

Statement of Research

1 Research Goals

Magnetic fields are a major component in almost every process of the active Sun. However, our knowledge of magnetic fields, and therefore our knowledge the processes they take part in, is severely limited by our ability to measure the magnetic field. Spectral lines which are magnetically sensitive due to the Zeeman or Hanle effects give us information about the magnetic field over a continuum of heights in the solar atmosphere where they are formed. Lines formed over a narrow range of heights, as in the photosphere, give a fairly discrete measure of the magnetic field at a given optical depth. Lines formed over a broad range of heights, as in the chromosphere and corona, may encompass large gradients in the magnetic field or a large volume along the line of sight. Magnetic field measurements are therefore sensitive to the diagnostics used, the accuracy with which the observables are measured, and the interpretation of the observations by inversion techniques. **My research is targeted on improving our knowledge of the Sun's magnetic field**, and encompasses three major topics:

- How do instrumental short-comings affect our ability to accurately measure magnetic field diagnostics?
- How good are inversion techniques? How are their results related to the physical parameters of the Sun's atmosphere?
- What does the 3D magnetic field of the Sun look like?

During the course of my dissertation at the University of Hawai'i I encountered these questions through the development of new instrumentation which I used to conduct an observational study of sunspot magnetic fields, the analysis of those observations with inversion techniques, and the application of atmospheric models to derive results. At Montana State University I have continued this work, broadening my expertise working on a new instrument project, investigating multi-height spectropolarimetry, and comparing model spectra from numerical simulations with observations.

Here I will give a brief sketch of my research and outline my goals for ongoing and future work.

2 Past Research

2.1 Dissertation: Molecular Hydrogen and Sunspot Magnetohydrostatic Equilibrium

In a sunspot the vertical component of the magnetic field prevents the normal overturning motion of the photosphere, suppressing the convective transport of energy from the interior. The magnetic field also exerts a horizontal force which keeps the hot, high pressure quiet Sun from intruding into the cool, low pressure sunspot interior. By making some simplifying assumptions to the magnetohydrostatic force balance equation for an ideal, round sunspot, we find that there should exist a simple linear relationship between the magnetic pressure (B^2) and temperature (T) inside the sunspot. Early studies of this thermal-magnetic relation in sunspots seemed to confirm the linear relationship (eg. Gurman & House 1981), but these observations often suffered from poor spatial resolution and used observations from single-slit positions or data compiled from many sunspots. Modern spectropolarimeters and inversion techniques have made the detailed characterization of sunspot magnetic fields increasingly routine, and virtually all observations with sufficient spatial sampling show that the thermal-magnetic relation even in well-behaved sunspots can be highly non-linear (e.g. Mathew et al. 2004).

An example of the observed relation for the main sunspot in NOAA 11130 is shown in Figure 1. The sunspot penumbra (yellow +'s) is highly structured, non-static, and has a highly inclined field, and therefore cannot be included in our considerations of magnetohydrostatic equilibrium for the sunspot. The more static sunspot umbra (black x's) with its vertical field should be easily described by the thermal-magnetic relation, however this sunspot shows an unexpected sharp increase in the umbral magnetic field strength at low temperature. Various authors have ascribed the non-linear behavior in the thermal-magnetic relation to contributions

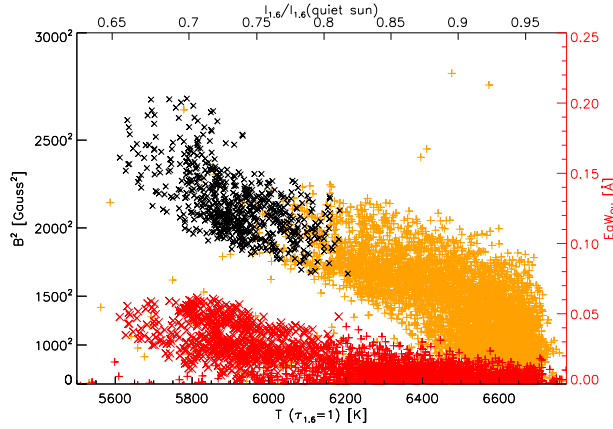


Figure 1: B^2 vs. the infrared continuum brightness temperature in the umbra (black) and penumbra (gold) and OH equivalent width (red) for the main sunspot in NOAA 11130. The relation was derived from Fe I 15650 Å observations taken with FIRS on Dec 2, 2010.

from radiative transfer effects (i.e. the Wilson Depression) and the magnetic curvature force which would tend to increase the slope of the thermal-magnetic relation. Neither of these effects can account for a purely vertical increase, therefore something else must be affecting the magnetohydrostatic equilibrium in the sunspot umbra.

The increasing equivalent width of OH (red points in Figure 1) in the umbra may provide a valuable insight into this mystery. The transition from a predominantly atomic gas to a molecular gas represents a phase change in the solar plasma. The OH molecule by itself does not comprise a significant fraction of the total particle number in the umbral atmosphere. However, OH has a similar dissociation energy to molecular hydrogen (H_2), which should be by far the most abundant molecule. Observations of the fluorescent H_2 lines in the ultraviolet have confirmed its presence in the chromosphere above sunspots (Jordan et al. 1978, Innes 2008), while atmospheric models of the sunspot umbra predict a H_2 population of up to 10%, peaking near the height of continuum formation (Maltby et al. 1986). If H_2 comprises a significant fraction of the total particle number in the sunspot umbra there are widespread consequences for sunspot physics. **The priority of my dissertation work was to observationally confirm the**

presence of H_2 in the sunspot photosphere and determine the effect of molecule formation on sunspot evolution. More details of this research are available in Jaeggli, Lin, & Uitenbroek (2012) and Jaeggli (2011).

FIRS Sunspot Survey

To obtain evidence of the evolutionary effects of molecule formation, I used the 6302/15650 Å configuration of the Facility Infrared Spectropolarimeter (FIRS) on the Dunn Solar Telescope (DST) to characterize the photospheric magnetic fields of a statistical sample of sunspots of different sizes and at different stages of their evolution. The 15650 Å spectra contain several strong OH lines in addition to the Zeeman-split Fe I lines. The finished sunspot sample consists of 61 observations from FIRS taken between July 2009 and December 2010. Haosheng Lin and I began commissioning FIRS in April 2007 and the instrument was completed in December 2009. A more detailed description of the instrument can be found in Jaeggli et al. (2010). In addition to aiding in the commissioning of FIRS, I have also been responsible for the development of the IDL reduction pipeline for processing observations. The reduction software, manuals, and additional information on the instrument are freely available and distributed to FIRS users through the web: <http://kopiko.ifa.hawaii.edu/firs>.

Inversion Techniques

I retrieved the detailed magnetic topology from the 6302 and 15650 Å observations by applying a Milne-Eddington inversion. I decided to develop my own code following the formalism of Jefferies, Lites, & Skumanich (1989). To confirm the validity of the solutions from my inversion code, I conducted a comparison of the results from 2C MO and those from the Milne-Eddington gRid Linear Inversion Network (MERLIN). MERLIN fits the same set of parameters as my code, and although the subtleties of the implementation, initialization, and calculation are different, the two codes describe the same physics and should produce similar results when performed on identical data. In Figure ?? I show the scatter-plot comparison of the magnetic field parameters from MERLIN and 2C MO inversions performed on a Fe I 6302 Å observation of the main sunspot in NOAA 11024 taken on July 7, 2009 by the Solar Optical Telescope Spectro-Polarimeter onboard the Hinode space-

craft. The two codes produce largely the same magnetic field strength in the umbra to within 70 G (rms). The increased scatter in the filling factor and magnetic field strength at low values demonstrates the problem with the ambiguity of these two variables.

Atmospheric Models

Because the abundance of photospheric H_2 cannot be measured directly, I established the theoretical relationship between the H_2 abundance and the equivalent width of the 15651.9 Å OH line using the Rybicky-Hummer (RH) radiative transfer and chemical equilibrium code developed by Han Uitenbroek. I supplied the code with 1-D plane parallel model atmosphere grids of different effective temperatures with solar gravity and abundances. The RH code produced a synthetic spectrum of the 15650 Å range including the Fe I and OH lines for each atmospheric model, from which the OH equivalent width was measured and could be compared with the infrared observations.

Survey Results

Although the FIRS sample was obtained sporadically throughout the minimum of solar cycle 23 and the beginning of cycle 24, it contains many sunspots ranging from tiny transient pores to large long-lasting sunspots. All of the sunspots with magnetic field strengths in excess of 2600 G show some form of non-linear behavior in the umbra, often an abrupt increase in slope in the coolest regions. The observed thermal-OH relation agrees surprisingly well with the theoretical relation from the RH code, providing additional confidence in its results. The large equivalent width of OH in these bigger sunspots indicates a H_2 fraction of around 3%. Smaller sunspots and pores with magnetic field strengths below 2600 G show little or no observed OH (less than 0.5% H_2) and fairly linear behavior of the B^2 vs. T relation, suggesting that in these sunspots the magnetic field does not provide a cool enough environment to allow H_2 molecules to form.

In the survey four of the sunspot observations show a sharp, sudden increase in the magnetic field strength of the umbra, including the example shown in Figure 1. These sunspots were all medium-sized, with a maximum umbral field of about 2700 G, and from the OH equivalent width we can infer that they all have just over 1% max-

imum molecular hydrogen content in the umbra. They are all in a state of quiescent evolution or slow decay, and are either monolithic spots or are the dominant sunspot in a multi-spot region. The umbrae of these spots also show small-scale dark features.

Molecules in Sunspot Evolution

These results indicate that the formation of molecular hydrogen may hasten the emergence of sunspots, and slow their decay. When molecules begin to form in a sunspot the internal pressure support must decrease with the number density of particles. The umbra must shrink a little to reach a new equilibrium, concentrating the magnetic field. Energy transport from below the umbra is suppressed further by the strengthened magnetic field, and the temperature decreases further allowing even more molecules to form. This feedback process, kept in check by radiative dissociation, would tend to rapidly concentrate the magnetic field during the emergence process, and increase the slope of the thermal-magnetic relation. This would explain a majority of the sunspot sample.

During the decay phase in a sunspot which has already formed a substantial H_2 population, as the sunspot atmosphere warms up, H_2 begins to dissociate, and the number density and pressure increases. The increase in pressure compresses the remaining regions with H_2 , concentrating the magnetic field, maintaining the cool interior, and safeguarding the sunspot against dissipation. This would continue to increase the slope of the existing thermal-magnetic relation, resulting in the steep upturn shown by the four unambiguous observations.

There is evidence that the formation of H_2 causes observable evolutionary effects in the thermal-magnetic relation of sunspots. This has widespread consequences for sunspot physics which must be addressed in future research. Molecules have rotational and vibrational degrees of freedom which do not contribute to the thermal signature of the gas. This ability to hide energy may explain where part of the solar irradiance goes when it is blocked by a sunspot (i.e. the sunspot irradiance problem).

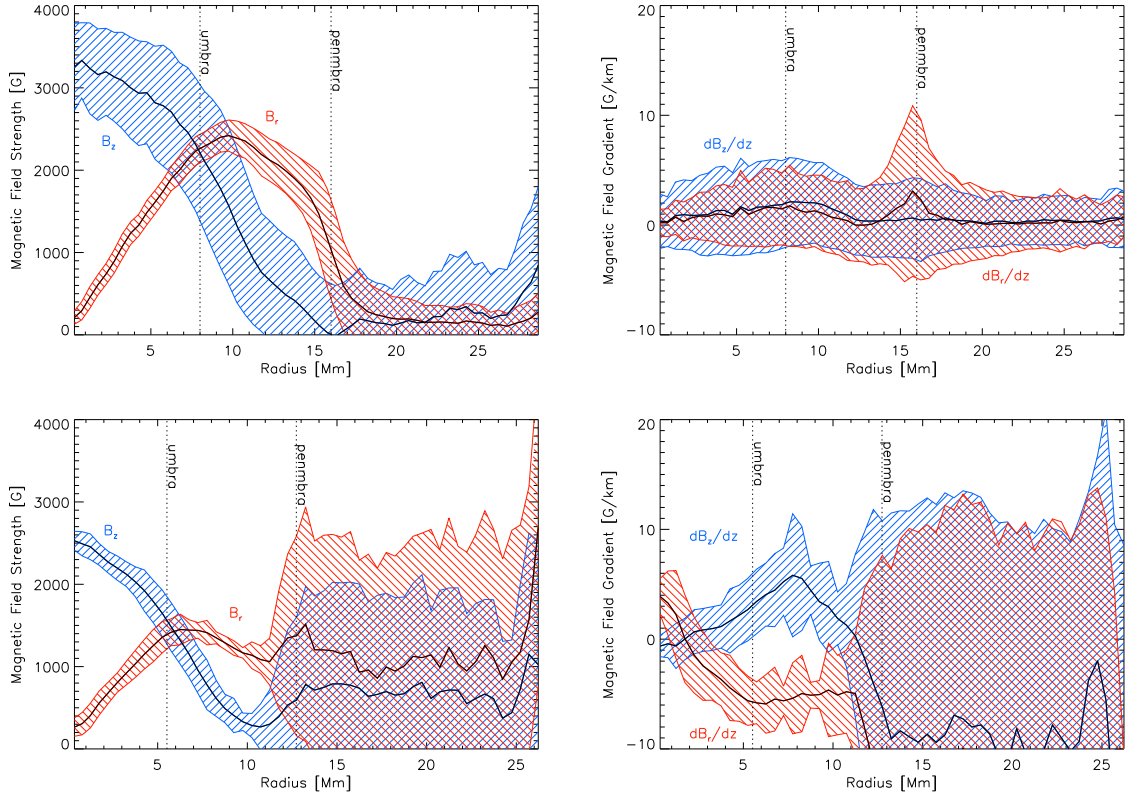


Figure 2: The vertical and horizontal components of the magnetic field (left panels), and their gradients (right panels) in the Rempel model sunspot (top panels) and an observed sunspot (bottom panels) as a function of radius.

3 Current and Ongoing Research

3.1 Comparison of Observations with a 3D MHD Sunspot Simulation

A natural continuation of my dissertation research stemmed from the question of how the thermal-magnetic relation looks in realistic MHD simulations of sunspots such as those shown in Rempel, Schussler, & Knolker (2009). As a preliminary part of this investigation I have compared the magnetic field from the Rempel sunspot model on surfaces of optical depth corresponding to the heights of formation of the Fe I 6302 and 15648 Å lines to a multi-wavelength observation of a fairly round sunspot from the FIRS sample. While the simulated and observed sunspots show similar intensity, vertical, and horizontal components of the magnetic field as a function of radius, the magnetic field gradi-

ents show very different forms as shown in Figure 2. These differences may be due to the lower resolution of the measurement by FIRS, that the model’s representation of reality is flawed in some way, or possibly a systematic difference in the measurement of magnetic field by the inversion technique.

More detailed comparison with the simulation requires detailed line synthesis, using the RH code for example. For her master’s thesis I have been mentoring MSU graduate student Erica Lastufka as she uses the Rempel sunspot model and RH to investigate the fundamental size limit of structures in the photosphere. She has been particularly interested in the effects of LTE and NLTE in 2D and 3D on the full-Stokes line profiles of the 6302 Å lines in discrete tube and sheet-like features found in the Rempel models. Her work will be a good starting point for full synthesis of the Rempel sunspot model.

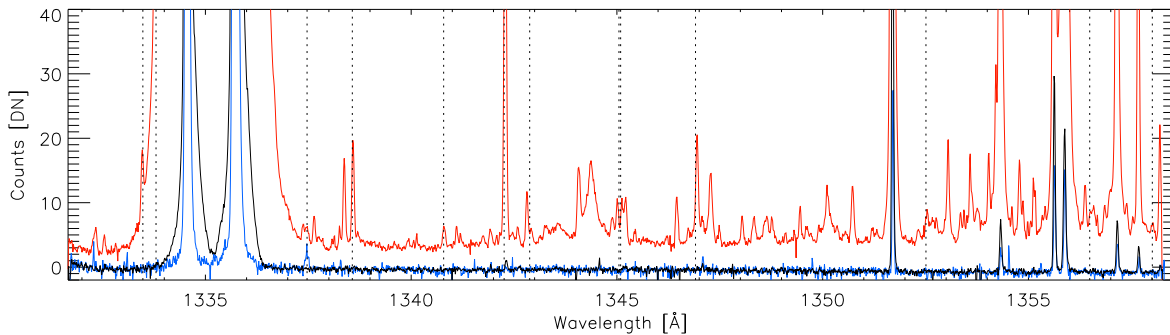


Figure 3: Average spectra from a flaring region (red), a sunspot umbra (black), and a light bridge across a sunspot, from the short wavelength channel of the IRIS FUV spectrograph. H_2 lines are indicated by the dotted lines.

3.2 IRIS

The Interface Region Imaging Spectrograph has provided me with an opportunity to directly measure the molecular content of sunspots using the fluorescent Lyman bands of H_2 to provide an independent measure of the results of my dissertation. IRIS represents a significant improvement over previous spectrographs at this wavelength, with considerably better sensitivity and spatial resolution. From the results of SUMER (Innes 2008, Schule et al. 1999) and HRTS (Jordan et al. 1978, Bartoe et al. 1979) I expected to see these lines prominently around active region features, in sunspots, and in flare spectra. New results from IRIS show that these lines are prominent in flare spectra, but are much fainter in sunspots than e.g. the results from Innes (2008). This is likely due to the excitation pathways, which are activated by CII, SiIV, and O IV, which are faint directly over sunspots, instead of Ly α which excites the shorter wavelength lines. Figure 3 shows an example of an average flare spectrum and umbral spectrum in the FUV short wavelength channel. Considerable modeling effort is necessary in order to properly interpret the strength of the H_2 lines, which is dependent on column density and the excitation source. This work is currently underway. In addition to providing information regarding the molecular content of sunspots, H_2 could also be used to measure the impact of flare energy on the photosphere.

Working on IRIS has also given me a considerable amount of instrument experience. As part

of my post-doctoral duties at Montana State University, I have been involved in a variety of pre- and in-flight calibration activities for the Interface Region Imaging Spectrograph (IRIS), these include: characterization of the instrument flat fields, characterization and correction of the FUV stray light background, characterization of the detector properties, correction of spectra for the effects of spectral geometry, determination of the most optimal method for the compression of images transmitted to the ground, deconvolution of the non-stationary PSF of the NUV slit-jaw imager, and measurement of the partial polarization of the NUV spectrograph. I have also been involved with planning observations, and I coordinated ground-based observations between IRIS and the DST. Working on calibration, instrumental problems, and observing experience has given me special insight into the analysis of IRIS data and the kinds of scientific observations that are possible with IRIS.

3.3 Transit of Venus

The transit of Venus in June 2012 provided a unique chance to view a well studied planetary atmosphere as we might see that of a transiting exoplanet, through scattered and refracted illumination of its parent star. This is the second time that Venus's IR atmospheric transmission has been measured during a transit; previous observations were made with the Tenerife Infrared Polarimeter during the 2004 transit by Hedelt et al. (2011), who confirmed well established isotopic abundances and atmospheric scale height.

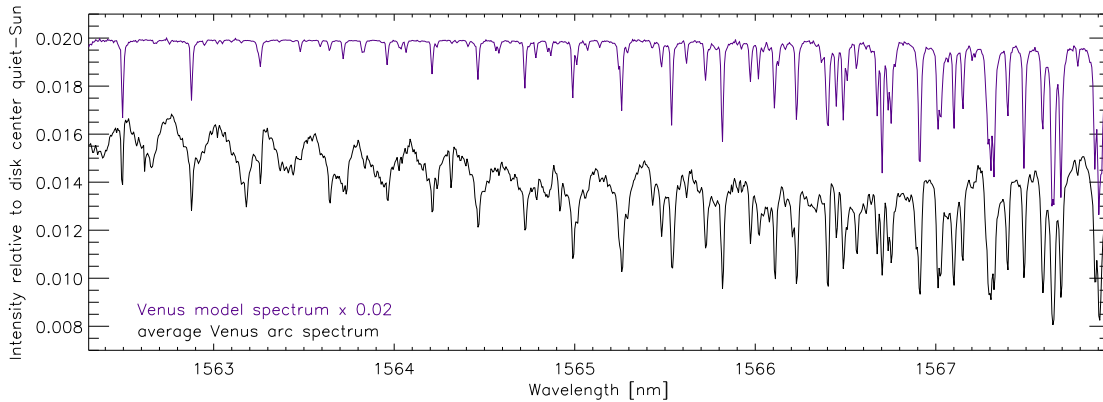


Figure 4: An average spectrum of the aureole of Venus taken after first contact on June 5, 2012 (black), and an atmospheric model of Venus (violet).

As part of the Williams College Venus Transit Expedition led by Jay Pasachoff, I performed spectroscopy and polarimetry during the transit of Venus using FIRS, focusing on extracting signatures of CO_2 absorption. An average spectrum of the off-limb arc of Venus, or aureole, is shown in Figure 4. A synthetic spectrum of the Venus model atmosphere provided by Pascal Hedelt was resampled and convolved with the FIRS spectrograph profile to produce the model spectrum shown in violet. The strong agreement between the observed and model spectra is highly encouraging for further analysis of this dataset. Polarimetry was performed after Venus had moved onto the solar disk, however no polarization signal from Venus is apparent even in highly averaged data.

The transit also provided the opportunity to characterize stray light and other instrumental properties of FIRS. The off-limb scans during the transit revealed that a component of the stray light in FIRS is actually a faint and spatially offset version of the image, probably due to a back-reflection upstream from the spectrograph in the telescope. The processing of the Venus data has lead to further analysis of optical and digital fringes due to the infrared optics and array detector respectively. More rigorous analysis and removal of the fringe patterns will greatly improve analysis of this and other datasets from FIRS.

4 Future Research

As my previous research indicates, I have gained a wide variety of skills and experiences across the discipline of solar physics. While I intend to continue my observational and theoretical research of sunspots, my primary interest is the development of new instruments and observational techniques. The new flagship facilities for solar research which are currently operating (SDO, Hinode, NST) and those under development (GREGOR, ATST, EST, Solar-C) will continue to provide unprecedented tools for the investigation of solar magnetic fields. These facilities are a crucial proving ground for new technologies and techniques which will advance understanding of the Sun and its phenomena. It is my goal to gain a diverse experience and become an independent researcher capable of leading a major instrumentation project to explore the full potential of these exciting new facilities.

4.1 He I 10830 Å Spectropolarimetry

The He I lines at 10830 Å are a magnetic field diagnostic with enormous potential because they are sensitive to both strong magnetic fields due to the Zeeman effect and weak magnetic fields due to the Hanle effect. The lines of 10830 are formed high up in the chromosphere, so combined with other chromospheric and photospheric magnetic field diagnostics it could be a powerful tool for investigating the 3D structure of the Sun's magnetic field. One of the biggest

obstacles to a successful observation with He I 10830 Å is measuring the linear polarization with sufficient sensitivity. The Stokes Q and U components of the lines are often just a few percent, close to the photon counting noise for a typical spectropolarimeter with a signal to noise ratio of $\sim 10^3$. Instrumental errors due to the camera, flat field errors, instrumental polarization, and optical fringing further frustrate efforts to measure the linear polarization (see Casini, Judge, & Schad 2012), however the measurement is ultimately limited by the full-well capacity of the detector.

The difficulty with measuring the polarization in the 10830 Å lines needs to be addressed in the design of the spectropolarimeters for the Solar-C mission and for ATST. A ground-based test of a high-dynamic range spectropolarimeter would provide an excellent test-bed for the Solar-C instrument. The instrument Zurich Imaging Stokes Polarimeter (ZIMPOL, Stenflo & Keller, 1997) uses a combination of fast chopping of the polarimeter and on-detector charge shifting to achieve detection of polarization signals at the level of 10^{-5} of the continuum intensity. I believe that such techniques combined with a modern silicon detector sensitive to the IR can produce results superior to ZIMPOL. I intend to further investigate possibilities for polarization and charge shuffling schemes to make this instrument a reality.

4.2 CLASP

The Chromospheric Lyman Alpha Spectropolarimeter (CLASP) sounding rocket mission will provide a unique opportunity to expand our knowledge of chromospheric magnetic fields with the largely unexplored diagnostic of the Hanle effect in Lyman α . I believe that with my experience on IRIS and FIRS I can greatly contribute to the preparation of instruments for the CLASP mission. It appears that a detailed line synthesis and modeling effort is already underway for CLASP. With atmospheric models from Bifrost, such as those we have used on the IRIS mission, I can also participate in this effort, using the RH code to generate the full-Stokes spectra so that we can gain a physical intuition for the polarization spectra in a variety of chromospheric features before flight.

My research is targeted at improving the way the Sun's magnetic field is measured. Through a multi-faceted approach I intend to build observational and analytical tools to provide greater accuracy to the measurement and interpretation of magnetic field diagnostics, and contribute to a clearer understand of the Sun's magnetic processes.

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