SUNRISE: A 1-M BALLOON BORNE SOLAR TELESCOPE

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ABSTRACT

Sunrise is a light-weight solar telescope with a 1 m aperture for spectro-polarimetric observations of the solar atmosphere. The telescope is planned to be operated during a series of long-duration balloon flights in order to obtain time series of spectra and images at the diffraction-limit and to study the UV spectral region down to $\simeq 200$ nm, which is not accessible from the ground.

The central aim of Sunrise is to understand the structure and dynamics of the magnetic field in the solar atmosphere. 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. In addition, Sunrise aims to provide information on the structure and dynamics of the solar chromosphere and on the physics of solar irradiance changes.

1. INTRODUCTION: SCIENCE GOALS

The solar atmosphere is pervaded by magnetic fields which are at the root of the many fascinating phenomena grouped together under the name solar activity. The magnetic processes that govern solar activity locally determine 'space weather' as well as being potentially significant drivers of terrestrial climate variability on a time scale of decades to centuries. If we are to understand these fundamental processes, we must learn how the magnetic field interacts with the solar plasma and uncover the conversion of energy between its mechanical, magnetic, radiative, and thermal forms.

The solar photosphere represents the key interaction region: thermal, kinetic and magnetic energy all are of the same order of magnitude and transform easily from one form into another. The interaction between convection, radiation and magnetic field in the electrically conducting solar plasma leads to the creation of a rich variety of magnetic structure, from huge sunspots down to intense magnetic field concentrations on length scales down to a few tens of km. The wealth of fine-scale structure in the solar photosphere is illustrated in Fig. 1.
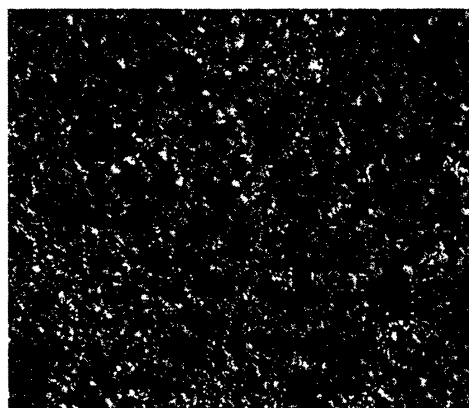

Figure 1. Granulation, pores, and magnetic elements in the solar photosphere as visible in the Fraunhofer G band at 430.4 nm, a wavelength range dominated by lines formed by the CH molecule. The magnetic flux outside the pores resides in tiny field elements located in the dark intergranular lanes. Their actual size is below the $\simeq 150$ km resolution of the telescope. The field of view is about 40 Mm×35 Mm on the Sun (image taken by G. Scharmer with the Swedish Vacuum Solar Telescope on La Palma, Spain)

The injection of mechanical and electromagnetic energy into the solar atmosphere takes place in the dense, turbulent layers of the photosphere [1], [2], [3], which act as a driver for plasma heating, impul-

sive and catastrophic energy release, and mass ejections in the overlying chromosphere and corona. The photospheric magnetic structure is essential for these processes of energy conversion and transport.

Sunrise aims to observe manifestations of small-scale magnetic structure on a spatial scale of 30–100 km (0.05 arcsec). Magnetic structures at such fine scales are seen in the simulations of Cattaneo [4], Stein and Nordlund [5] and Vögler et al. [6]. Sunrise also aims to follow their evolution on the relevant time scales, ranging from seconds (Alfvén crossing time) over roughly a day [7], to weeks in the case of sunspots.

Another aim of Sunrise is to provide simultaneous high-resolution observations of the chromospheric dynamics and brightness together with the photospheric magnetic field and velocity structure. This should enable us to determine wave modes and shock propagation, so that the transport of mechanical energy to the upper atmosphere may be quantitatively investigated. Hence, we may be able to identify the dominating heating mechanism of the chromospheric network as well as to determine the spatial distribution of hot and cool material in the chromosphere [8], [9], [10], [11] and to clarify its association with the magnetic field structure.

Such studies of small-scale magnetic concentrations afforded by Sunrise will help to uncover the physics of global solar variability, both for the total (wavelength-integrated) irradiance variations [12], [13] and for the larger variations at short wavelengths affecting the Earth's upper atmosphere (e.g. [14]).

The high-resolution and polarimetric capabilities of Sunrise should enable a test of the paradigmatic hot wall scenario of flux tube heating [15], [16]. The magnitude of the brightness variations as a function of size, inclination, and position of magnetic flux concentrations will be precisely measured [17], [18]. The direct accessibility to the UV will be able to extend such studies to the portion of the spectrum showing large variations.

Since a balloon environment allows long time series at a uniformly high resolution, Sunrise can provide information regarding the evolution of magnetic flux and the primary processes of flux emergence, recycling, magnetic reconnection, and removal from the photosphere.

The large magnetic flux emergence rates observed in the quiet solar atmosphere suggest that magnetic stresses leading to current dissipation and reconnection could be the dominant factor for coronal heating [19]. With Sunrise it could become possible to extend these measurements to the sub-arcsec range, where the emergence rates possibly increase by another two orders of magnitude due to convective flux recycling [20] or local dynamo action [4].

2. INSTRUMENT CONCEPT

The Sunrise instrumentation [21] consists of a main telescope with an aperture of 1 m, feeding three focal-plane instruments: the spectrograph-polarimeter (SP) for measurements of spectral line profiles in all 4 Stokes parameters, the filtergraph (FG) for images in selected wavelength bands, and the magnetograph (Imaging Magnetograph Experiment, IMaX) for maps of the vector magnetic field. A correlation tracker controlling a tip-tilt steering mirror provides image stabilisation and high-precision guiding.

2.1. Main Telescope

The main telescope has an aperture of 1 m and consists of a parabolic primary mirror (M1) with a focal length of 2.5 m and an elliptic secondary mirror (M2); the resulting effective focal length is 25 m (f/25). The telescope has a Gregorian configuration, with the primary image formed between the two mirrors (see Fig. 2). At this location a field stop is
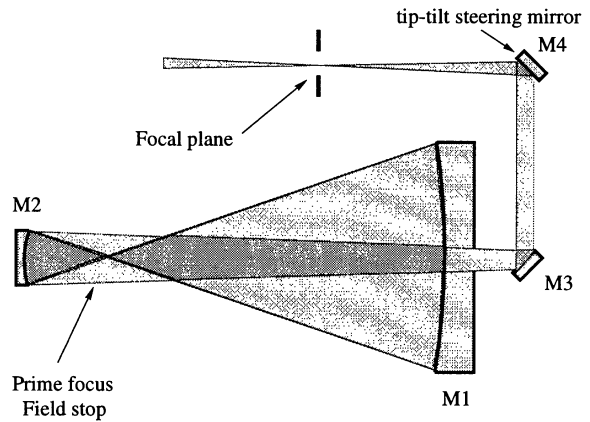

Figure 2. Optical layout of the Sunrise telescope

placed, a heat rejection cone with a central hole that defines the useable field of view, corresponding to 148 000 km on the solar surface. The field stop reflects 99% of the incoming flux out of the telescope. This reduces the heat load on the focal-plane instrumentation to about 10 W. The light passing through the field stop is reflected off M2 and folded back by the flat mirrors M3 and M4 to feed the focal-plane package. The latter (spectrograph-polarimeter, filtergraph, and magnetograph) is mounted piggy-back on the telescope structure. The tip-tilt steering mirror M4 is controlled by the correlation tracker unit and provides precise pointing and guiding. Stray light is minimized by covering the telescope structure with multi-layer insulation (MLI) from both inside and outside, by a set of baffle rings, and by a conical primary-mirror-bore baffle.

The primary mirror (M1) will be made of silicon carbide ceramic (C/SiC). The strength of this material makes extremely light-weight mirrors possible, which

retain their shape in virtually all orientations. The primary mirror and mount together weigh 65 kg. Because of C/SiC's high thermal conductivity a rather simple thermal design with passive cooling is possible. The field stop at the prime focus is also passively cooled: heat absorbed by the field stop is removed by heat pipes to a radiator mounted on the instrument structure.

The 45 degree reflections by M3 and M4 introduce a constant instrumental polarisation, which leads to a crosstalk between the Stokes parameters (the polarization analyzers are placed after the secondary focus). This effect will be calibrated on the ground, so that the polarisation data can be corrected accordingly.

2.2. Pointing and Precision Guiding

Meeting the requirement of very high spatial resolution down to 0.05 arcsec implies a substantial effort to accurately point and guide the telescope. Fluctuations of the index of refraction due to atmospheric turbulence (the main reason for image deterioration in ground-based observations) are negligible at balloon altitudes of 40 km, but image motions due to the operation of the various mechanisms and motors in the gondola, the telescope, and the instruments, as well as the swinging of the gondola must be compensated down to a level of about 0.01 arcsec. In order to reach this goal, the pointing and guiding system of Sunrise works on two levels:

a) solar pointing of gondola/telescope in azimuth by a torque motor drive as part of the momentum transfer unit (MTU) at the gondola support point; pointing in elevation by tilting the telescope, and

b) precision guiding and compensation of image motion. The guiding is performed in a closed-loop servo system that consists of a correlation tracker (CT) to provide the error signal and the piezo-driven steering mirror M4 performing the correction.

2.3. Wavefront Control System

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 a wavefront control system is envisaged 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 generating tip and tilt error signals. However, instead of sensing the position of a single image derived from the entire pupil of the telescope, seven subapertures sense the local wavefront tilt in two zones of 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. The system is able to measure and compensate axial and lateral displacement of the secondary mirror, M2, as well as dynamic image displacement errors.
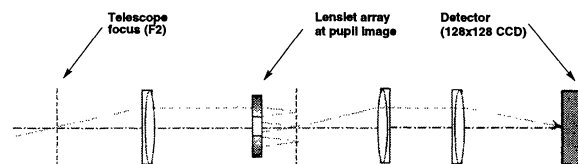

Figure 3. Optical configuration of wavefront sensor

Fig. 3 shows a sketch of the wavefront sensor, which is located in the vicinity of the secondary focus. The sensor consists of a collimating lens, a hexagonal lenslet array with seven – one central and six peripheral – elements covering the pupil of the telescope, and lenses that reimage the lenslet array focal plane onto a matrix array detector (CCD camera).

2.4. Spectrograph-Polarimeter

The achievement of the main science goals of Sunrise depends on quantitative and accurate measurements of the strength and orientation of the magnetic field with appropriate spatial, spectral, and temporal resolution. The spectrograph-polarimeter (SP) combines high-resolution vector-polarimetry with 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 scanning Echelle spectrograph in a modified Littrow configuration. A preliminary schematic view of the Spectrograph-Polarimeter is shown in Fig. 4. Apart from the UV capability, the SP is similar to the PO-LIS instrument now installed at the VTT on Tenerife [23].

The polarimetric branch of the SP is dedicated to the determination of the magnetic field vector in the solar photosphere. This is carried out by measuring the full Stokes vector using the pair of Fe I lines at 630.2 nm. The 630.25 nm line is one of the most Zeeman-sensitive lines in the visible spectrum (Zeeman triplet with a Landé factor of 2.5), thus providing large Stokes signals. The design of the polarimetry unit draws upon the heritage of the Advanced Stokes Polarimeter [22], which has been very
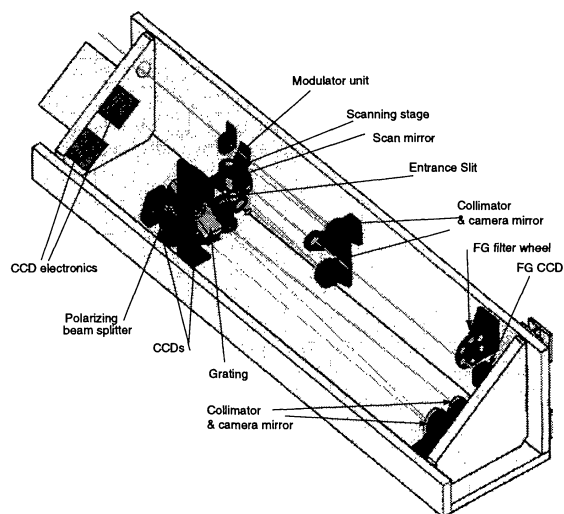
Figure 4. Perspective view of spectrograph-polarimeter and filtergraph in their common enclosure. The light enters from the rear. The modulator unit consists of a waveplate mounted in a rotary stage and a precision encoder to synchronize the CCD cameras.

successfully used for ground-based observations, and the spectro-polarimeter for the FPP instrument on Solar-B. The polarimetry unit is a dual beam system with a rotating modulator and a polarizing beam splitter mounted in front of the corresponding CCD.

The diagnostic branch of the SP measures the intensity profile of a spectral line that is chosen from a number of preselected lines by way of a set of narrow-band filters mounted on a filter wheel. With Sunrise, the observable wavelength range extends well into the UV, down to 200 nm. In principle, this permits spectroscopy of the Mg II k line core at 279.6 nm, an excellent diagnostic of the chromosphere.

2.5. Filtergraph

The filtergraph (FG) is realized as a multi-wavelength slit-jaw camera of the spectrograph-polarimeter (see Fig. 4). This allows both instruments to receive the full amount of light in all wavelengths. In addition, 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). At the same time this wavelength is important for the stratospheric ozone household. 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 II k (279 nm), Ca II K (393 nm), and Mg I (285 nm). Each of these lines samples the chromospheric height range and thermal structure in a different way. In order to ensure diffraction limited images at even the shortest wavelengths, we propose to carry out a phase diversity reconstruction of the images. An appropriate optical element will be introduced into the imager.

2.6. Magnetograph (IMaX)

The Imaging Magnetograph Experiment for Sunrise (IMaX) is an imaging vector magnetograph based upon narrow-band filters. The instrument will provide fast-cadence two-dimensional maps of the complete magnetic vector and the line-of-sight velocity with high spatial resolution. The optical scheme of the magnetograph is shown in Fig. 5.
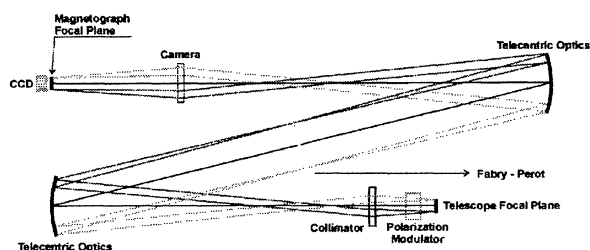

Figure 5. Optical scheme of the magnetograph.

IMaX images will be taken in two narrow wavelength bands in either wing of a photospheric spectral line. Wavelength selection will be made by using a tunable system of Fabry-Perot etalons in a telecentric path. In this way, one ensures the homogeneity of the selected wavelength over the field of view.

For the modulation of the polarization signals, a unit based on liquid crystals is currently being considered [24]. The main advantage is that no rotating parts are needed.

3. BALLOON CONCEPT

The Sunrise telescope is mounted on the elevation axis to a frame consisting of standard aluminium components. It is designed to withstand the vertical acceleration that is applied to the attachment rings when the parachute is opened near the termination of the flight. This structure and aeroflex shock absorbers protect the payload from the vertical and horizontal components of the landing shock load in case of landing in cross winds. The gondola can be moved in azimuthal direction to point the telescope and the solar panels towards the Sun. This is realized by means of a momentum transfer unit (MTU) mounted at the top of the gondola. The telescope deployed in the gondola is shown in Fig. 6.
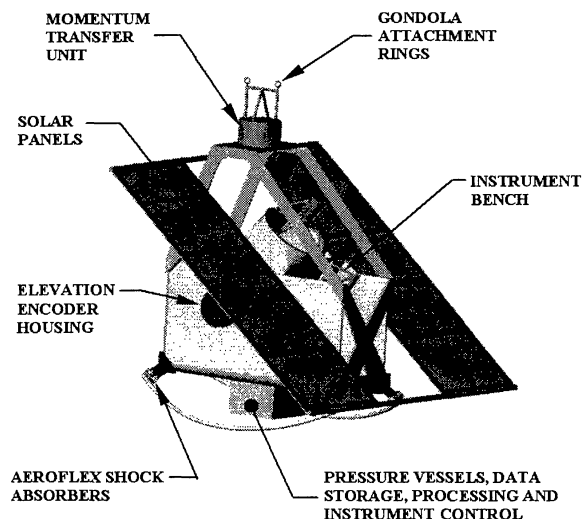
Figure 6. Sunrise telescope assembled in the balloon gondola: operation mode. During ascent, descent, and landing the telescope is stowed horizontally, so that it is protected by the 'cradle'. The gondola is suspended from the main telescope frame and rotates with its structure while the telescope is being driven directly via the MTU, which will be designed to minimize jitter in pointing stability.

Sunrise will be flown in the framework of NASA's LDB (Long Duration Balloon) program. We plan a flight of 10-12 days during a southern hemisphere summer from the ballooning facilities at McMurdo (Antarctica, 77.86 south latitude, 167.13 deg east longitude). The flight trajectory is circumpolar, bounded between 72 deg and 83 deg south latitude. Float altitudes are 35–40 km. Flying during summer over Antarctica has the advantage of permanent sunlight and small elevation changes of the Sun, so that observation and power generation are uninterrupted; furthermore, the thermal conditions do not vary significantly and the balloon floats at nearly constant altitude. These advantages more than compensate for the logistical difficulties associated with campaigns in Antarctica.

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