beside the tracking coordinates of the structures, also the intensity changes of the structure throughout the time with the intensity error. We performed wavelet analysis on each of the UDs’ intensity curves to detect the oscillations emitted by UDs (Figure 4(a)). The power curve for the UDs shows a significantly smaller oscillatory power than the power emitted by the whole umbra. The maximum power peak for UD emitted oscillations is at ~1 minute, with a broad peak that covers periods from ~2 to ~3 minutes, finishing with the peak at the ~5 minute period. The registered power is close to the noise level, since the intensity error is ~20% (Figure 4(b)).

The oscillatory curve of NIR continuum shows the power peak at the 3 minute period with another broad peak around 6 minutes. The small peak at 3 minutes most probably represents oscillations emitted by UD. The other, more powerful oscillations registered in the other peak might, in part, originate from a different source. Considering the depth of the spectral line formation layer, we can speculate that the observed oscillations have a close connection to helioseismic oscillations. The spectrum of the helioseismic oscillations arises from modes with periods ranging from about 1.5 minutes to about 20 minutes (Gough & Toomre 1991). The observed oscillatory peak may be a consequence of the plasma conditions and the shape of the cavity below the umbra.

Due to seeing conditions, the G-band data induce too large an error into the phase difference calculations designed to determine if there is wave propagation. The umbra observed in our G-band data set did not show any distinguishing substructures or umbral flashes. We used a combination of the Fourier and Hilbert transforms to obtain the amplitudes and phases of the oscillations on both levels (Figure 5).

At the NIR level, the oscillations with significant power have a phase of 0°. The range of the phase angle for all registered oscillations is from −0.29 to 0°. From this range, 89% of pixels in the umbra have 0° phase, i.e., the registered waves are not propagating in any direction. The other 11% of pixels in the umbra show signals of downward propagation with phase angles less than 0.5, indicating velocities <1 m s⁻¹.

We also calculated the phase difference spectra of the oscillations detected in both spectral bands to see if there is any detectable wave propagation that might indicate a connection between the oscillations from both spectral bands. The calculations showed a very slight phase difference angle, less than 0.5 (Figure 6). This small angle might be caused by the excessive noise in the G-band data set or by the small effects of dissipation through the atmosphere and not the true wave propagation. Hence, we cannot state that there is connection between oscillations detected in both spectral bands.

These findings indicate that there is no observable wave propagation between the levels. However, due to the high noise levels in G-band data, this observation has to be re-evaluated with another data set.

The oscillations observed in the NIR continuum data set are distributed over the whole umbra. To ensure that the oscillations we analyzed are real, we strengthened the restrictions for automated wavelet technique as well as the procedures for the preparation of time sets. Use of de-stretching procedure reduces the possibility of intensity oscillations induced by shifting the object along the X–Y plane (where X and Y stand for the spatial coordinates). However, the induced intensity oscillations could not be 100% removed, because the alignment and de-stretching were not performed at sub-pixel values.

The umbra emits oscillations sporadically over time (Figure 7). There are no constant oscillatory sources. Hence, we can state that over time the oscillatory emission in the NIR continuum level is random for almost all periods. However, we have to limit this statement. Our time series is short and cannot cover the longer period oscillations for more than a few periods; hence, we could not draw reliable conclusion about the behavior of the longer period oscillations over time.

We also checked the spatial distribution of the dominant oscillation frequency across the umbra (Figure 8). The umbra does not oscillate as a whole but in patches which are distributed across the umbra. For each pixel in the umbra, we marked the period of the registered oscillations that carried the most power. That period was declared dominant for that analyzed pixel. Each patch in the umbra emits oscillations over the whole period range we analyzed; however, the maximum power is contained within different period oscillations for the neighboring patches. We could not detect a connection of the period preference and the structures of the umbra.

The patches are clearly defined and separated from each other with a sharp change in the oscillatory period. Some of
Figure 2. UD tracked over time in the NIR data set. Arrow at each frame marks an example UDs, in this instance twin UDs. All selected frames have a contrast above 90% of maximum contrast. The marked UDs stay in the same position for the duration of the time series.

Figure 3. Observed oscillatory power obtained with wavelet analysis, both curves normalized at the maximum of the NIR curve. The solid line represents the power observed in the NIR continuum, while the dashed line represents the power in G band.

Spatially, these patches do not correspond to anything special inside the umbra and cannot be connected with either UD or the spaces between. Some of the low period oscillations are connected with the observed UDs; however, some of the UDs have short period oscillations. We do not know what causes the difference. We hope that with higher resolution, we will be able to resolve the cause of the difference in the patches.

4. DISCUSSION AND CONCLUSIONS

We observed well-defined UDs in the NIR continuum level, 50 km below $r_{500} = 1$, and we detected oscillations in the umbra with power peaking at 3 and $\sim 6.5$ minutes.

The UDs were distributed across the umbra and lasted longer than the duration of our data set (Figure 2). We did not observe the appearance or disappearance of existing prominent UDs. Their average size is $0^\prime.8$, and in our data set they tended to stay at approximately the same location (Figure 2). The Schüssler & Vögler (2006) model of magnetoconvection in the umbra predicts that UDs are caused by rising plumes. This aspect
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Figure 4. Panel (a) presents the oscillatory power calculated for the intensity profiles of the individual UDs and averaged over the total number of UDs. The power profile shows peaks for 3 and 5 minute oscillations. Panel (b) presents the averaged intensity variations (blue line) of the UDs, with the error bars. The intensity error for UDs intensities is 20%.

Figure 5. Phase angle of the oscillations registered at NIR continuum.

Figure 6. Phase difference spectrum between oscillations registered at the G-band level and the NIR level. A small phase angle can be caused by excessive noise in the G-band data and not the result of real wave propagation. Positive phase difference indicates upward wave propagation.

was confirmed by the observational work of Rimmele (2008), Riethmüller et al. (2008), and Ortiz et al. (2010). In Figure 5 of Schüssler & Vögler (2006), we can see the rising of a plume and the corresponding appearance of UDs in the brightness images. The lifetime of the average UD should be around 30 minutes of detectable brightness according to this model. However, from the figure, it is clear that at lower levels in the umbra we would be able to see UDs for longer time. The example from Schüssler & Vögler (2006) demonstrates that plumes exist for almost 40 minutes in the sub-photosphere. Moreover, Bharti et al. (2010) found that larger UDs live longer. We were only capable of resolving large UDs, which were stable for the 30 minute duration of our data sequence. Thus, we can speculate that the longevity of the observed UDs is a consequence of efficient convection at the NIR continuum formation level. Although this line of reasoning implies that the same would happen for smaller UDs, we could not observe them, hence we cannot broaden the statement to include the unobserved UDs.

Figure 7. Changes of the observed oscillatory power in the umbra over time. We integrated the power for each period individually over the whole surface of the umbra.

Figure 8. Spatial distribution of the dominant oscillation periods across the umbra.

Our result disagrees with Hamedivafa (2008) who found that the lifetime of UDs is between 7 and 10 minutes. However, Hamedivafa expresses doubt about his result, since possible effects were introduced by the automated analysis used for statistical analysis of the UDs. On the other hand, Watanabe et al. (2009) also used an automated detection code and found the mean lifetime to be 7.3 minutes.

The oscillations observed in the NIR continuum have power peaks at 3 and ~6.5 minute period oscillations, while the testing of simultaneous observations in the G band show umbral oscillations with power peaks near 3 and 5 minutes. The observed 3 minute oscillations are most probably connected with the oscillations of the UDs (Figure 4), while the broader peak around 6 minute oscillations might originate from a different source.

Watanabe et al. (2009) found in UDs intensity curves low-frequency components close to ~8 minutes, while Sobotka & Puschmann (2009) reported that UDs substructures vary with the timescale of ~3 minutes. Thus, we can speculate that observed power peaks in the intensity oscillations could be connected with same physical mechanism that caused the UDs and the
UDs’ structures to exist and change for the noted period in the spectral lines used in the cited works, but at NIR continuum height we see those as pure oscillations and not the variations of the UDs and the UDs’ structures.

Oscillations registered in the NIR continuum have small negative phase angles obtained by combining the Fourier and Hilbert transforms. Phase angles close to zero indicate evanescent waves. The phase angle close to zero is observed for 89% of the powerful oscillations, indicating that oscillations which contribute the most to the power peak around 6 minutes do not propagate upward. The small negative phase angle is most probably associated with the dissipation of evanescent waves. We can speculate that these oscillations are helioseismic oscillations, which buffet the photosphere and that these oscillations do not have a direct connection with the upward layers. The typical helioseismic oscillations have periods ranging from ∼1.5 minutes to ∼20 minutes (Gough & Toomre 1991). It is possible that the oscillations we observed are closely connected with the condition of the plasma directly below the umbra.

The phase angle for the most powerful oscillations is close to zero and the minimum oscillatory power is larger than the maximum oscillatory power registered in the G band. The phase spectra we used in this work weight phase angles with the power of the oscillatory signal in question, and hence phase angles of the weak oscillations will be lost in our figure. We observed some waves with positive phase angle, indicating upward propagation. However, the weaker power oscillations are closer to the sporadic noise detections of the oscillations and their reliability is questionable. Thus, we cannot state that there is upward propagation of the detected oscillations.

The peaks at 3 and 5 minutes observed in the G band agree with the previous works (Balthasar & Wiehr 1984; Lites 1992; Tsiropoula et al. 2000), confirming the accuracy of our analysis methods. Our data set in the G band has poor S/N, and thus cannot be used for establishing reliable connections between NIR data set findings and chromospheric findings.

The power curve in Figure 3 for the NIR data set shows power for the 3 minute oscillations as a small peak. This power peak is probably the contribution of the oscillations in the UDs. Although this might be taken as a confirmation of the origin of the oscillations from sub-photospheric levels (López Ariest et al. 2001; Rouppe van der Voort et al. 2003; Bogdan & Judge 2006), the low quality of the G-band data did not allow us to detect the vertical propagation of these oscillations and their connection with the upper atmospheric levels. Hence, we cannot present firm proof that umbral oscillations originate on the NIR continuum level.

The question remains about the other possible sources of the registered NIR oscillations. The instrumentation and the optical bench did not induce any oscillations. However, the data set consists of raw data, and the seeing influences differ from visible (G band) to NIR spectral lines. Hence, it is necessary to adjust the co-alignment procedure to include the changes in the NIR as well as in the visible part of spectra. The change of the interval used for the mean reference image for the co-alignment of the data set caused a shift in the oscillatory power peak toward longer periods. With an interval of 10 images (i.e., 20 s), we got a strong power peak around the 10 minute period. With the interval of 20 images (i.e., 40 s), same peak shifted toward the longer period oscillations, peaking at a ∼13 minute period, and with the interval of 30 images (i.e., 1 minute), the peak shifted to a ∼15 minute period. These oscillations were the strongest around the high-contrast areas (i.e., an edge of the umbra). The position of these oscillations and the changes caused by enlarging the image interval indicates that seeing distortions cause a shift in the images that might cause false oscillatory detections. There is a possibility that even with the 30 image interval used for co-alignment, we were not completely successful in removing all seeing induced oscillations. Thus, these findings have to be re-evaluated using a data set where the seeing influences are removed.

Although the whole umbra oscillates, the dominant periods of the oscillations are not equally distributed over the umbra (Figure 8). There are distinct areas over the umbra that oscillate within the whole period range we analyzed. This result agrees, in part, with the result of Socas-Navarro et al. (2009), with a slight variation. Our patches have different dimensions and behave differently from the patches described in Socas-Navarro et al. (2009). The difference in the oscillatory patches in this work and in the work by Socas-Navarro et al. (2009) might be caused by the different heights of formation for the spectral lines used. The NIR spectral band used in this work is located deep in the photosphere, and we do not have a direct connection to the chromospheric observations. Thus, we cannot say that these patches are the same as the ones observed in the work by Socas-Navarro et al. (2009).

The location of the NIR spectral band might also lead to the speculation that the dominant oscillations with a ∼6.5 minute period are helioseismic oscillations that do not propagate upward, while the oscillations detected in UD that have peaks close to 3 and 5 minutes might be the oscillations connected with the upper atmospheric layers. However, the high error in intensity curves of UD points to the necessity of checking this finding with some other data set.

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