

Measurement of the Polarization of the Flash Spectrum during a Total Solar Eclipse.

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Abstract. Total solar eclipses offer the unique opportunity for a clean observation of the light emitted by different chromospheric layers without being disturbed by photospheric stray light, since the moon is operating as a sharp knife edge. During the 29th March 2006 total solar eclipse we thus performed a pioneering measurement of the polarization of the flash spectrum from UV to the near IR with a spectral resolution of order 0.6 nm. The measurement has been obtained with a dedicated instrument composed of an 8-inch Dall-Kirkham type telescope and a slitless spectropolarimeter. The complete flash phase at the second contact was observed with a cadence of 25 frames per second corresponding to a height resolution of about 20 km in the solar atmosphere. We could nicely register the dramatic transition from an absorption-line spectrum to an emission spectrum dominated by the strong chromospheric resonance lines. At the third contact we recorded the opposite transition with a variable frame rate reaching up to 75 frames per second.

1. Introduction

The chromospheric emission spectrum, called flash spectrum, has already been recorded successfully during multiple eclipse expeditions (Cillié and Menzel 1935; Mitchell 1947; Dunn *et al.* 1968; Shen *et al.* 1981). The mentioned authors have compiled catalogues itemizing the calibrated absolute fluxes of more than a thousand emission lines in the range 300 to 910 nm. The spectra of Dunn *et al.* (1968) cover 4500 km on the Sun with a height resolution of 100 km in the direction of lunar movement. Although these data lack polarization information, they have been very helpful for the design of our instrument, allowing us to narrow down the required sensitivity range.

In terms of polarimetry we know of two past eclipse observations, which allowed to set an upper limit of 5% for the Ca II K line (Hanson *et al.* 1976) and a general upper limit of 10% estimated by eye for the whole optical spectrum (Stokley 1948).

The flash spectrum is extremely difficult to observe outside an eclipse. The steep intensity decrease at the extreme limb of the Sun makes a coronagraph very vulnerable to stray light caused by the earth's atmosphere and by the optics of the instrument itself. The main challenge here is the occulting disc. It must not exceed the solar disc by more than a fraction of an arcsecond, to properly isolate the thin chromospheric layer from the photosphere while still leaving it uncovered. Another serious drawback of out-of-eclipse observations is

the spatial resolution of current solar telescopes, which is limited to about 100 km. In contrast, as the eclipsing Moon is moving at a relative speed of about 350 km/s, a height resolution of order 10 km on the Sun can already be achieved with a moderate rate of 50 frames/s.

The lunar limb is somewhat serrated, but the corresponding height variations can be easily accounted for (Espenak and Anderson 2004) since our spatial resolution is about $5''$ in the limb direction.

The scientific rationale of our observations is described in detail by Stenflo (2006). A theoretical reference has been developed by Chandrasekhar (1950) in terms of an idealized model for a plane-parallel purely scattering atmosphere. The conditions at the extreme limb of the Sun are approaching this Chandrasekhar limit, but the real polarization can nevertheless be significantly influenced by different physical processes: the relative importance of different opacities, collisions, deviation from plane-parallel stratification (spherical geometry at the limb, small scale inhomogeneities), atomic physics (quantum interference, optical pumping), radiative-transfer physics and magnetic fields (Hanle effect). These processes affect the individual spectral lines in different ways. By recording a large part of the spectrum, we may be able to untangle and quantify them with the help of differential diagnostics.

2. Instrument

2.1. Sensitivity

When designing a polarimeter one has to make a trade-off between spatial, spectral, and time resolution and polarimetric sensitivity. The chromospheric sickle is not resolved in practice in the direction of lunar movement, because of the steep intensity drop with height.

The huge dynamic range between the strongest ($H\alpha$) and the weak lines of interest cannot be handled by the camera at once. At maximum frame rate the instrument has to be sensitive enough to just saturate in the weak lines at the beginning of the flash phase. The stronger lines will then drop into the sensitivity range later on. It is important to have a CCD with an anti-blooming factor of at least $1000 \times$ saturation, to avoid any crosstalk from the strong lines during the saturated phase. As we were able to obtain a very fast F/2.8 spectrograph, we can adequately expose the camera with a modest and easily transportable 8-inch telescope (see Fig. 1).

Close to saturation the intensity signal to noise ratio, given by photon-statistics, is about 250. This meets the requirements on polarimetric precision and is adequately sampled with a 10 bit A/D conversion (*cf.* Table 1). At less than $0.1 \times$ saturation the readout noise begins to dominate. Dark current is negligible. For a more detailed discussion see Feller et al. (2006).

2.2. Telescope and spectropolarimeter unit

The telescope is an 8-inch Dall-Kirkham Cassegrain reflector. The imaging is nearly diffraction limited within our small field of view and the Cassegrain design is virtually free of instrumental polarization.

spectral range	340 - 870 nm
spectral sampling	0.21 nm/pixel
time resolution	13 - 40 ms
spatial sampling	5"/pixel
field of view	150"
sampling	50 e ⁻ /count, 10 bit
anti-blooming factor	1000

Table 1. Main instrument characteristics.

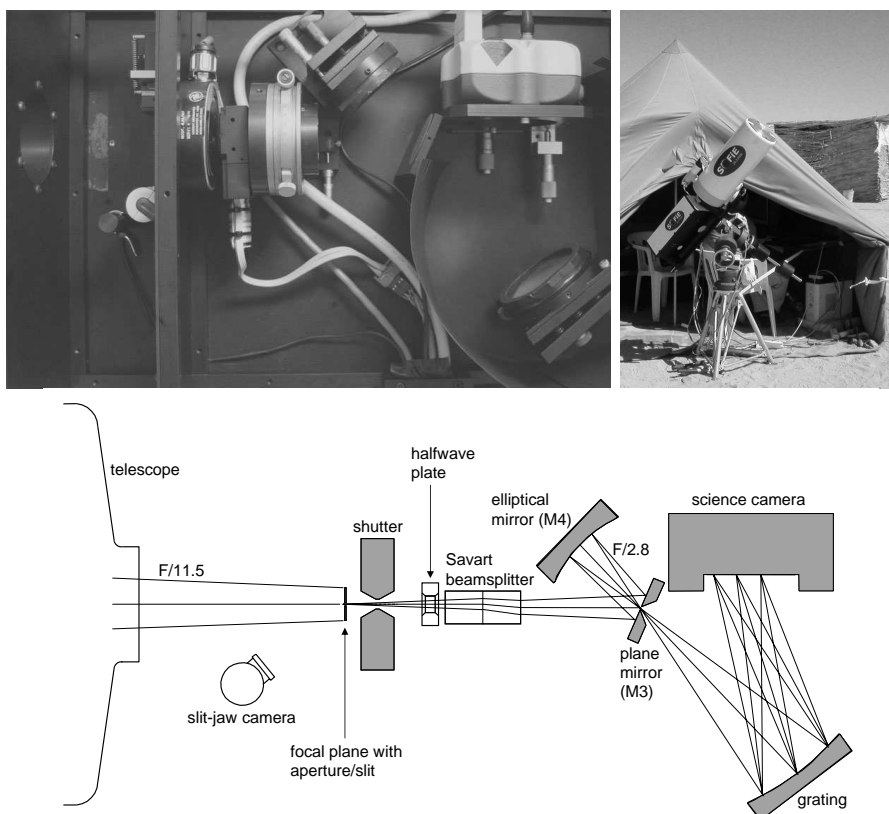


Figure 1. **Bottom:** optical setup. **Top left:** top view of the spectropolarimeter unit. **Top right:** overview of the setup at the eclipse site near Waw an Namos, Libya. The spectropolarimeter unit is mounted behind the telescope. In the background one can see the tent which is used as work place and protection for the electronic equipment. The electrical power of the whole setup (150-200 W) is provided by fuel generators and secured with a UPS.

A scaled drawing and a close-up photograph of the spectropolarimeter unit are shown in Fig. 1. To keep the optical efficiency high and chromatic aberrations at a minimum, the use of glass in the beam path is avoided, except for the half wave plate and the beam splitter. At the telescope focus one can choose between a 50 μm slit of length 1.6 mm and an aperture of 1.6 mm \times 1.6 mm. With the slit

we record calibration spectra of the solar disk or a spectral lamp. The aperture is used for the actual observation of the flash spectrum. This slitless mode has some important advantages: it allows the imaging of extended solar structures and relaxes the tolerances on guiding and pointing of the telescope. Then again we observed disadvantages like aberrations caused by an off-axis position of the sickle or the smearing of nearby spectral lines.

In terms of polarimetry we opt for a Savart beam splitter. It is installed in the slower F/11.5 beam to keep its aberrations below the size of a pixel. The disadvantage of this position is the need of rather thick calcite elements. We have 2×22.8 mm, giving us a beam separation between 3.40 and 3.76 mm, depending on wavelength. To eliminate the effect of the polarization dependent grating efficiency, the beam splitter has to be turned so that the polarization direction of both beams is oriented $\pm 45^\circ$ to the grooves of the grating. A half wave plate is needed in this context to realign the Moon's limb with the direction of Stokes $+Q$. We renounce the use of true beam exchange because of the intricacies of getting an adequate fast-switchable and achromatic half wave plate. Instead the retarder is turned mechanically by 45° one single time between the two flash phases of second and third contact.

After the Savart plate the two beams are deflected by a plane mirror (M3) with a circular hole of 2.5 mm diameter, reduced by an elliptical mirror (M4) to F/2.8 and then focused through the hole in M3 into the spectrograph.

The spectrograph consists of an aberration corrected holographic concave grating with 405 grooves/mm, serving as both the dispersive and focussing element. Operated in first order it provides a practically linear dispersion of 0.21 nm/pixel over the whole wavelength range. The grating efficiency varies between about 45% (393 nm) and 23% (866 nm). We find however a significant residual astigmatism, clearly dominating the total aberrations of the instrument. As a trade-off we adjust the grating and camera position to align the detector plane as good as possible with the spectral focal plane, but accepting therefore a strong wavelength dependent spatial defocussing.

Both the telescope and the spectropolarimeter unit are assembled on a parallactic mounting with computer-controlled stepping motors on both axes. The guiding and pointing accuracies in the hour axis are limited by the worm gear which has a period of about 12 minutes at guiding speed and a mean amplitude of some $40''$. Due to their periodicity, the hour axis errors can at least be partly compensated with the guiding software. The guiding and pointing accuracies in the declination axis are of order $1''/\text{minute}$ and $10''$ respectively and can be neglected for our purpose. The knowledge of the pointing accuracies is crucial for the eclipse observations as the telescope has to be moved blindly to the opposite limb during totality. It defines the minimum size of the aperture in the spectropolarimeter unit.

Our observing spot is located near Waw an Namos in the Sahara of southern Libya (24:28:03 N, 17:57:52 E), on the center line of the eclipse path and close to the point of maximum duration of totality. The center-line position is necessary to avoid sickle movements during the flash phases and it has the advantage that the sickles of second and third contact are parallel.

2.3. Instrument control and observing procedure

The science camera and shutter as well as the rotation of the half wave plate are controlled with software developed in-house and optimized for the particular requirements of the eclipse observation.

The time server is providing UTC with an accuracy of about 10 ms, which corresponds to the time resolution of the instrument.

For accurate pointing on the Sun a special guiding software has been developed in-house which uses the solar limb as reference frame. Before the first contact the pointing position is determined by scanning the solar disc in the two axis directions with the spectropolarimeter in slit-mode, and determining the limb position by the corresponding inflection point in the measured intensity. First contact is used to check the positioning and orientation of the spectropolarimeter. Measurements started 30 seconds before second contact at a fixed rate of 25 frames per second and lasted for more than one minute. The third contact was observed with variable rates between 25 and 75 frames per second, based on a visual evaluation of the flash intensity. After the eclipse dark and flat calibration were performed. In addition the reference spectrum of a Rb I lamp was recorded.

3. Conclusions and outlook

The instrument described here has been developed and built from scratch within one year for the 29 March 2006 eclipse. The observing location in the desert, hundreds of km away from any infrastructure, called for robust, compact, reliable and completely autonomous equipment as well as elaborate logistics.

Despite all these challenges the equipment was running faultlessly. The eclipse was passing under ideal weather conditions and we were able to measure both flash phases of second and third contacts, on opposite solar limb positions.

Our requirements were however not entirely satisfied. The main drawback of the instrument is the residual aberrations caused by the grating, in particular the differential effects between the two beams (*cf.* Fig. 2). They have been discovered only during the tests of the final instrument, and we were not able to fully resolve them in due time. On the other hand the slitless mode has proven to be an advantage for isolated spectral lines like $H\alpha$, allowing to image extended structures like a prominence, but a disadvantage for adjacent lines like He D₃, Na D₁ and D₂.

The data reduction is still ongoing, and the results as well as the reduction techniques will be discussed in detail in a later publication. The main challenge is to study and model the aberrations in order to determine the cospatial regions in both images and to improve the spatial resolution in some parts of the spectrum.

Finally we are already thinking of incorporating our experiences for a second generation eclipse experiment. The key enhancements we will be working on are the replacement of the slitless mode with an array of optical fibers, the use of an Echelle grating, and a true achromatic beam exchange.

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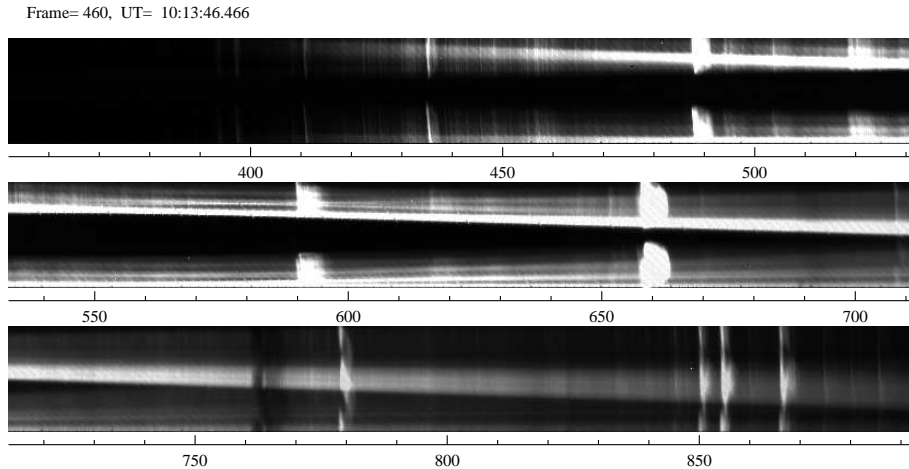


Figure 2. Sample frame from the flash phase at second contact, representing the raw data (only corrected for bias and flat field). The scale gives the wavelength in nm. The two orthogonally polarized spectra are imaged above each other. Since the separation between them is strongly wavelength dependent, they are well separated in the UV (so well that vignetting is severe), while they significantly overlap in the infrared. While some strong lines, like $H\beta$, the Helium D3 lines, and $H\alpha$, are still saturated in this particular frame, the Ca H and K lines in the UV are already quite faint. The almost horizontal bright band represents the remaining part of the photospheric sickle. In this frame one can discern the main instrumental problems: vignetting, overlap, and aberrations, in particular the differential effects between the two spectra.

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