Properties of Sunspots and Pores

C. Denker, T. J. Spirock, P. R. Goode, and H. Wang

Big Bear Solar Observatory/New Jersey Institute of Technology
40386 North Shore Lane, Big Bear City, CA 92314, U.S.A.

Abstract. In this paper, we show observations of sunspots and pores to illustrate various aspects of the high resolution observing program at the Big Bear Solar Observatory (BBSO). We address the question as to how a sunspot develops a penumbra. This process seems to occur on time scales of a few tens of minutes. Even pores with a size of a few arc seconds show fine-structures. Bright points with a diameter of a few tenth of an arc second are located inside pores and resemble umbral dots. Pores often exhibit cloud-like, fuzzy borders which may be the prenatal stages of a penumbra. Therefore, diffraction limited observations of high temporal resolution are necessary to study the temporal evolution of sunspots and pores, the onset of the Evershed flow, and the accompanying changes in the magnetic field configuration. We present speckle masking observations taken in white-light and G-band, infrared observations obtained with frame selection at 1.56 μm, and magnetograms obtained with the new digital magnetograph system. Finally, we will report on our progress in reducing the dome seeing at BBSO.

1. Introduction

Speckle masking imaging can provide almost diffraction limited observations of solar fine structures. A detailed study of sunspots and pores was recently published by Denker (1998). First high spatial resolution observations from BBSO by means of speckle interferometry were reported in Denker & Wang (1998) who studied the flare producing mechanism in an active region with a small δ-spot. Utilizing the expertise of the New Jersey Institute of Technology in near infrared imaging technology, near infrared observations are now a primary field of research at BBSO (Wang et al., 1998b). Finally, we will report on the progress in improving BBSO’s magnetograph system. A description of the video magnetograph system was given by Varsik (1995) and first results from the new digital magnetograph system were presented by Wang et al. (1998a).

2. Observations

A 256 × 254 pixels, 12-bit CCD camera manufactured by Dalsa, Inc. was used to record images at approximately 90 frames s⁻¹ with an exposure time of approximately 10 ms. A 320 × 240 pixels, 12-bit, room temperature, near infrared InGaAs CCD camera manufactured by Sensors Unlimited, Inc. was used to
Figure 1. 12-minute time series of speckle reconstructions obtained in the G-band at 430.1 nm showing bright points and pores observed on August 14th, 1997.

record images at 30 frames s$^{-1}$ at 1.56 $\mu$m $\pm$ 2.5 nm. The quantum efficiency is greater than 70% from 1.0 $\mu$m to 1.7 $\mu$m and the exposure time was 127 $\mu$s. The image scale at the primary focus of the 65 cm reflector is approximately 6$''$ mm$^{-1}$ which corresponds to a field of view of 76.8$''$ $\times$ 57.6$''$ for the near infrared CCD camera and to 24.6$''$ $\times$ 24.4$''$ for the visible light CCD camera. The diffraction limit of the 65 cm reflector is $\alpha_{430} = 1.22\lambda/D = 0.17''$ at 430 nm, $\alpha_{520} = 0.20''$ at 520 nm, and $\alpha_{1565} = 0.61''$ in the near infrared.

2.1. G-Band speckle reconstructions

G-band images are commonly used to follow the evolution of small-scale magnetic elements. Here, we present observations of a cluster of pores within the decaying active region NOAA 8071. We observed the pores in the G-band at 430.1 $\pm$ 0.2 nm with the Dalsa CCD camera from 16:55 to 17:19 UT on August 14th, 1997. We took 24 sequences of 200 short-exposure images and reconstructed the images with the speckle masking technique. We measured a Fried-parameter of $r_0 = 8.44$ $\pm$ 0.55 cm, where the standard deviation reflects the temporal variation of the seeing. A detailed description of the speckle interferometric setup and further references are given in Denker & Wang (1998).

The peak brightness of G-band bright points is typically around 1.2 times the average intensity of the granulation. Extreme cases exceed 1.4 times this intensity. The size of the bright points ranges from around 1$''$ down to the diffraction limit of the telescope. Some G-band brightenings are elongated and move along the intergranular lanes. This motion seems to be dominated by the
2.2. White-light speckle reconstructions

Another interesting phenomenon associated with small scale magnetic fields are facular points around sunspots near the solar limb. Fig.2 shows a sunspot (NOAA 8263) and surrounding faculae observed at 520±3 nm from 17:03 to 18:03 UT on July 11th, 1998. The solar limb is just outside the field of view depicted in Fig.2 at the lower right corner. We took 60 sequences of 200 short exposure images. The Fried-parameter during the observations was $r_0 = 9.19 \pm 0.85$ cm.
Many bright points are located at the inner part of the limb-side penumbra. Especially, the small light-bridge attracts many of these brightenings. In a time lapse movie, we can follow individual bright points traversing the light-bridge towards the limb-side penumbra. Bright points near the disk-side penumbra are predominantly located along the outer periphery of the penumbra. Only in isolated cases, we find brightenings traveling along penumbral filaments toward the umbra. These observations are quite different from high spatial resolution observations of sunspots near disk center where numerous penumbral grains move along the penumbral filaments towards the umbra (e.g., Denker, 1998). However, the lack of moving penumbral grains might be explained by geometrical foreshortening and the Wilson effect.

2.3. Near Infrared Observations

The near infrared CCD camera from Sensors Unlimited is the very first large format, 12-bit, InGaAs camera ever built. In August 1998, we performed a series of observations to test the performance of the CCD camera at a frame rate of 30 frames s$^{-1}$. This high frame rate is essential for a future near infrared magnetograph system (Spirock, Goode, & Wang 1998) where one has to scan either one spatial or the spectral dimension to obtain the full spectral information for a two-dimensional field of view. From comparison with Fried-parameters measured at 520 nm and a few measurements at 1.56 $\mu$m, we expect the Fried-parameter to be larger than $r_0 = 30$ cm at 1.56 $\mu$m for most of the observing days at BBSO.

Fig.3 shows part of active region NOAA 8293 observed with the InGaAs CCD camera in the near infrared at 1.56 $\mu$m on August 8th, 1998. The umbrae of the sunspots exhibit a multitude of umbral dots. The lower contrast in the infrared makes it more difficult to identify individual umbral dots above a surrounding background. However, we can still detect umbral dots with sizes down to the diffraction limit of the telescope. The granular pattern surrounding the
Figure 4. Magnetograms of the quiet Sun near disk center observed on July 4th, 1998. (a) 100-frame integration and (b) 16 x 100-frame integration after image alignment with sub-pixel accuracy.

sunspots is also clearly discernible and the granular contrast is approximately 1%. These sunspot observations represent the best near infrared observations at BBSO so far (cf., Wang et al., 1998b).

2.4. Digital magnetograph system at BBSO
The advantage of a digital magnetograph system is the accessibility of individual frames so that we can apply various post-processing techniques. In Wang et al. (1998a), we demonstrated that frame selection, image alignment, and speckle interferometric techniques can significantly improve the spatial resolution and sensitivity of magnetograms. The spatial resolution of the magnetograms was better than 1″.

Figure 4 shows two magnetograms of the quiet Sun observed near disk center on July 4th, 1998. Since the memory of the Dalsa system was limited, we derived a magnetogram by subtracting 100 frames of left- and right-handed circular polarization. The resulting magnetogram is shown in Figure 4(a). We aligned 16 of these magnetograms with sub-pixel accuracy and averaged them to improve the signal-to-noise ratio by a factor of four. Intranetwork magnetic elements are clearly discernible in Fig.4(b). The gray-scales for both magnetograms were chosen so that the degree of polarization is displayed between ±10⁻³. Small scale magnetic fields can be detected even below ±10⁻⁴. The calibration of the system is such that 1% polarization corresponds to a flux density of 115 Gauss (Varsik, 1995), i.e., the detection threshold is approximately 1 Gauss. In time-lapse movies, we can follow the motion of individual magnetic elements and we observe flux cancellation and emergence even close to the detection threshold.

In the near future, we will improve the software so that routine observations with long integrations, on-line frame-selection, and image alignment are possible. With the implementation of a correlation tracker at the 65 cm vacuum reflector,
on-line image alignment will become superfluous so that we can improve the temporal resolution of the magnetograms. In a next generation magnetograph system, we will upgrade to a larger detector and use a tunable Fabry-Pérot system as primary filter. This will allow us to scan across the spectral line and to measure the true strength of magnetic fields.

3. Combined Observations of NOAA 8299

One unique characteristic of the telescope setup at BBSO is that the 65 cm vacuum reflector, the 25 cm vacuum refractor, and two full disk telescopes share a single equatorial mount. Each of the high resolution telescopes has three optical benches and the 65 cm telescope feeds a spectrograph at the Coudé-focus. A computer-controlled mirror system directs the light to the optical benches and the spectrograph so that seven experiments can run nearly simultaneously in addition to the synoptic full disk observations.
Figure 6. Comparison of scintillometer records of the dome and outside seeing before improving the dome seeing (October 28th, 1997) and afterwards (May 18th, 1998).

Our goal is to combine the observations described in the previous section. The data set shown in Fig.5 reflects the current status of the high resolution observing program at BBSO. We observed active region NOAA 8299 from 18:47 to 20:41 UT on August 16th, 1998. Fig.5(a) and 5(b) show a typical filtergram and magnetogram of NOAA 8299 obtained with the videomagnetograph system (Viers, 1995) at the 25 cm refractor. NOAA 8299 consists of two major spots with the same polarity embedded in several smaller spots of opposite polarity. A close-up of the left major sunspot obtained in the near infrared at 1.56 μm is depicted in Fig.5(c). Again, the umbra of this sunspot is filled with umbral dots. Finally, Fig.5(d) illustrates the spatial resolution that can be achieved with the speckle masking technique.

During the almost 2-hour time-series, we took 99 sequences of 100 frames with the Dalsa CCD camera separated by 1 minute in time. The Fried-parameter during the observations amounts to r_0 = 10.08±1.08 cm indicating excellent seeing conditions. The white-light speckle reconstruction depicted in Fig.5(d) shows at almost diffraction limited resolution three pores, several magnetic knots, and the tips of some penumbral filaments that can be identified in Fig.5(c). Again, fragmentation of granules and concentration of filigree precede the formation of small pores and magnetic knots. A time-lapse movie shows that the intergranular lanes in the lower right corner are often co-aligned with the direction of the penumbral filaments. Interestingly, the pores exhibit various fine structures resembling umbral dots. Many of these dots originate from the fragmentation...
of cloud-like structures at the border of the pores. The dots move around inside the pore where they either merge with other dots or fade away.

4. Improving the Dome Seeing at BBSO

During the last year, we devoted our energies on improving the dome seeing at BBSO. The electronics and computer equipment were removed from the observing floor to reduce the heat load, and the observing floor was thermally insulated from the rest of the building. In addition, the interior of the dome was coated with TiO₂ paint to reduce local turbulence and a fan sends a gentle air current through the dome to insure that there are no large temperature gradients with the ambient air. As Fig.6 shows, all the passive measures added up so that subsequent measurements from solar scintillometry (Beckers et al., 1997) show now a clear correlation of the dome and outside seeing. All these vigorous efforts to improve the seeing break new ground for high spatial resolution observations at BBSO.

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References

Spirock, T. J., Goode, P. R., Wang, H., 1998, AGU Meeting, Boston, SH52H-01

Group Discussion

Rutten: How much time do the Speckle reconstructions take?
Denker: One hour on a 266 MHz Pentium PC.