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High-resolution solar polarimetry with *Sunrise*

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Abstract. *Sunrise* is a solar telescope with an aperture of 1 m, and is dedicated for spectropolarimetric measurements in the visible and the near UV. The total wavelength range is 200 to 1000 nm for narrowband imaging and diagnostic spectroscopy. *Sunrise* is planned as a stratospheric long-duration balloon mission with a first flight in 2006.

Key words: telescopes – techniques: polarimetric

1. Overview

Sunrise is a light-weight solar telescope with 1 m aperture for spectro-polarimetric observations of the solar atmosphere on the intrinsic spatial scale of its magnetic structure. Initially, the telescope will be operated during a series of long-duration balloon flights in order to obtain diffraction-limited image quality and to study the UV spectral region down to $\simeq$ 200 nm, which is not accessible from the ground. Later, the telescope shall become the core instrument of a space-borne solar observatory. The light-weight mirror technology developed in the course of this project is a major step towards affordable large telescopes in space for astronomical and Earth-observation purposes.

Sunrise is a joint project of the Max-Planck-Institut für Aeronomie (MPAe), Katlenburg-Lindau (P.I.: S. K. Solanki), with the Kiepenheuer-Institut für Sonnenphysik (KIS), Freiburg, the High Altitude Observatory (HAO), Boulder, the Lockheed-Martin Solar and Astrophysics Lab. (LMSAL), Palo Alto, and the Instituto de Astrofísica de Canarias (IAC), Tenerife. Funding institutions are the respective national space agencies of the participating countries.

2. Scientific objectives

Solar magnetism provides one of the great challenges of astrophysics. Its intricate field structure exemplifies cosmic magnetic fields. Its modulation affects the human environment.

The central aim of *Sunrise* is to understand the structure and dynamics of the magnetic field in the solar atmosphere. The magnetic field is the source of solar activity, controls the space environment of the Earth and causes the variability of solar irradiance, which may be a significant driver of long-term changes of the terrestrial climate. Interacting with the convective flow field, the magnetic field in the solar photosphere develops intense field concentrations on scales below 100 km, which are crucial for the dynamics and energetics of the whole solar atmosphere. These spatial scales cannot be studied systematically from the ground because of image distortion by turbulence in the lower atmosphere of the Earth. The balloon-borne *Sunrise* telescope will, for the first time, provide measurements of the magnetic structure of the solar atmosphere on its intrinsic spatial and temporal scales. These measurements will directly attack basic problems:

- What are the origin and the properties of the intermittent magnetic structure?
- How is the magnetic field brought to and removed from the solar surface?
- How does the field provide momentum and energy for the outer solar atmosphere?
- How does the magnetic field variation modify the solar brightness?

These questions are of fundamental importance, not only for understanding the influence of solar activity on the human environment but also for astrophysics in general. The

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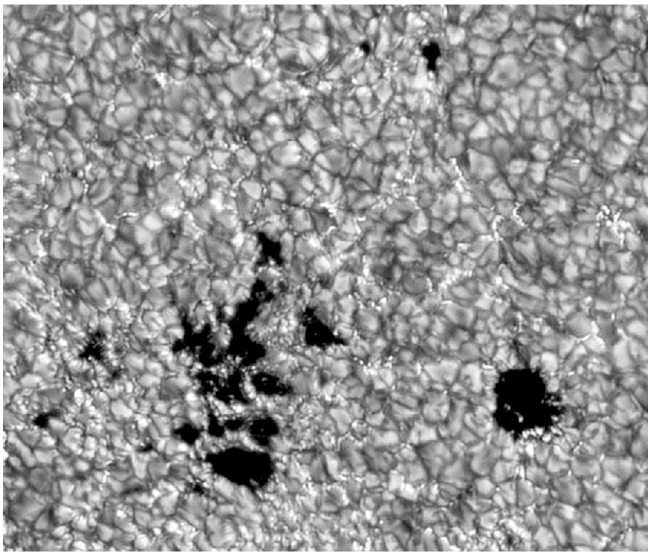

Fig. 1. Granulation, pores, and magnetic elements in the solar photosphere as visible in the Fraunhofer G band at 430.4 nm, a wavelength range dominated by lines formed by the CH molecule. While larger magnetic structures are darker than the average photosphere, small-scale magnetic concentrations appear bright, possibly due to local plasma heating. The magnetic flux outside the pores resides in tiny field elements located in the dark intergranular lanes (convective downflow regions). Their actual size is below the $\simeq 200$ km resolution of the telescope. The field of view is about 40 Mm×35 Mm on the Sun; this corresponds roughly to the field of view of the Sunrise telescope with a 1 k×1 k detector and 0.05 arcsec pixels (image taken by G. Scharmer on 18 Sep. 1993 with the Swedish Vacuum Solar Telecope at the Roque de los Muchachos Observatory on La Palma, Spain).

universe abounds with objects that are dominated by magnetohydrodynamical and plasma processes, but of all astronomical objects only the Sun offers the possibility to directly and quantitatively investigate these processes with sufficient resolution.

3. Instrumentation

The 1-m Gregory telescope with silicon carbide lightweight mirrors provides diffraction-limited spatial resolution down to 0.05 arcsec at 200 nm, corresponding to $\simeq$ 35 km on the Sun. The telescope is kept aligned and focussed by an innovative control system based upon a wavefront sensor. Image stabilisation is achieved with a correlation tracker controlling a high-speed steering mirror. A 10-cm telescope with a 4k×4k pixel CCD provides full-disk images and will be used for local helioseismology with high-degree acoustic oscillations. The 1-m main telescope feeds a focal-plane package consisting of a spectrograph-polarimeter for high-precision spectral line measurements of the four Stokes parameters, a filtergraph for high-resolution images in the visible and the UV, and a magnetograph providing two-dimensional maps of the complete magnetic field vector and the line-of-sight velocity.

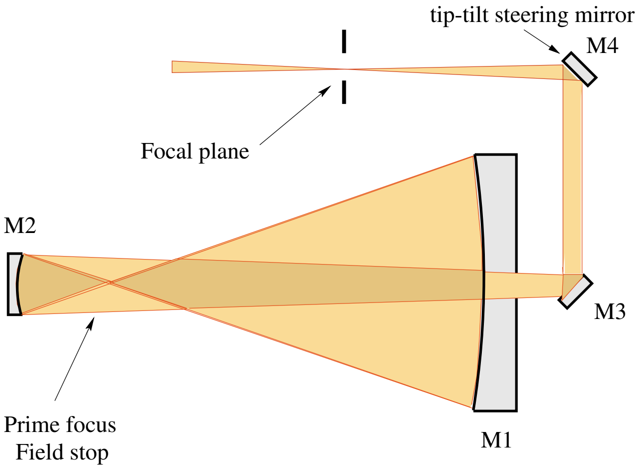

Fig. 2. Optical layout of the telescope. A field stop (not shown) at the prime focus reflects most of the incoming light out of the telescope. M3 and M4 are folding mirrors. The final focal plane is located inside the spectrograph-polarimeter unit (denoted F2 in Fig. 4).

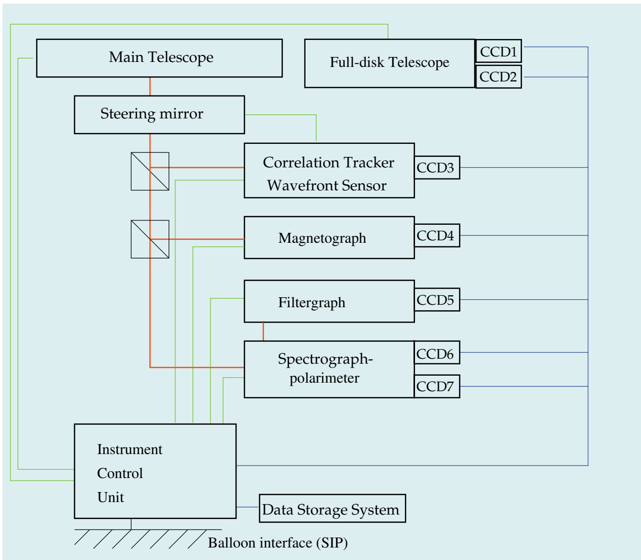

Fig. 3. Instrument block diagram. The light from the main telescope is fed into the focal-plane instruments: the spectrograph-polarimeter, the filtergraph, and the magnetograph. The wavefront sensor in the correlation tracker unit provides control signals for both the steering mirror (image stabilisation) and for the adjustment system of the secondary mirror (telescope alignment and focus). The full-disk telescope is used for (intensity) helioseismology, pointing, and target selection. All instruments and data flows are controlled by a central Instrument Control Unit. The red lines indicate light paths, blue lines are data connections, and green lines signify control connections.

3.1. Full disk telescope

The Full Disk Telescope serves multiple purposes:

- It provides the guiding information on the arcsec level, one stage before the correlation tracker.
- Full-disk images in a broad-band channel are used to identify and select the targets for the high-resolution instruments.

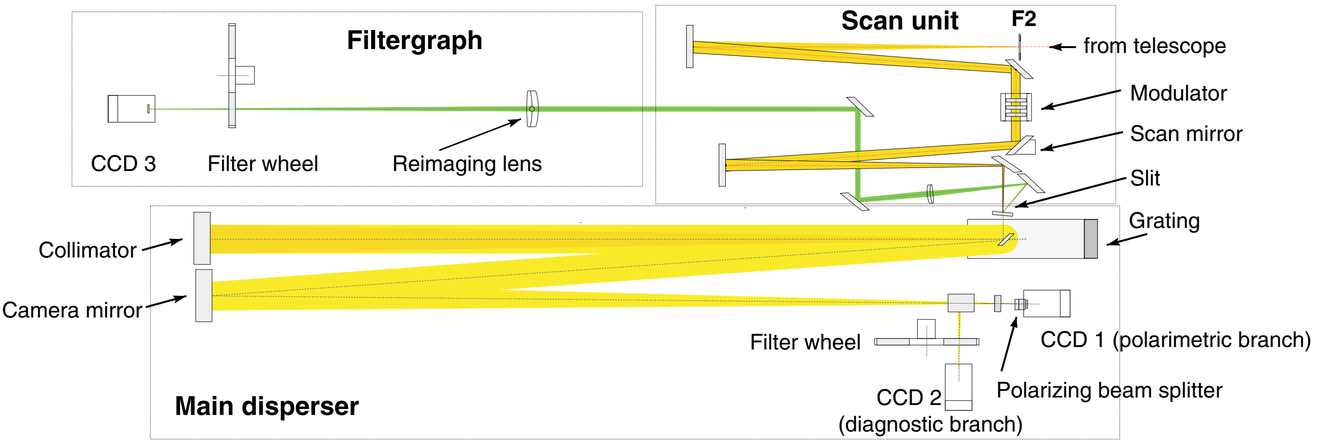

Fig. 4. Scheme of the spectrograph-polarimeter and the filtergraph. The light beam from the telescope enters at F2. After traversing the scan unit and the rotating polarimetric modulator it enters the main disperser through the entrance slit. The slit jaws reflect the remaining light into the filtergraph (green light path). The spectrum formed in the main disperser is shared by the polarimetric branch (CCD 1) and the diagnostic branch (CCD 2). The spectral band observed in the diagnostic branch is selected by way of a set of narrow-band filters mounted on a filter wheel. All distances are drawn to scale.

– Velocity maps obtained by a narrow-band tunable filter system are used to measure high-degree solar oscillations.

The instrument consists of a Cassegrain or Ritchey-Chrétien mirror system with 10 cm aperture and an effective focal length of about 4 m, a beam splitter to divide the light between the broad-band guiding channel and the narrow-band helioseismic channel with the corresponding filter systems, and large format CCD detectors for the guiding channel and the helioseismic channel. The latter provides images and velocity maps of the full sun with a spatial resolution of 1 arcsec.

3.2. Wavefront control system

The optical alignment of *Sunrise* is an important and critical issue. Because of the large temperature differences between ground and flight conditions it is important to have reliable and accurate in-flight alignment capabilities. To this end (and based upon experience available at LMSAL and KIS) we propose a wavefront control system that is capable of detecting low-order modes of wavefront deformations in the telescope. A wavefront sensor measures the actual state of the optical alignment and generates an appropriate error signal. A control system converts this error signal into actuation signals which are used to drive the position of the secondary mirror, M2, and the tip-tilt mirror, M4.

The detection principle is based on a correlation tracker. Instead of sensing the position of a single image derived from the entire pupil of the telescope, seven subapertures sense the local wavefront tilt across the pupil. The information derived from the seven independently analysed images of the same solar scene suffices to determine the coefficients of a Zernike function decomposition of the wavefront error up to the third radial degree. The coefficients for tip and tilt, defocus, and Seidel coma are used as error signals for the control system.

3.3. Spectrograph

The spectrograph-polarimeter (SP) combines the power of a high-resolution vector-polarimeter having a polarimetric accuracy of 10^{-4} with the versatility of a multi-line Echelle spectrograph, simultaneously providing photospheric magnetic field measurements (polarimetric branch) and diagnostic spectroscopy of photospheric and chromospheric lines (diagnostic branch). The SP is based on an all-mirror Echelle spectrograph in a modified Littrow configuration. It consists of four subsystems: the scan unit, the main disperser, the polarimetry unit, and the slit-jaw imaging unit. The latter is used as a multi-wavelength filtergraph (see following section).

3.4. Filtergraph

The filtergraph (FG) is realized as a multi-wavelength slit-jaw camera of the spectrograph-polarimeter. Both instruments receive the full amount of light in all wavelengths. The image of the spectrograph entrance slit in the filtergrams allows a precise identification of the region simultaneously observed with the SP. Three wavelengths each are chosen to sample the photosphere and the chromosphere. The 205 nm continuum allows studies of the upper photosphere at a spatial resolution of 0.05 arcsec (35 km on the Sun). The CN-band at 388 nm provides the highest contrast, and thus sensitivity to thermal inhomogeneities, in the photosphere. The continuum radiation at 550 nm samples the deep layers of the photosphere. The chromospheric wavelength bands center on strong spectral lines: Mg IIk (279 nm), CaIIK (393 nm), and Mg I (285 nm).

3.5. Magnetograph

The Imaging Magnetograph Experiment for *Sunrise* (IMaX) will be contributed by the IAC. IMaX is an imaging vector magnetograph based upon narrow-band filters. The instrument will provide fast-cadence two-dimensional maps of the

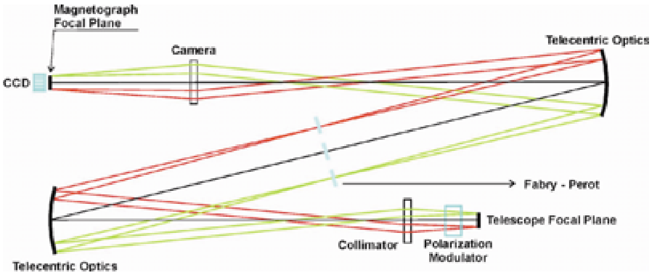

Fig. 5. Optical scheme of the magnetograph.

magnetic vector and the line-of-sight velocity a spatial resolution of 0.2 arcsec. The spatial integrity of the IMaX data will be of key value to follow the rapid evolution of the photospheric magnetic elements.

4. Mission requirements

The scientific objectives and the properties of the physical system require that *Sunrise* be able to:

- resolve the atmospheric structure down to the intrinsic scale of magnetic elements, about 30–100 km,
- resolve and cover the evolutionary history of the small-scale magnetic structure (requiring a time resolution of 5 s and uninterrupted measurements lasting hours),
- measure the 3D-distribution of the thermodynamic state, magnetic field vector, and flows (requiring spectra in order to infer the variations with height in the solar atmosphere),
- image the Sun at high cadence in radiation coming from different photospheric and chromosphereic layers in order to simultaneously follow their dynamics.

The requirements for spectro-polarimetry are:

- High signal-to-noise (S/N) ratio ($\simeq$ 1000:1) and corresponding polarimetric precision to detect weak polarisation signals (also valid for the magnetograph)
- High spectral resolving power ($\simeq$ 250 000) to obtain detailed spectral line profiles
- Simultaneous measurements of a number of lines to infer height profiles
- Mitigation of the effect of intensity variations on the polarisation measurement. Intrinsic evolution of solar features requires that the polarimetric measurement technique be insensitive to intensity changes of the image. This demands either rapid sampling of the polarisation (a fraction of a second for 0.1% accuracy) and/or a dual-beam measurement system. A full Stokes measurement sequence must be completed in a time shorter than 5–10 s to avoid blurring by the intrinsic motion and internal dynamics of magnetic features (also valid for the magnetograph)

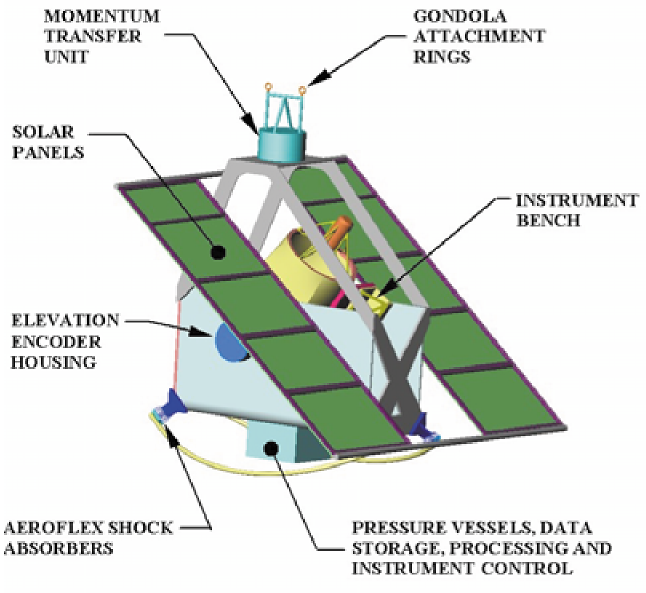

Fig. 6. *Sunrise* telescope assembled in the balloon gondola: operation mode. During ascent, descent and landing, the telescope is stowed horizontally, so that it is protected by the frame. The shock absorbers allow for large deflections and high energy dissipation. The gondola is suspended from the main telescope frame and rotates with its structure while the telescope is being driven directly via the MTU, which will be designed to minimize jitter in pointing stability.

- Sufficienctly large field of view ($\simeq$ 100 arcsec) to simultaneously observe both footpoints of a magnetic loop to study the effects of magnetic connectivity (also valid for the magnetograph)

The requirements for imaging are:

- S/N ratio $>$ 200 to detect subtle brightness variations
- Spectral resolution better than 1 nm in order to separate photospheric (continuum) and chromospheric (cores of strong spectral lines) contributions
- Multiple wavelength bands in the visible and UV spectral regions to cover various heights in the photosphere and chromosphere, to provide context information for spectro-polarimetric measurements, and to observe in prominent lines in the UV (e.g. the h or k line of ionized Magnesium)

5. Mission concept

Beginning in 2006/2007, a series of balloon flights of *Sunrise* are planned. The facilities of the National Scientific Balloon Facility of NASA and, when available, Ultra Long Duration Balloons will be used. The experience gained by successful balloon flights will put *Sunrise* in a good position to become the central element of a future space borne solar observatory.