A&A 428, 215–218 (2004)
DOI: 10.1051/0004-6361:20041515

Astronomy & Astrophysics

Observational evidence of Joule heating in some umbral dots

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Received 23 June 2004 / Accepted 27 July 2004

Abstract. We investigate the effect of the Joule heating (JH) mechanism on the brightness of umbral dots (UDs), proposed by Hamedivafa (2003, A&A, 407, 761). Time series of high-resolution images of UDs in a developed sunspot and in a large pore are used for this purpose. The effect of the JH mechanism is characterized by a specific shape of the temporal variations of UD brightness and area and it is observed better in those UDs where the magnetic field strength is very weak compared to their surroundings. In our observations, about 12% of UDs in the sunspot and about 14% of UDs in the pore show indications of the effective presence of the JH power.

Key words. Sun: sunspots – Sun: magnetic field

1. Introduction

According to our present knowledge, umbral dots (UDs) can be considered either as the tops of modified convection cells embedded in a fairly homogeneous vertical magnetic field (Knobloch & Weiss 1984) or as the tips of intrusions of field-free hot gas columns between flux tubes, where the magnetic field suppresses convective motions (cluster model of sunspots; Parker 1979 and Choudhuri 1986).

Both these mechanisms produce a hot volume (a UD column) inside the umbra, where, at the beginning, the internal pressure of hot gas balances laterally the total pressure of the magnetized surrounding umbra (Degenhardt & Lites 1993a). Hamedivafa (2003, hereafter Paper I) suggested that when the supply of heat from deep layers ceases, then, because of quick heat dissipation (see a discussion about the mean free paths of photons in Paper I and references therein) and an escape of gas from the column, the temperature and density inside the UD column decrease substantially. So, the lateral balance does not hold any more. At this instant, the UD column begins to shrink.

If the magnetic field inside the UD column is much weaker than the surrounding field and/or the magnetic field gradient at the border of the column is large, the evolution of the UD enters a new stage, where the brightness of the UD can be maintained by the Joule heating (JH) power. In other words, the JH power, which has a direct relation with a) the reduction coefficient of magnetic field and b) the magnetic field gradient (see Paper I) becomes more efficient and the produced heat can sustain the UD as a bright point for a certain period. The possibility of JH as a source of brightness of UDs has been mentioned by García de la Rosa (1987).

Section 2 gives a description of the observations and data sets that have been used in this work. Section 3 describes our criterion for finding the JH phenomenon in the observations. The results are presented in Sect. 4, where we discuss the correlation between UD area and JH duration, and the locations of UDs showing the JH phenomenon in the sunspot and in the pore. In Sect. 5, some possible signatures of the JH phenomenon in spots are presented and, finally, in Sect. 6 we summarize the results.

2. Observations and data analysis

Two data sets are utilized to check for the presence of the JH phenomenon in UDs. Both are based on time series of white-light images obtained with high spatial resolution (about 0.25 arcsec) at the 50-cm Swedish Vacuum Solar Telescope, La Palma, Canary Islands (Scharmer et al. 1985).

The first data set is a result of feature tracking applied to a series of images of the sunspot NOAA 7519 observed on 5 June 1993 (Simon et al. 1994). The details are fully described by Sobotka et al. (1997a,b), so that only a brief overview is given here. An 8-bit CCD camera was used in a frame-selection mode to sample images at $\lambda 4680 \pm 50$ Å. The image scale was 0.125 arcsec per pixel and the typical exposure time 10–14 ms. The sunspot was observed in the central zone of the solar disk (position N05 E15) for a period of 4 h 26 min, during which 360 frames with rms granulation contrast higher than 7% were selected. The frames were aligned, corrected for the instrumental profile of the telescope, de-stretched to minimize seeing

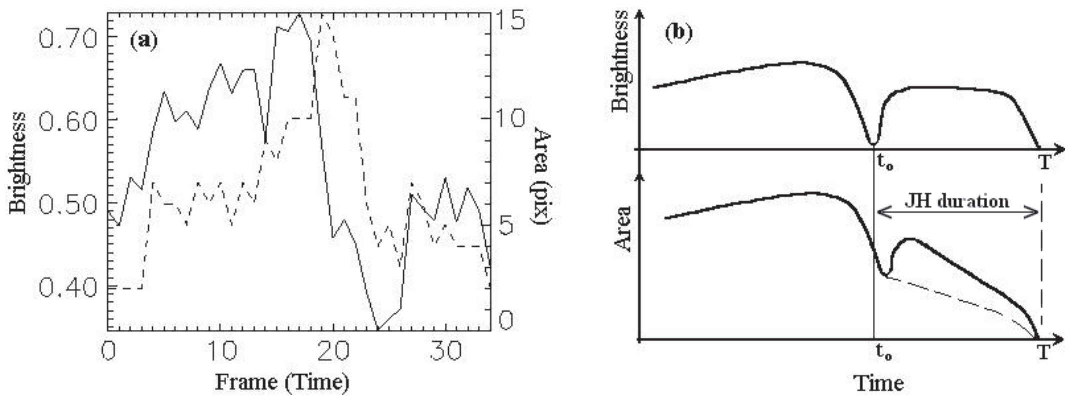

Fig. 1. Temporal variations of UD brightness and area when Joule heating is present: **a**) an example of an observation (solid line and dashed line show brightness and area variations, respectively); and **b**) idealized curves. Probably, due to the increase of brightness, the observed area (solid line) becomes substantially larger than the true one (dashed line).

distortions, and interpolated in time to obtain a time series with a constant lag of 44.5 s. UDs were identified and tracked in the largest umbral core of the spot. Intensities, areas, and positions of 662 UDs during their lifetimes were obtained from the tracking procedure (Sobotka et al. 1997a). From these, 334 UDs with lifetimes longer than 6 min (8 frames) were selected for the further analysis.

The second data set contains results of feature tracking applied to a series of images of a large pore (diameter 8.9 arcsec) in the active region NOAA 7886 observed on 30 June 1995 (Sobotka et al. 1999). We refer to the reference specify above for a detailed description of the observing and data-reduction procedures. In summary, 220 frames at $\lambda 5425 \pm 50$ Å were collected by an 8-bit CCD camera running in a frame-selection mode, with image scale 0.062 arcsec per pixel and typical exposure time 11 ms. The duration of the series is 1 h 7 min and the average time lag is 20 s. The typical value of the rms granulation contrast is 7.6% before any correction is applied. The pore was located in the central zone of the solar disk ($\mu = 0.92$). The images were aligned, corrected for the instrumental profile of the telescope, de-stretched, and filtered for p-modes using the subsonic filter with a cut-off phase velocity of 4 km s^{-1}. UDs were identified and tracked inside the pore, using the same technique as for the first data set. As a result, intensities, areas, and positions of 171 UDs during their lifetimes were obtained. For the further analysis we selected 159 UDs living longer than 2.7 min (8 frames).

3. Temporal variations of UD brightness and area

The instant when the supply of heat into the UD column from deep layers ceases (the upflow of hot gas is interrupted) cannot be calculated or predicted. Owing to this fact and to the absence of observational data on the strength and/or gradient of magnetic field in UDs, the existence of the JH phenomenon has to be searched for indirectly, by analyzing and comparing temporal variations of the UD brightness and area.

The inspection of observed temporal variations of UDs brightness and area has shown that there are some cases when, near the end of the UD lifetime, the UD brightness increases substantially, simultaneously with a decrease of the UD area. As an example, Fig. 1a shows this behavior for a UD seen in the sunspot. This was our starting point for obtaining a reasonable criterion to find the effect of the JH mechanism in UDs.

This point, together with the scenario of the JH mechanism presented in Sect. 1, can be used to predict idealized variations of the UD brightness and area, as shown in Fig. 1b: first, a UD is formed as a magneto-convective blob or as an intrusion of field-free hot gas into the umbra. This phase is characterized by increasing or constant brightness and area of a UD. After some time, the supply of heat from below ceases (around t_0 in Fig. 1b). At this instant, the internal gas pressure starts to decrease and does not balance the external pressure anymore. Umbral gas moves into the UD column and the UD area starts to decrease. The JH mechanism switches, which is manifested by an increase of brightness. From this time, the JH power heats the UD column until the umbra fills it completely at instant T (see Fig. 1b).

Therefore, the shape of temporal variations of UD brightness and area corresponding to Fig. 1 is our criterion for finding the UDs which show the JH phenomenon. For more accuracy and to avoid any error, to measure the JH duration (i.e., $T - t_0$; see Fig. 1b), we select the UDs with a JH duration greater than 7 frames (equivalent to 5.2 min and 2.3 min for the sunspot and the pore, respectively). In this investigation, 39 UDs out of 334 UDs in the sunspot (11.7%) and 22 UDs out of 159 UDs in the pore (14%) meet this criterion and they are candidates for the presence of JH power in the final phase of their evolution.

4. Results

4.1. Area versus duration of Joule heating phenomenon

It can be expected that the duration of the JH phenomenon, (i.e., $T - t_0$; see Fig. 1b), is directly related to the true size of the UD at the instant when the JH mechanism switches. The broader the UD area, the longer the time that umbral gas moves across the UD area to fill it and the longer the JH duration. So a positive correlation between the JH duration and the true UD area at t_0 can serve as a confirmation of the presence of the JH effect. Assuming that the observed size is related to the true

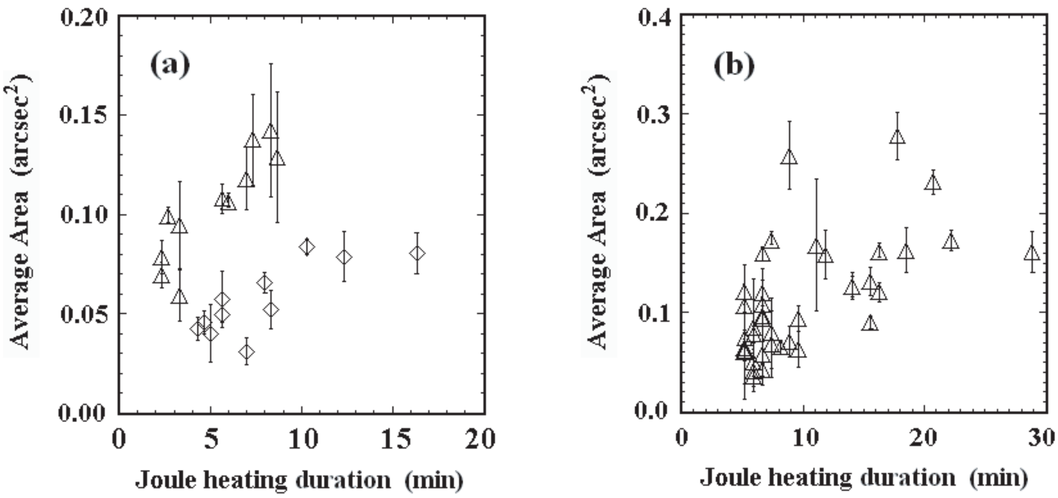

Fig. 2. Scatter plots of average UD area versus Joule-heating duration: **a**) in the pore; and **b**) in the sunspot.

one, we can look for the correlation between the JH duration and the observed area. Because there is little information about the exact time of starting of the JH mechanism (in other words, of when the JH power becomes significant in the UD) and also because of the observed fluctuation in the measured area, the exact area of the UD is difficult to determine at this instant. Thus the average area over the JH duration has been considered as a measure of the UD area when the JH mechanism becomes efficient. In all cases, the *average* is calculated for the interval from t_0 to T.

The average areas of selected UDs in the pore versus their corresponding JH durations are shown in Fig. 2a. It seems that there are two branches in Fig. 2a. One branch containing 11 UDs with a linear correlation coefficient of 0.8 has a slope of about 0.004 arcsec^2 min^{-1}, while the other branch with 11 UDs and a linear correlation coefficient of 0.9 has a larger slope, approximately 0.01 arcsec^2 min^{-1}. The average of JH duration and lifetime of the UDs are 5.2 min and 18.3 min for the upper branch, and 8 min and 20 min for lower branch, respectively. Also, their average radius is 130 km and 110 km in the upper and lower branch, respectively.

Figure 2b shows the correlation between the average area of selected UDs in the sunspot and their corresponding JH duration. In this figure the two branches are not clearly resolved. These two unresolved branches contain 39 UDs. The linear correlation coefficient between the area and the JH duration is 0.6 and the slope of the linear approximation is about 0.006 arcsec^2 min^{-1}. The averages of JH duration and lifetime of the UDs are 10.2 min and 20.2 min, respectively. Also, their average radius is 140 km.

This split into two branches may be caused by our small sample of UDs, because of considering the observed average area instead of the true instantaneous one or, basically, by the differences in the properties of the UDs. By considering the available (measured) properties of UDs and studying the distribution of JH durations, lifetimes, areas and positions of the UDs, no obvious differences were seen between the two branches in Fig. 2a. Anyhow, we believe that the high correlation between the area and the JH duration confirms the existence of the JH phenomenon in the selected UDs.

4.2. Locations of UDs which show the JH phenomenon

Time-averaged positions of UDs where the JH phenomenon is detected are shown in Figs. 3a,b for the sunspot and the pore, respectively. We can see clearly that these UDs are located mostly in bright regions, at the periphery of the umbra in the sunspot and far from light bridges in the pore and the sunspot. The light bridges in Fig. 3a are located at the upper and lower-right borders of the umbral core. In the pore (Fig. 3b), they are protruding from the upper-right border into the umbra.

Because the JH mechanism is considerable in UDs in which the magnetic field strength is very weak, Fig. 3 induces an idea that many UDs (at least those where the JH effect is observed) formed in bright umbral regions have a strongly reduced magnetic field or are field-free. This idea may affect our ideas concerning to the deep structure of the magnetic fields of sunspots: a possible picture of the magnetic field structure below the visible surface of a spot could consist of large magnetic flux tubes (dark nuclei) surrounded in bright umbral areas by many thin magnetic flux tubes separated by nearly magnetic-free hot regions. This picture is also consistent with the fact that the magnetic field strength is reduced in bright regions compared to dark ones (e.g. Martínez Pillet & Vázquez 1993).

Although little decrease in magnetic field has been observed above UDs (e.g. Degenhardt & Lites 1993b), lines formed very deep in the atmosphere are expected to show the magnetic field reduction in UDs. The observations of Wiehr & Degenhardt (1993) support this interpretation. They obtained a 20% lower field strength in peripheral UDs in the low umbral photosphere (measured in the line Fe I 6843 Å), but no reduction was measured in Ca I 6103 Å which is emitted from higher layers. High resolution observations in lines near the opacity minimum at 1.6 μm are needed to measure the magnetic field reduction in UDs.

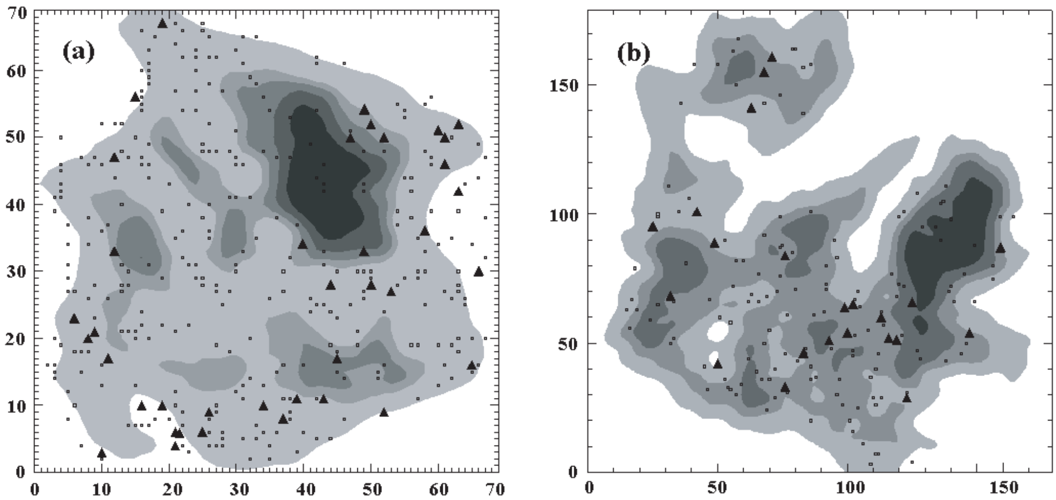

Fig. 3. Time-averaged positions of UDs showing the Joule heating (JH) phenomenon (triangles): **a**) in the sunspot; **b**) in the pore. The small squares represent the positions of UDs where the JH phenomenon was not detected. The underlying gray-scale plots show contours of time-averaged images of the series corresponding to the intensities **a**) 0.24, 0.26, 0.28, 0.30, 0.45 $I_{\rm Phot}$ and **b**) 0.4, 0.5, 0.6, 0.78 $I_{\rm Phot}$. The coordinates are in pixels, scales **a**) 0.125"/pixel; and **b**) 0.062"/pixel.

5. Further possible signatures of JH phenomenon

Roudier et al. (2002) studied the possible influence of horizontal velocities around the large pore – used also in this paper – on its intensity field. They detected a phase delay between the temporal variations of velocity and intensity around the pore. They found that the velocity variations precede the intensity ones and presented some explanations of this phenomenon. Nevertheless, the JH mechanism also provides another explanation for this: it may be related to the variations of the magnetic field gradient at the border of the pore caused by variations of horizontal motions. Then the enhanced heat produced by the JH mechanism produces the coupling between the intensity and the horizontal velocity variations.

Sobotka et al. (1995) reported the brightening of a central UD after the *collision* of a moving peripheral UD with a dark nucleus. This phenomenon can be explained by enhanced JH power resulting from variations of magnetic field gradient at the border of the central UD caused by, for example, a wave propagation across the dark nucleus.

6. Conclusions

In this investigation we found that, in some cases, the brightness of a UD increases simultaneously with the decrease of its area during some time at the end of its lifetime. We accepted this behavior as a sign of the JH phenomenon in UDs. According to this criterion, 12% of UDs in a sunspot and 14% of UDs in a large pore show the JH phenomenon. Since the JH duration is related to the time that umbral gas moves across the UD area to fill it, the obtained high correlation between the UD area and the JH duration confirms the JH scenario in these UDs. Another important consequence which has been obtained here is that the UDs that are sustained by the JH power as bright points for an extended period after the interruption of the heat supply from below have been observed in bright regions at the periphery of umbrae. This result may indicate that the magnetic fields of UDs which are created in these regions are very weak.

Acknowledgements. H. Hamedivafa is much indebted to Prof. Jalal Samimi for his invaluable support. He also thanks the Astronomical Institute, Academy of Sciences of the Czech Republic (ASCR), for hospitality. This work was supported by the Grant Agency of ASCR (grant IAA 3003404). The Swedish Vacuum Solar Telescope was operated by the Royal Swedish Academy of Sciences at the Spanish Observatorio del Roque de los Mochachos of the Instituto de Astrofiśica de Canarias.

References

Choudhuri, A. 1986, ApJ, 302, 809
Degenhardt, D., & Lites, B. W. 1993a, ApJ, 404, 383
Degenhardt, D., & Lites, B. W. 1993b, ApJ, 416, 875
García de la Rosa, J. I. 1987, in The Role of Fine-Scale Magnetic Fields as the Structure of the Solar Atmosphere, ed. E. H. Schröter, M. Vàzquez, & A. A. Wyller (Cambridge University Press), 140
Hamedivafa, H. 2003, A&A, 407, 761
Knobloch, E., & Weiss, N. O. 1984, MNRAS, 207, 203
Martínez Pillet, V., & Vázquez, M. 1993, A&A, 270, 494
Parker, E. N. 1979, ApJ, 234, 333
Roudier, Th., Bonet, J. A., & Sobotka, M. 2002, A&A, 395, 249
Scharmer, G. B., Brown, D. S., Pettersson, L., & Rehn, J. 1985, Appl. Opt., 24, 2558
Simon, G. W., Brandt, P. N., November, L. J., Scharmer, G. B., & Shine, R. A. 1994, in Solar Surface Magnetism, ed. R. J. Rutten, C. J. Schrijver (Dodrecht: Kluwer), 261
Sobotka, M., Bonet, J. A., Vázquez, M., & Hanslmeier, A. 1995, ApJ, 447, L133
Sobotka, M., Brandt, P. N., & Simon, G. W. 1997a, A&A, 328, 682
Sobotka, M., Brandt, P. N., & Simon, G. W. 1997b, A&A, 328, 689
Sobotka, M., Vázquez, M., Bonet, J. A., Hanslmeier, A., & Hirzberger, J. 1999, ApJ, 511, 436
Wiehr, E., & Degenhardt, D. 1993, A&A, 278, 584