Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author
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Solar cycle variations of the Second Solar Spectrum

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Abstract. The average strength of the spatially unresolved turbulent magnetic field in the Sun's photosphere can be measured with the Hanle effect. The possible variations of this average value over time scales of a solar cycle is the topic of an ongoing synoptic program at IRSOL that was started in 2008. The scattering polarization of C_2 molecular lines around 5140 Å is regularly measured, typically once per month. These lines allow the application of the differential Hanle effect to determine the turbulent field strength. Here we report about the behavior of the determined field strength during the beginning active phase of the solar cycle and about our intention to start a new synoptic program based on the Hanle effect in the Sr I 4607 Å line, with which turbulent field strengths are found that are an order of magnitude larger than those determined with the molecular C_2 lines. These synoptic programs allow us to explore the nature of the magnetic fields at the small-scale end of the magnetic scale spectrum and to determine the possible role of a local dynamo for the generation of these fields.

1. Introduction

The scale spectrum of solar magnetic field extends over many order of magnitude (cf. Stenflo 2012b). Only the large-scale portion of this spectrum is accessible to direct observations, depending on the current spatial resolution of the telescopes. Even next generation solar instruments like ATST or Solar Orbiter (a mission bringing the telescope close to the Sun) will be unable to resolve the smallest scales where we expect a significant fraction of the total magnetic flux to exist. An indirect method to investigate the spatially unresolved magnetic fields is provided by the Hanle effect, which in contrast to the Zeeman effect is sensitive to a turbulent fields with mixed polarities and no net flux across the spatial resolution element (Stenflo 1982). Because of the instrumental difficulties in measuring the small Hanle polarization signatures with an accuracy of about 10^{-4} or better, it has only recently been possible to more systematically exploit the Hanle effect as diagnostic tool for spatially unresolved fields. Instruments like ZIMPOL, TIP, and dual beam exchange polarimeters now give us the needed access to these fields.

The solar-cycle variations of large scale magnetic fields have long been explored with the help of the Zeeman effect. In contrast the behavior of the spatially unresolved magnetic fields on solar-cycle time scales remains unknown and needs to be addressed with a synoptic program for the Hanle depolarization effect.

In December 2007 we started such a synoptic program in the form of regular measurements (about once per month) of the scattering polarization of C_2 molecular lines around 5140 Å (Kleint et al. 2010a). Five measurements for each observing run are performed near the solar limb at N, NW, W, SW, and S, about 5 arcsec inside the limb (where μ, the cosine of the heliocentric angle, is 0.1). The data are reduced in terms of the differential Hanle effect (Stenflo et al. 1998; Berdyugina & Fluri 2004). The results of the observations carried out during the years 2008-2010, near the minimum phase of the solar cycle, did not reveal any significant variations of the strength of the turbulent magnetic field (Kleint et al. 2010b, 2011).

Here we report about preliminary results from observations carried out after 2011, when the solar cycle was in its increasing phase. We also outline plans to start a new synoptic program for the Hanle depolarization effect in the Sr I 4607 Å line.

We also report on some technical and instrumental upgrades that have been carried out to improve the accuracy of the observations needed for the mentioned synoptic programs.

2. Instrumental improvements

The observations have been carried out at IRSOL in Locarno, Switzerland, with the 45 cm aperture Gregory Coudé telescope and the 10 m focal length Czerny-Turner spectrograph, which is equipped with a grating of size 360 mm $\times$ 180 mm, 316 groves/mm, and 63°blaze angle. The polarimetric observations are done with the ZIMPOL polarimeter that was developed at ETH Zurich and is currently being upgraded in collaboration with SUPSI (University of Applied Science of Southern Switzerland).

The new ZIMPOL-3 version has been used since 2010 for spectropolarimetric observations at IRSOL (Ramelli et al. 2010). The improvements with respect to ZIMPOL-2 include better detector efficiency, larger size of the CCD sensor (in the spectral direction), and state of the art electronics. Technical improvements of the instrumentation at IRSOL allow the application of new observing modes and a better precision.

To select the wavelength range that enters the spectrograph we now use interference filters in a filter wheel instead of the previously used monochromator predisperser. The filters have high rectangular transmission band passes and allow us to gain up to 50 % in total transmission as compared with our previous system.

We also have found a way to greatly reduce the uncertainty in the observationally determined true zero level of the polarization scale, through the following set of improvements: The orientation of the optical components (calibration optics, polarization analyzer, and image derotator) can now be set more accurately. New strategies and calculations that make use of precise ephemeris codes now lead to the elimination of the faint drifts in the background polarization zero level that we had before. This allows us to use observations carried out at the center of the solar disk (where the polarization in the continuum is expected to be zero) to determine the true instrumental polarization and then use it to be subtracted from the observations that are made at other positions of the solar disk.

Due to seeing-induced image motions, residual mechanical imprecision in the telescope tracking, and to image wobbling caused by imperfect adjustments of the mirrors inside the telescope, the position of the limb with respect to the slit in the spectrograph slit plane (focus F2) can vary with time. With the help of the adaptive optics system this positional error gets drastically reduced, but at the expense of considerable light loss.

An alternative that we have now implemented makes use of a tilt-plate that is adjusted a few times per second, based on the real-time reduction of the slit jaw camera images. This allows us to eliminate slow drifts of the limb distance.

The guiding system (Küveler et al. 2011) is connected to the local computer network and can be controlled by the ZIMPOL software.

These improvements now allow entirely automatized observations. In particular the synoptic programs can now be carried out in this way.

3. The C_2 synoptic program

The program has been described in detail in Kleint et al. (2010b), where first results until 2010 are reported, and in Kleint et al. (2011), where the theoretical approach for the interpretation is described. The goal of this program is to measure the turbulent magnetic field strength and its variation with time. In the period 2008-2010, during the solar minimum phase, it was not possible to notice any significant variations, neither with respect to time nor with respect to heliographic latitude. This program is still continued: about once per month measurements are made at different position angles, at heliographic N, NW, W, SW, and S, at $\mu = 0.1$, i.e. about 5 arcsec inside the solar disk, with 1000 s effective exposure time per position. Since mid 2012 these observations can be done in a fully automatic way.

In Fig. 1 we give an example of data recorded on 1 March 2013 at the SW limb. The intensity spectrum and the corresponding Q/I of the Second Solar Spectrum are shown. The C_2 molecular R and P triplets are used with the differential Hanle effect to derive the strength of the turbulent magnetic field. The three peaks of the R triplet should have the same amplitudes if no magnetic fields were present. The amplitudes are unequal because of the different Hanle response of the three lines as a consequence of their different Landé factors. This allows us to apply the differential Hanle effect as explained in Kleint et al. (2011).

The publication of the results collected since 2011 is in preparation. Here we just want to report the very preliminary results that we cannot detect any clear difference of the turbulent magnetic field strength between the quiet and early active phase of the solar cycle. The strength seems to remain constant, but the quantitative constraints on the possible variations need to be accurately determined. This will be dealt with in the dedicated publication that is in preparation.

It should however be stressed that these observations by themselves do not allow us to determine whether or not the turbulent magnetic field varies with the solar cycle. The reason is that the C_2 molecular lines are formed almost exclusively inside the granular cells, while the Hanle effect in atomic lines like Sr I 4607 Å, which also gets its contributions from the intergranular lanes, reveals turbulent field strengths that are an order of magnitude larger than those found with the C_2 lines (Trujillo Bueno et al. 2004). The only known consistent explanation for this enormous discrepancy in the derived field strengths is that the bulk of the spatially unresolved turbulent magnetic fields are located in the intergranular lanes. This implies that the C_2 measurements do not give field strengths that are representative of the average properties of the turbulent fields, they selectively reflect what goes on in the granular cell interiors. To resolve this issue and get a full assessment of the turbulent magnetic field in the solar photosphere and the extent of its solar-cycle variation, the C_2 synoptic program urgently needs to be complemented with a corresponding program for an atomic line like Sr I 4607 Å.

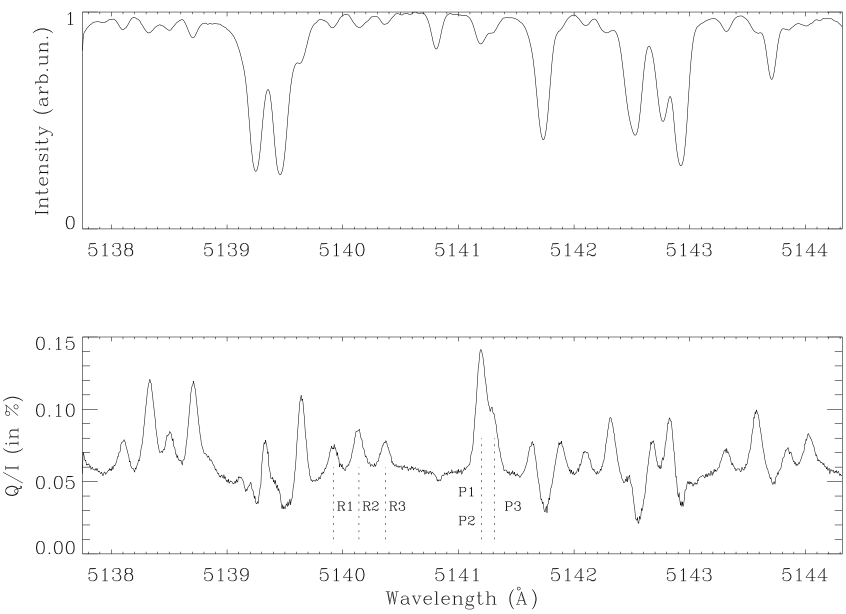

Figure 1. Stokes profiles I and Q/I of the 5140 Å spectral region recorded at $\mu = 0.1$ near the SW limb and averaged over 140 arcsec. This spectral window contains several peaks due to scattering polarization by molecular C_2 lines. The two R and P triplets of C_2 that are used by the synoptic program for the differential Hanle effect are marked in the lower panel.

4. The Sr I 4607 Å synoptic program

The most suitable atomic line for Hanle diagnostics of the turbulent magnetic field is the Sr I 4607 Å line, which in the past has indicated turbulent field strengths of at least 60 G (Trujillo Bueno et al. 2004), approximately an order of magnitude stronger than derived from the C_2 lines. The technical advantage of using this strontium line is its exceptionally high scattering polarization amplitude, one of the highest in the visible part of the Second Solar Spectrum. Its disadvantage has been the absence of any useful scattering polarization lines nearby, which could serve as reference lines for normalization purposes or for applications of the differential Hanle effect.

Since it is not technically possible to ensure that we can keep the instrumental polarization scale and the limb distance constant over solar cycle time scales with the precision needed to determine subtle cycle variations of the Hanle depolarization effect, a synoptic program is only feasible in terms of *line ratios*. Since we cannot apply the differential Hanle effect for a Sr I synoptic program, which would require a suitable partner line from the same atomic multiplet, which we do not have, we need to use a scattering polarization reference signature, for which we can safely assume that it is sufficiently invariant with the solar cycle. This invariance can only be assured if the scattering polarization signature is immune to the Hanle effect. The most ideal such signature is that of the blue wing of the Ca I 4227 Å line, for two reasons: (1) The Hanle effect can only operate in the Doppler cores of spectral lines (cf. Stenflo 1998),

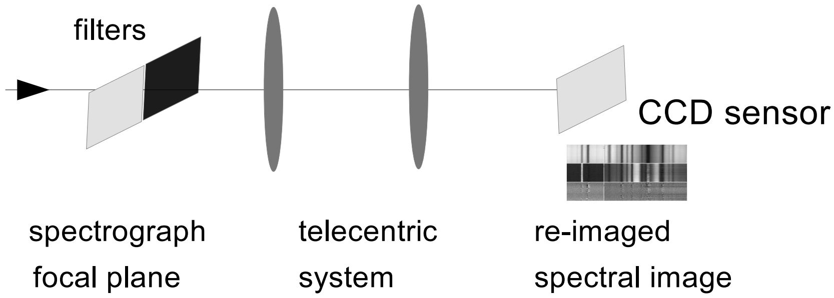

Figure 2. Illustration of the optical setup in the spectrograph focal plane that allows us to simultaneously record the two spectral regions around the Sr I 4607 Å and the Ca I 4227 Å lines. They belong to two different grating orders that get separated with the help of two adjacent interference filters.

and is therefore absent in the Ca blue wing, which has been verified by observations. (2) The polarization amplitude of the 4227 Å line is the largest of all lines in the visible Second Solar Spectrum, which optimizes the S/N ratio of the observations.

If we could form a ratio between the simultaneously observed polarization amplitudes of the Sr I 4607 Å line and the blue wing of the Ca I 4227 Å line, then we get a dimensionless measure that can be converted to turbulent field strengths due to the Hanle effect in the Sr line alone. This dimensionless measure is insensitive to errors in the limb distance of a given observation, because the relative center-to-limb variation of both lines is nearly identical, with the consequence that the errors in the limb distance will ratio out. Since the Ca blue wing is invariant with the cycle, any determined cycle variation of the dimensionless ratio can be safely ascribed to cycle variations of the Hanle effect in the Sr line.

Although the Sr I 4607 Å line and the Ca I 4227 Å line are so far apart in the spectrum, the ratio between their wavelengths λ is close to the rational number 12/11, which makes it possible to use overlapping grating orders k to bring them side by side on the same detector area. For a given position of the grating, the product $k\lambda$ remains invariant. From this we see that the Sr I 4607 Å line in the 11th order and the Ca I 4227 Å line in the 12th order are very close to each other.

The modified instrumental setup in the spectrograph focal plane, which allows simultaneous recording of the two lines, is illustrated in Fig. 2. Two square-shaped interference filters, one for each grating order, are placed beside each other in the focal plane, such that one part of the spectral field of view contains the 11th order with the Sr line, the other part the 12th order with the Ca line. The resulting image, which now contains the two lines side by side, is reimaged by a telecentric lense system on the ZIMPOL CCD camera.

Figure 3 shows the result of a test recording. The effective exposure time was 20 min, with the spectrograph slit parallel to the limb near the N pole at $\mu = 0.15$. On the left side of Fig. 3 we recognize the intensity, Q/I, and V/I Stokes images of a 1.9 Å wide spectral band around the Sr I 4607 Å line. The spatial field of view (length of the vertical axis) is 180 arcsec. On the right side we see the same Stokes images for the spectral region around the Ca I 4227 Å line. Note that the two lines are recorded with

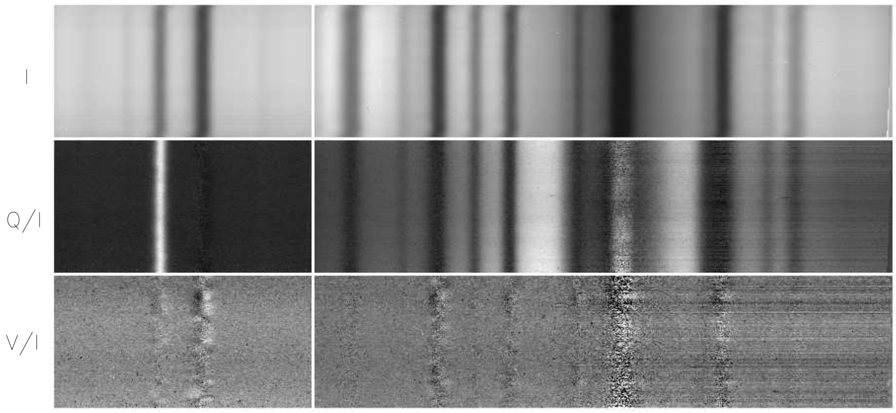

Figure 3. Simultaneously recorded Stokes images of the intensity, Q/I, and V/I in two different grating orders. The spectral band to the left shows the Sr I 4607 Å line with its strong Q/I peak, while the spectral band to the right with the Ca I 4227 Å line shows to the left of the line core the prominent broad Q/I polarization band in the blue wing, which is immune to the Hanle effect and therefore will serve as an ideal reference, with which the measured strontium polarization will be normalized. The spatial field of view along the slit is 180 arcsec.

the same exposures, as explained before. They should therefore represent the identical regions on the Sun, with identical limb distance and atmospheric seeing.

The Zeeman effect only shows up in the V/I images, but is too weak to be visible in the linear polarization (transverse Zeeman effect). Therefore everything that we see in the $Q//$ images is due to scattering polarization. The spatial variations in the Ca I line core are exclusively due to the Hanle effect.

The profiles that are shown in Fig. 4 represent an average over a 10 arcsec segment of the upper portion of the Stokes images (from 108 arcsec to 117 arcsec along the scale that goes from 0 to 180 arcsec). While the core peak of the Ca I Q/I profiles is sensitive to the Hanle effect, the dominating broad peak in the blue wing is not. Since it is not affected by the presence of magnetic fields, it should not vary with the phase of the solar cycle or with heliographic latitude. Therefore the blue wing peak is ideal as a reference for the Sr I measurements. The dimensionless measure that is formed when normalizing the Sr I polarization amplitude with the Ca I blue wing amplitude is insensitive both to errors in the exact limb distance of the observations and to subtle drifts in the instrumental polarization scale over solar cycle time scales. Any variations seen in this dimensionless measure can therefore safely be interpreted in terms of variations in the magnitude of the Hanle depolarization effect, i.e., to variations of the turbulent field strength.

Some instrumental improvements are still needed to optimize the setup. As the solar image on the slit jaw plane of the Gregory Coudé telescope rotates, we need an image derotator to keep the desired solar limb parallel to the spectrograph slit. The presently used derotator is a Dove prism, which therefore has chromatic properties. For certain orientations of the prism the two images of the solar image in the Sr and Ca colors are shifted along the slit relative to each other. Although this shift is quite small (typically less than 1.5 arcsec), its effect needs to be monitored. As alternative we

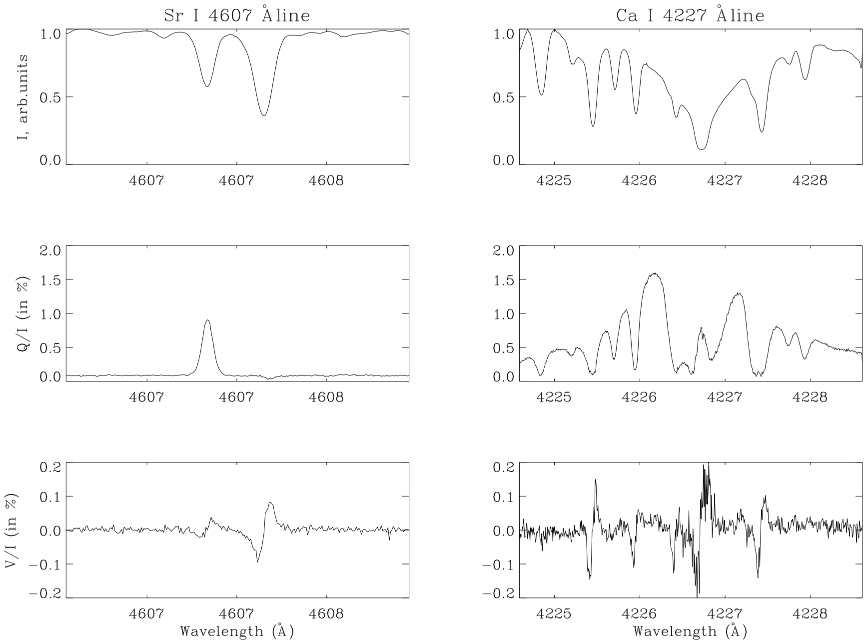

Figure 4. Stokes line profiles obtained by averaging over a 10 arcsec section of the spectrograph slit in the images of Fig. 3. The observable to be used for the synoptic program is the ratio between the amplitude of the Q/I peak of the strontium line (left panel) and the amplitude of the blue wing of the calcium line (right panel). This dimensionless observable is insensitive to errors in the limb position and subtle drifts of the polarization scale and will only exhibit variations if the strength of the turbulent field really varies.

are preparing a derotator based on three mirrors, which would eliminate the chromatic problems.

5. Conclusions

We are continuing the ongoing synoptic program to search for possible variations of the turbulent magnetic field based on the C_2 molecular lines around 5140 Å. The already published results from the observations done in the years 2008-2010 (Kleint et al. 2010b, 2011) lead to a turbulent field strength of 7.4 ± 0.8 G only, and they reveal no significant variations of the turbulent magnetic field during the minimum phase of the solar cycle. Observations done during the previous solar maximum for the Atlas of the Second Solar Spectrum (Gandorfer 2000) indicate that the turbulent magnetic field during the maximum cycle phase could be different from the field during the minimum phase. Our preliminary results for the time interval 2010-2013, still close to the minimum but with increasing solar activity, fail to reveal a clear changing trend. The definite analysis of the data will be published in the near future.

The above results are based on analysis of the differential Hanle effect in optically thin C_2 lines, which are formed almost exclusively in the interior of the granulation cells

(Trujillo Bueno et al. 2004) and therefore do not account for the field concentrations in the intergranular lanes. In addition, the turbulent field strengths that are derived from the C_2 measurements are smaller by approximately an order of magnitude than those derived from Hanle depolarization measurements in atomic lines like the Sr I 4607 Å line, which get their contributions from both the lanes and the cell interiors. This indicates that the bulk of the turbulent magnetic flux is located in the intergranular lanes (Trujillo Bueno et al. 2004), and therefore that the turbulent field that is sampled by the optically thin C_2 lines is not representative of the spatially averaged properties of the field. The key to the question about the cycle variability is therefore expected to be found with the atomic lines and not with the optically thin molecular lines.

The ideal atomic line for this purpose is the Sr I 4607 Å line, but the difficulty has been that it is spectrally isolated without good polarizing reference lines in its spectral neighborhood. Since it is technically not feasible to perform observations with a well-defined limb distance and polarization scale that can be kept constant over solar cycle time scales with the needed precision, a Hanle synoptic program is only feasible by the application of *differential* techniques. We need a reference polarization signature that can be assumed to be invariant with the cycle phase, and which has nearly the same center-to-limb variation as the strontium line that is used to diagnose the turbulent field.

By a fortunate circumstance the ideal reference signature, the blue wing of the Ca I 4227 Å line, has a wavelength ratio relative to the Sr I 4607 Å line that is very near the rational number 11/12. The blue wing of the calcium line is ideal because it has the largest scattering polarization amplitude in the whole visible spectrum, and it is not affected by the Hanle effect and therefore immune to cycle-varying magnetic fields. We can record the 4227 Å line in the 12th grating order simultaneously with the 4607 Å line in the 11th order with the help of two square-shaped order-separating interference filters placed side by side in the spectrograph focal plane, using the ZIMPOL-3 camera. By forming the ratio between the amplitudes of the strontium line and the blue wing of the calcium line, we get a dimensionless measure of the turbulent field that is insensitive both to errors in the limb distance and in the polarization scale. Any cycle variations of the turbulent magnetic field will be reflected in variations of this dimensionless measure. We therefore intend to start such a synoptic Hanle program for the Sr I 4607 Å line to be carried out in parallel with the ongoing program for the C_2 molecular lines.

One of the main scientific questions that the described synoptic programs will answer concerns the existence and role of a local solar dynamo, which does not contribute to the solar-cycle variations of the magnetic field but is conjectured to be responsible for ubiquitous small-scale structuring of the field. Although it has been shown that the bulk of the magnetic flux at all resolved scales, down to the Hinode 200 km scale, is supplied by the global dynamo, a local dynamo is needed to explain the vast amounts of “hidden” turbulent magnetic flux with strengths in excess of 60 G that has been revealed by observations of the Hanle depolarization effect in the Sr I 4607 Å line (cf. Stenflo 2012a, and the contribution by Stenflo to the present SPW7 proceedings). The temporal variation of the turbulent field that we will find with our strontium Hanle program may be decomposed into a constant part and a fluctuating component (with zero minimum). While the fluctuating component cannot have a local dynamo as its source, the constant component will most likely have such an origin. At present our C_2 synoptic program indicates that a turbulent field with a strength of at least 7 G may be due to a local dynamo. However, the main question concerns the nature of the much stronger fields that have been indicated by the previous Sr I observations. Any cycle variation of these fields must come from the global dynamo and pile up at the smallest scales through the turbulent cascade, whereas the cycle-independent component cannot have such an origin but needs a local dynamo. The Hanle synoptic program with the strontium line is therefore expected to clarify the role that the local dynamo may play on the Sun.

Acknowledgments. The research at IRSOL is financially supported by the Swiss Confederation (SEFRI), Canton Ticino, the city of Locarno, the local municipalities, and SNF grant 2200021_138016, the Fondazione Aldo e Cele Daccò. RR acknowledges financial support from the Carlo e Albina Cavargna Foundation.

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