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OBSERVATION OF THE MOLECULAR ZEEMAN EFFECT IN THE G BAND

A. Asensio Ramos,[1] J. Trujillo Bueno,[1,2] M. Bianda,[3,4] R. Manso Sainz,[1,5] and H. Uitenbroek[6]
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ABSTRACT

Here we report on the first observational investigation of the Zeeman effect in the G band around 4305 Å. Our spectropolarimetric observations of sunspots with the Zürich Imaging Polarimeter at the Istituto Ricerche Solari Locarno confirm our previous theoretical prediction that the molecular Zeeman effect produces measurable circular polarization signatures in several CH lines that are not overlapped with atomic transitions. We also find both circular and linear polarization signals produced by atomic lines whose wavelengths lie in the G-band spectral region. Together, such molecular and atomic lines are potentially important for empirical investigations of solar and stellar magnetism. For instance, a comparison between observed and calculated Stokes profiles suggests that the thermodynamical and/or magnetic properties of the photospheric regions of sunspot umbrae are horizontally structured with a component that might be associated with umbral dots.

Subject headings: molecular data — polarization — radiative transfer — Sun: magnetic fields

1. INTRODUCTION

The Fraunhofer G band around 4305 Å includes significant contributions from vibrorotational transitions of the $A\,^2\Delta$–$X\,^2\Pi$ electronic system of the CH molecule. This band has been important in high spatial resolution studies of solar surface magnetism because photospheric bright points are seen with very high contrast when observed in the G band (see Sánchez Almeida et al. 2001 and references therein; see also the recent G-band images of Scharmer et al. 2002 and of Sánchez Almeida et al. 2004 that show bright points around sunspots and in the internetwork quiet Sun, respectively). For this reason, theoretical and observational investigations of the Zeeman effect in the G band are of great scientific interest.

In a recent paper (Uitenbroek et al. 2004), we have investigated theoretically the Zeeman effect in the G band, including radiative transfer simulations of the emergent Stokes profiles in "quiet-Sun" models. In spite of the fact that this spectral region contains a multitude of overlapping atomic and molecular lines, we could find several isolated groups of CH lines that were predicted to produce measurable circular polarization signals in the presence of magnetic fields. In particular, in one wavelength location near 4304 Å, the overlap of several magnetically sensitive and nonsensitive CH lines was predicted to produce a single-lobed Stokes *V* profile that could be of great interest for future high spatial resolution narrowband polarimetric imaging of the solar surface.

The main aim of this Letter is to report on the first observational study of the Zeeman effect in the G band, but including also radiative transfer calculations in a semiempirical model of sunspot atmospheres. Our spectropolarimetric observations of sunspots fully confirm the above-mentioned theoretical prediction. As we shall see below, a preliminary comparison of the observed and calculated Stokes profiles demonstrates that the Zeeman effect in the G band offers a new diagnostic window for empirical investigations of solar and stellar magnetism.

2. THEORETICAL PREDICTION OF THE G-BAND POLARIZATION IN SUNSPOTS

Prior to reporting on our spectropolarimetric observations, it is useful to show first the emergent Stokes profiles that we expect for the atmospheres of sunspot umbrae. To this end, we have used the cool semiempirical model of Collados et al. (1994), but assuming a vertical magnetic field of constant strength. This is sufficient for our demonstrative purposes—that is, for showing that the *shapes* of the computed *V*/*I* profiles agree with those we have observed in sunspots and for highlighting the diagnostic interest of the Zeeman effect in the G band. The vector radiative transfer equation for the emergent Stokes profiles has been solved by applying the quasi-parabolic Diagonal Element Lambda Operator method (Trujillo Bueno 2003), in a way similar to that described by Uitenbroek et al. (2004).

Figure 1 shows the calculated *V*/*I* profiles in two spectral regions of the G band assuming a vertical magnetic field of 2000 G. The left and right panels correspond to the 4304 and 4312 Å spectral regions, respectively. The chosen line of sight is given by $\mu = \cos\theta = 0.95$, where θ is the heliocentric angle. It is important to advance here that the observed Stokes profiles described in § 3 are affected by a stray-light contamination of ∼4%, which we have determined by comparing the intensity profiles of Kitt Peak's atlas, observed with the Fourier Transform Spectrometer, with our own observations at the solar disk center. For this reason, in Figure 1 we have also shown the artificial reduction in the *amplitude* of the computed *V*/*I* profiles that results when a 4% contribution of the intensity profiles obtained in the quiet-Sun model C (Fontenla et al. 1993) is added to the calculated Stokes *I* profiles in the umbra model. The solid line shows the emergent Stokes profiles calculated by including both the atomic and CH lines, while the dashed line represents the emergent Stokes profiles obtained by including only the CH lines. The dash-dotted line represents the emergent Stokes profiles calculated without including any stray-light contamination.

The wavelengths and oscillator strengths for the CH lines have been obtained from the line list of Jørgensen et al. (1996), while those for the atomic lines have been obtained from CD-ROM 1

[1] Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38205 La Laguna, Tenerife, Canary Islands, Spain.
[2] Consejo Superior de Investigaciones Científicas, Spain.
[3] Istituto Ricerche Solari Locarno, Via Patocchi, CH-6605 Locarno-Monti, Switzerland.
[4] Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland.
[5] High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder CO 80307-3000. The National Center for Atmospheric Research is sponsored by the National Science Foundation.
[6] National Solar Observatory, P.O. Box 62, Sunspot, NM 88349.

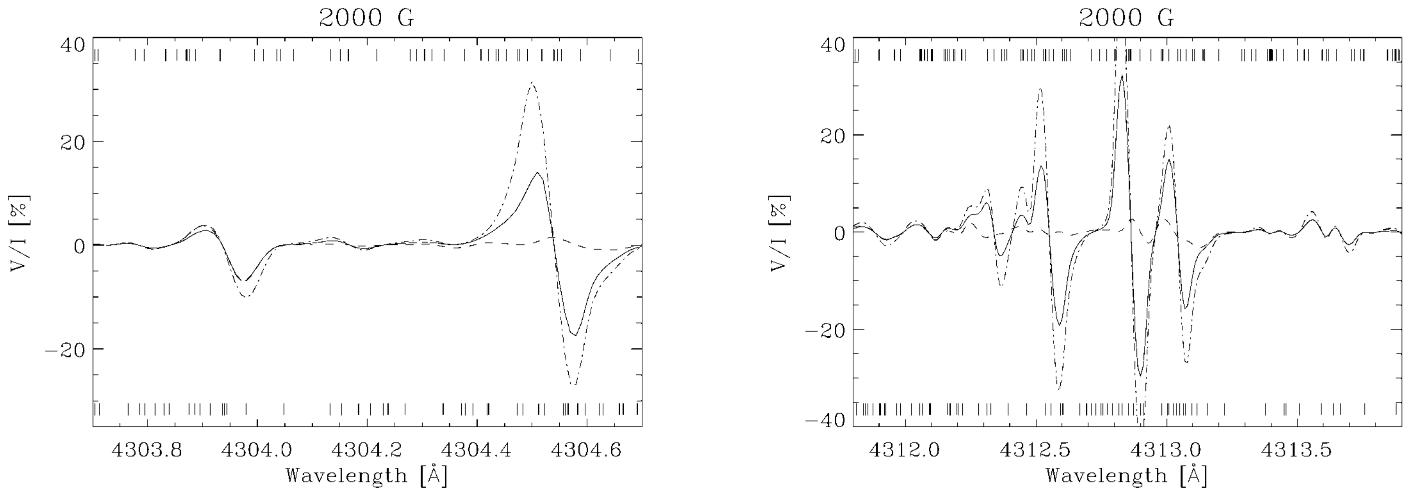

FIG. 1.—Emergent *V*/*I* profiles calculated in the cool umbra model of Collados et al. (1994) assuming a constant vertical magnetic field of 2000 G and filling factor $f = 1$. The solid line represents the emergent fractional circular polarization, taking into account both atomic and CH molecular lines, while the dashed line represents the emergent *V*/*I* including only CH lines. Both have been calculated considering the effect of a stray-light contamination of 4% from the surrounding quiet Sun. The dash-dotted line represents the calculated profiles without any stray-light contamination. The left panel shows the region around 4304 Å, in which we find the single-lobed *V*/*I* profile produced by CH only. The other circular polarization signal is produced by an atomic line of Fe I. The right panel shows the region around 4313 Å, where we can find the *V*/*I* profiles at 4312 and 4313.7 Å that are produced exclusively by CH transitions. The signals between both CH features are produced mainly by atomic lines. The strongest one is due to Ti II. The tick marks in the upper part of each panel indicate the position of an atomic line, while those in the lower part indicate the position of a CH line.

by R. L. Kurucz.[7] In both spectral regions, we have *V*/*I* features dominated by CH lines only. For example, the one-lobe *V*/*I* profile at 4304 Å results from the blend between the $R_{1e}(1.5)$ and $R_{1f}(1.5)$ lines of the $v = 0$–0 band, which gives a Λ-doublet with an effective Landé factor $\bar{g} = 0.8833$. The *V*/*I* profile at 4313.7 Å is produced by the blend of the CH lines $Q_{11fe}(3.5)$ and $Q_{11ef}(3.5)$. Finally, the *V*/*I* feature at 4312 Å is produced by many overlapping CH lines, but mainly by the $P_{12ff}(5.5)$, $R_{21ff}(4.5)$, $Q_{22fe}(4.5)$, and $P_{12ee}(4.5)$ lines from the $v = 0$–0 band and by the $R_{21ff}(1.5)$, $P_{12ff}(4.5)$, $R_{21ee}(1.5)$, and $R_{21ff}(2.5)$ lines from the $v = 1$–1 band. Note that the CH lines that produce clean *V*/*I* signals result from transitions between levels with small *J*-values (i.e., with $J \leq 5.5$).

3. OBSERVATIONS OF THE G-BAND POLARIZATION IN SUNSPOTS

The spectropolarimetric observations were carried out on 2003 August 30 using the UV version of the Zürich Imaging Polarimeter (ZIMPOL; see Povel 2001) attached to the Gregory Coudé Telescope of the Istituto Ricerche Solari Locarno (IRSOL). In order to facilitate an irrefutable observational proof of the predicted Stokes *V*/*I* profiles, we selected a bipolar sunspot group (NOAA Active Region 0447), which was located at $\mu = 0.95$. We observed simultaneously the two sunspots of opposite magnetic polarity. To this end, a dove prism located after the analyzer (modulator + linear polarizer) allowed us to rotate the solar image in order to get the image of the umbrae of the two main spots on the spectrograph slit. The direction of the slit formed an angle of 55° with respect to the closest limb. The slit width was 80 μm, which corresponds to 0″.7 on the solar surface. The spatial and spectral extensions covered by the ZIMPOL CCD were 160″ and 3.1 Å, respectively.

The ZIMPOL version used for these observations has one piezoelastic modulator (PEM), which allows to measure simultaneously the intensity *I* and the fractional Stokes parameters *Q*/*I* and *V*/*I* for linear and circular polarization, respectively. Due to the high modulation rate (42 kHz, which is much higher than the typical seeing frequencies of the order of hundreds of hertz), the seeing-induced cross talk is insignificant, and the noise level in the polarization signals is established only by photon statistics. ZIMPOL is a 1 beam system, and the same pixel of the CCD is used to measure all Stokes components. Therefore, no flat-field technique is needed to correct the polarization images. A calibration is performed by inserting known amounts of polarization in front of the analyzer (PEM + linear polarizer). The dark-current table correction is also applied. Our measurements were performed by adding 60 registrations, each of them taken with an integration time of 5 s. The reduced data are affected by instrumental polarization caused by the two folding mirrors inside the Gregory Coudé Telescope (for details, see Gandorfer & Povel 1997). The ensuing effects (i.e., a shift of the zero polarization level smaller than 1% and a 2% crosstalk from *V*/*I* to *Q*/*I*) were quite small and constant over the day and could be easily corrected. In order to increase the signal-to-noise ratio of the *V*/*I* profiles shown in the following two figures, we averaged over 4 pixels along the spatial direction, which corresponds to 4″.5 inside the sunspot umbrae. No other data reduction procedures, like smoothing or filtering, were applied.

Figure 2 shows examples of the observed Stokes *V*/*I* profiles around 4304 Å, which is the wavelength position of the CH lines that were predicted to produce a peculiar Stokes *V*/*I* profile dominated by its red lobe (see Fig. 1). The top panel of Figure 2 corresponds to the sunspot with the positive polarity (i.e., with the magnetic field vector pointing outward), while the bottom panel refers to the sunspot with the negative polarity. Each of the vertical tick marks in the lower part of the plot indicate the position of a CH line, while those in the upper part indicate the position of an atomic line. Note that each of the observed signals is produced by a blend of many lines. In full agreement with our theoretical *V*/*I* profiles of sunspot umbrae (see Fig. 1), the observed circular polarization at 4304 Å is dominated by a single-lobed Stokes *V*/*I* profile whose sign changes when going to the sunspot with the other magnetic polarity. The same occurs with the Stokes *V*/*I* profile at 4304.6 Å, which is produced by atomic lines only.

Figure 3 shows the observed *V*/*I* profiles for an extra spectral

[7] See http://kurucz.harvard.edu.

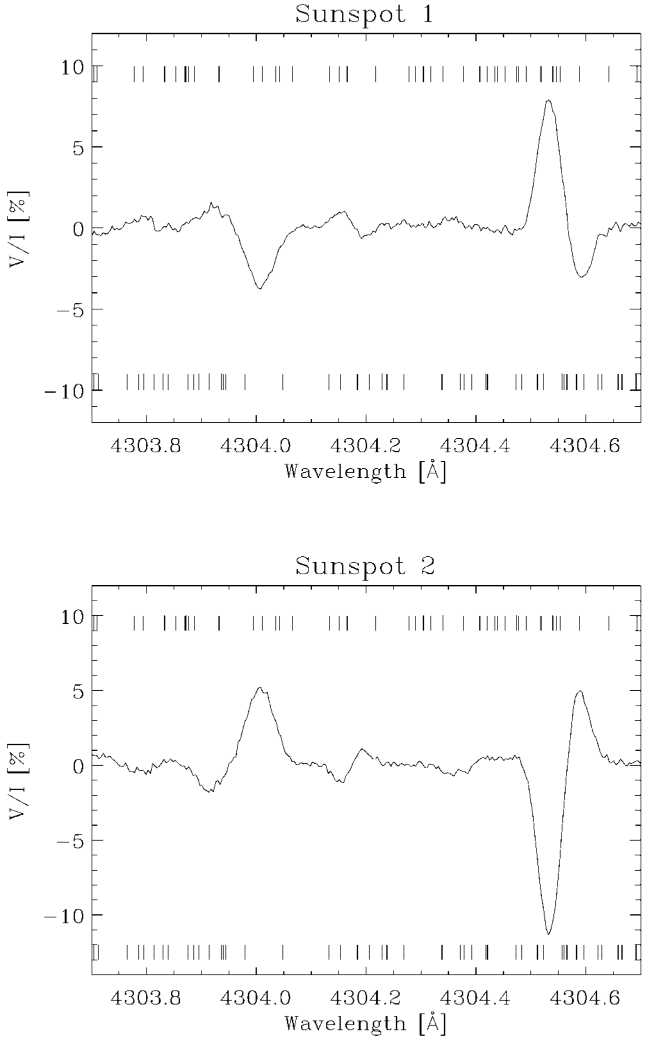

FIG. 2.—Observed *V*/*I* profiles in the two sunspots with opposite magnetic polarity for the 4304 Å spectral region. Compare with Fig. 1 and note the good agreement between the shapes of the calculated and observed *V*/*I* profiles. On the other hand, the calculated *V*/*I* amplitudes are significantly larger than the observed ones. The tick marks in the upper part of each panel indicate the position of an atomic line, while those in the lower part indicate the position of a CH line.

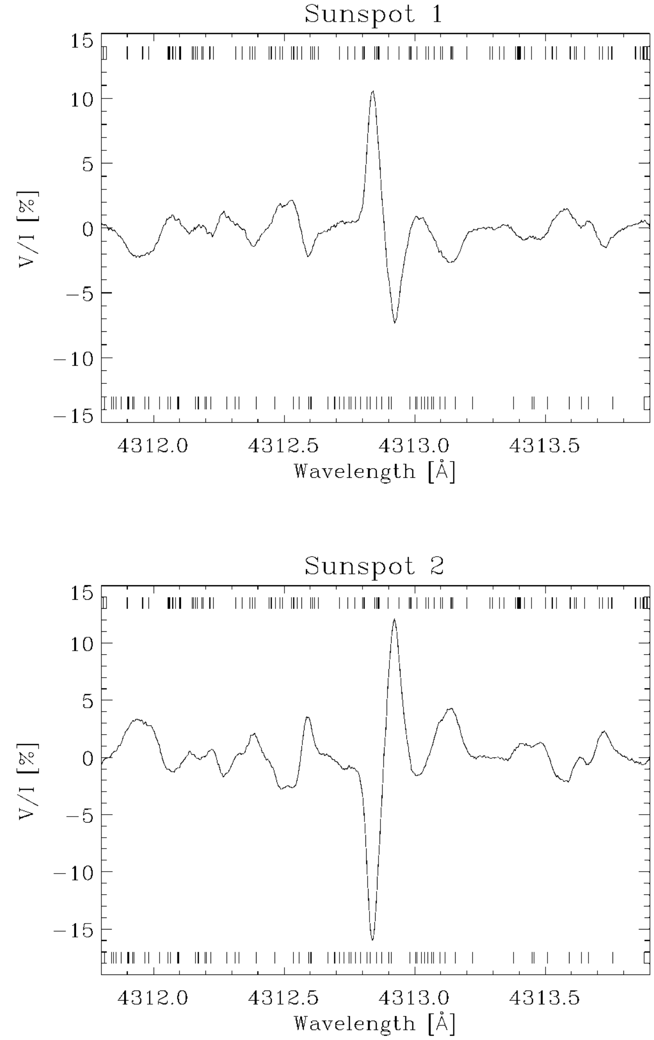

FIG. 3.—Observed *V*/*I* in the two sunspots with opposite magnetic polarity for the 4313 Å spectral region. Compare with Fig. 1 and note the good agreement between the shapes of the calculated and observed *V*/*I* profiles, especially concerning the spectral features dominated by CH transitions. Note that the curious shape of the *V*/*I* profile produced by CH lines at 4313.7 Å is very similar to the theoretical profile shown in Fig. 1. The calculated *V*/*I* amplitudes are again significantly larger than the observed ones. The tick marks in the upper part of each panel indicate the position of an atomic line, while those in the lower part indicate the position of a CH line.

region that also shows Stokes profiles dominated by CH lines only. Note the polarity reversal between the two observed sunspots and the good agreement with the shapes of the theoretical *V*/*I* profiles at 4312 and 4313.7 Å shown in Figure 1. The Stokes *V*/*I* profiles around 4313 Å are mainly due to atomic lines.

It is also interesting to mention that the observed linear polarization turns out to be very small at the above-mentioned wavelength locations that show *V*/*I* features dominated by CH lines. However, we have detected sizable *Q*/*I* signals (of the order of 1%) that are produced by atomic lines only. We find significant linear polarization *in both umbrae and penumbrae*, with the signals in the penumbral regions being slightly larger than in the umbral ones. Figure 4 shows an example of the observed fractional linear polarization in the penumbra of one of the observed sunspots. We think that the *Q*/*I* feature at 4304 Å is produced by the same CH lines that are responsible for the observed *V*/*I* profile shown in the left panel of Figure 1.

A comparison with Figure 1 shows that the agreement between the *shapes* of the calculated and the observed *V*/*I* profiles is remarkable. However, the *amplitudes* of the *V*/*I* profiles calculated in one-dimensional models of sunspot atmospheres are significantly larger than the observed ones when the theoretical modeling is carried out by assuming a magnetic filling factor $f = 1$ and a typical magnetic field strength of 2000 G, even after taking into account the reduction in the *V*/*I* amplitude obtained when accounting for the stray-light contamination mentioned in § 2. We consider this as an indication of the presence of horizontal inhomogeneities in the photospheric regions of sunspot umbrae coexisting within the spatiotemporal resolution element of the observation. These inhomogeneities might be associated with the multitude of umbral dots that are seen in high-resolution images of sunspots. Interestingly, our finding of linear polarization signals in the observed sunspot umbrae, which were located very close to the disk center during our observing period, could be indicating that the suggested umbral dot component has inclined magnetic fields, in agreement with the existing magnetohydrodynamic models for the subsurface structure of sunspots (see, e.g., the recent review by Socas-Navarro 2003).

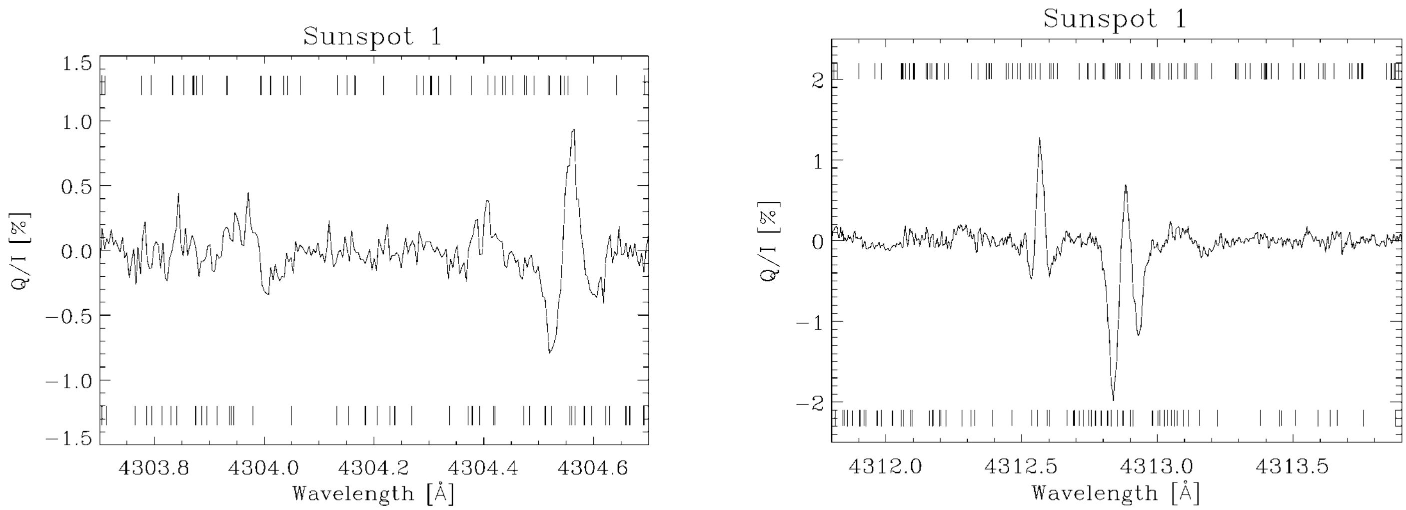

FIG. 4.—Observed Q/I profiles in the penumbra of sunspot 1. Note that the strongest Q/I signals are produced by the atomic lines that show the strongest V/I signals in Figs. 2 and 3. The reference direction for $Q > 0$ is along the slit.

4. CONCLUSIONS

The polarization profiles that we have observed in sunspots confirm our previous theoretical modeling of the longitudinal Zeeman effect in the G band. There are at least three wavelength locations that show measurable V/I profiles that are produced by CH lines only. In the sunspot group that we have observed (located at $\mu = 0.95$), the observed linear polarization at the wavelength location of such CH lines was very small but not negligible (see, e.g., the Q/I feature at 4304 Å in Fig. 4). However, we have found sizable circular and linear polarization signals in many of the atomic lines that are contained in the spectral region of the G band. Such polarization signals in molecular and atomic lines contain valuable information about the physical conditions in the solar atmosphere. For instance, a preliminary comparison between observed and calculated Stokes profiles suggests that the magnetic and/or thermodynamical properties in the photospheric regions of sunspot umbrae are horizontally structured with a component that might be associated with umbral dots.

We think that the theoretical interpretation of observations of the Zeeman effect in the G band offers a new diagnostic window for exploring the thermal and magnetic structuring of the solar photosphere. This type of investigation could help us to choose among competing MHD models on the subsurface structure of sunspot umbrae and/or to improve our physical understanding of the bright points of the "quiet" solar surface. In a future paper, we plan to address the issue of the inversion of spectropolarimetric observations in the G band since this also promises to be important for improving our knowledge of solar and stellar magnetism.

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