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SUNRISE: High resolution UV/VIS observations of the Sun from the stratosphere

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Abstract. SUNRISE is an international project for the development, construction, and operation of a balloon-borne solar telescope with an aperture of 1 m, working in the UV/VIS spectral domain. The main scientific goal of SUNRISE is to understand the structure and dynamics of the magnetic field in the atmosphere of the Sun. SUNRISE will provide near diffraction-limited images of the photosphere and chromosphere with an unpredecented resolution down to 35 km on the solar surface at wavelengths around 220 nm. The focal-plane instrumentation consists of a polarization sensitive spectrograph, a Fabry-Perot filter magnetograph, and a phase-diverse filter imager working in the near UV. The first stratospheric long-duration balloon flight of SUNRISE is planned in summer 2009 from the Swedish ESRANGE station. SUNRISE is a joint project of the German Max-Planck-Institut für Sonnensystemforschung (MPS), Katlenburg-Lindau, with the Kiepenheuer-Institut für Sonnenphysik (KIS), Freiburg, Germany, the High-Altitude Observatory (HAO), Boulder, USA, the Lockheed-Martin Solar and Astrophysics Lab. (LMSAL), Palo Alto, USA, and the Spanish IMaX consortium.
In this paper we will present a brief description of the scientific and technological aspects of SUNRISE.

1 Introduction: Science with SUNRISE

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 must 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, as illustrated in Fig. 1.

In order to best address these major scientific questions the SUNRISE instruments should provide images of the magnetic structure and measurements of the magnetic field, the flow velocity, and thermodynamic properties of the plasma . . .

- . . . with a spatial resolution down to $\simeq$ 35 km on the Sun,
- . . . on a sufficiently large field of view to cover the magnetic connectivity in the solar atmosphere ($\simeq$ 30 Mm),
- . . . over a sufficiently long time to follow the evolution of magnetically active regions (i.e., several days), and
- . . . simultaneously in different heights of the solar atmosphere.

This leads to the concept of a diffraction-limited operation of a telescope of 1 m aperture in the visible and UV spectral ranges (down to $\simeq$ 220 nm), with in-flight alignment capability, equipped with a filter imager, a polarimetric spectrograph, and an imaging magnetograph, on long-duration stratospheric balloon flights in the framework of NASA's LDB program.

2 SUNRISE mission concept

Ground based observations of the Sun are suffering from several limitations. The Earth's atmosphere does not allow access to the interesting solar UV radiation between 220 nm and 370 nm. In addition, atmospheric turbulence usually is creating image blur, so that high resolution imaging is possible only occasionally. Long term and high resolution observations especially in the UV are therefore conducted from space-borne instruments. Avoiding the high costs associated with space missions, but taking the advantages of being above 99% of the Earth's atmosphere, SUNRISE shall be flown as a balloon-borne stratospheric solar

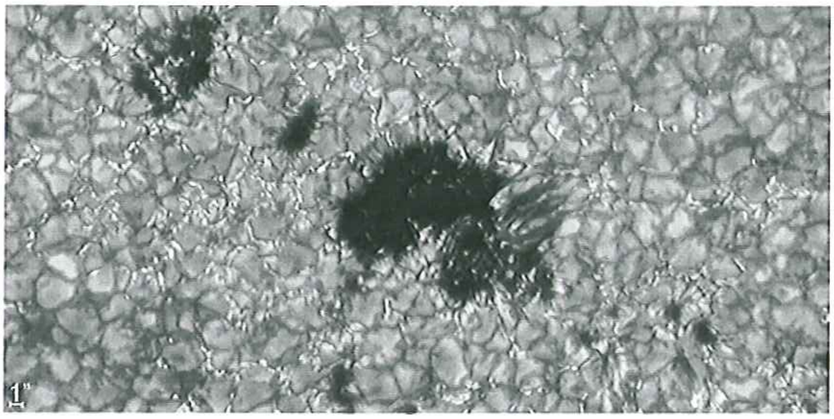

Figure 1. High resolution image of a magnetic solar region observed in the light of the so-called G band, an absorption band of the CH molecule at 430.5 nm. In this wavelength band the small scale manifestations of solar magnetism can be seen as bright features with high intensity contrast (image taken by V. Zakharov at the Swedish Solar Telescope on La Palma, Spain).

observatory in the framework of NASA's LDB (Long Duration Balloon) program. A zero-pressure helium balloon with an inflated volume of 835.000 m^3 and 130 m diameter will lift the ≈ 1800 kg science payload to float altitudes of 35–40 km. NASA LDB missions recently have been launched mainly from Williams Field near McMurdo, Antarctica (77.86°S, 167.13°E), with a launch window from December to January. NASA recently expanded their launch capabilities cooperating with ESRANGE (67.89°N, 21.10°E) near Kiruna, Sweden, allowing missions to be launched during the northern summer period in addition. Relatively stable wind systems at float altitude take the balloon and instrument on circum-polar trajectories with flight durations of 9–12 days per revolution. Launching balloons during solstice conditions close to the polar circle offers uninterrupted solar observations without day/night cycles at stratospheric altitudes. Permanent sunlight and only small elevation changes of the Sun form ideal conditions, so that undisturbed observation and power generation for the instruments are guaranteed. Furthermore, thermal conditions do not vary significantly and the balloon floats at nearly constant altitude. The preferred launch site for the first SUNRISE mission is ESRANGE, although the flight duration currently is limited to 4–5 days due to the lack of Russian overflight permissions for NASA balloons. ESRANGE provides excellent infrastructure and is accessible with much lower logistical effort compared to McMurdo. SUNRISE is designed for about two weeks autonomous operation. However, during commissioning and the initial phase of operation direct contact to the instrument is highly desirable. A high speed communication system (E-Link, developed by ESRANGE) will be used by SUNRISE on rental basis. It acts as transparent ethernet connection with up to 2Mbit/s up- and downlink over a distance of up to 500 km. Additional mobile ground stations along the trajectory would even allow extended line-of-sight communication.

3 Observational philosophy

The SUNRISE postfocus instrumentation consists of 5 units, three out of which are science instruments, the other two are system units for image stabilization and light distribution. The SUNRISE science requirements demand simultaneous observations of all three science instruments. This is ensured by ISLID, the Image Stabilization and Light Distribution system of SUNRISE, which will be described in detail below. ISLID contains a fast tip-tilt mirror, which is controlled by a correlating wavefront sensor (CWS), which will be described below. ISLID is based on dichroic beam-splitters, which guide the different wavelength bands to the individual science branches in the most efficient way. Part of the light, which is not used for scientific analysis is fed to the CWS. In this way, simultaneous observations are possible with maximum photon flux in each channel. While the technical realisation of the individual science instruments will be described in more detail below, we will list their specific roles here:

a) SUFI

The Sunrise Filter Imager (SUFI) samples the photosphere and chromosphere in distinct wavelength bands. The channel at 225 nm allows studies of the upper photosphere and lower chromosphere 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 OH band at 313 nm and the CN band at 388 nm provide high contrast, and thus sensitivity to thermal inhomogeneities in the photosphere. The Mg II k line (singly ionized magnesium) at 279.6 nm is an excellent thermometer for the chromospheric temperature structure.

b) SUPOS

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 Sunrise Polarimetric Spectrograph (SUPOS) allows high-resolution vector-polarimetry, simultaneously providing photospheric and chromospheric magnetic field measurements.

c) IMaX

The Imaging Magnetograph EXperiment for Sunrise (IMaX) is an imaging vector magnetograph based upon a tunable narrow-band filter. The instrument will provide fast-cadence two-dimensional maps of the complete magnetic vector, the line-of-sight velocity, and continuum frames with high spatial resolution.

IMaX images will be taken in two to four narrow wavelength bands in either wing of the photospheric spectral line of Fe I (neutral iron) at 525.06 nm.

4 Instrument description

4.1 Gondola

High resolution imaging requires a stable platform. This is one of the main tasks for the gondola, situated about 100 m below the balloon at the end of the flight train. The gondola core is designed as an aluminum/steel framework structure (see Fig. 2), being relatively lightweight but providing the required stiffness and protection to the sensitive optical instrument. The telescope and instrumentation need to be precision pointed toward the Sun. Azimuthal control of the whole payload is performed via a momentum transfer unit at the top of the gondola, the elevation of the telescope is adjusted by a two stage linear drive in a range of 0° to 45°. Control loops, fed by signals from a high precision Sun sensor, keep the pointing constant within a few arcsec. Electrical power is provided to the instruments and electronics via large solar panels, attached left and right at the front of the gondola framework structure. They benefit from the precision pointing toward the Sun, assuring nearly constant output of more than 1.5 kW. On the rear side of the gondola, shaded by the solar panels from direct Sun illumination, the instrument control elecronics is located on two racks. The racks are inclined with respect to the structure due to thermal reasons. This orientation minimizes radiative input from the Earth and the hot solar panels onto the electronics, and maximizes the dissipation of generated heat to the cold sky above the instrument. A commanding and communication package provided by CSBF (Columbia Science Ballooning Facility, a branch of NASA) is located underneath the gondola structure. It has separate solar panels at all four sides of the gondola to stay operational even in case of pointing loss. The package allows commanding and housekeeping downlink via TDRS and Inmarsat satellites along the complete trajectory. Shock absorbing crash pads at the very lower end of the gondola shall reduce mechanical loads during touch down and landing, thus enabling SUNRISE to be reflown with hopefully minimal refurbishment effort. The complete payload has dimensions of 5.5 meters in width and length and is about 6.6 meters high. The gondola structure, the power and pointing systems are provided by the High Altitude Observatory (HAO), NCAR, Boulder, USA.

4.2 SUNRISE Telescope

The SUNRISE telescope is a light weight Gregory-type reflector with 1 m clear aperture and 25 m effective focal length. The main mirror with a parabolic surface and focal length of 2.5 m is an extremely light-weight Zerodur mirror currently being manufactured under responsibility of SAGEM, France, under contract with the German Kayser-Threde company.

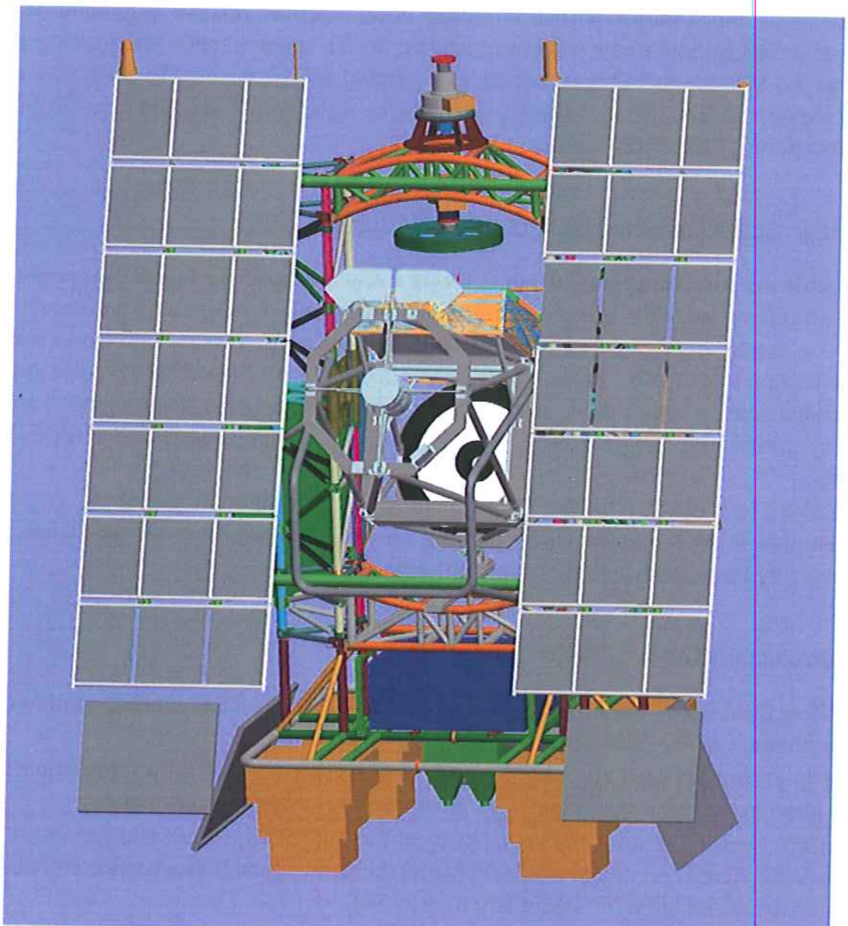

Figure 2. Sketch of the telescope in the gondola with solar panels, landing shock absorbers, and attachment ring to the balloon. The telesope is mounted in an altitude-azimuthal mount. The instrument platform carrying the science instruments is attached to the telescope central frame on top of the telescope. The instrument platform houses all three science instruments (SUPOS, SUFI, and IMaX) as well as the Image Stabilization and Light Distribution system (ISLID) and the Correlating Wavefront Sensor (CWS).

In the primary focus a field stop is placed, a heat rejection wedge with a 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 light 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 two flat mirrors M3 and M4 to feed the focal-plane package. The latter is mounted piggy-back on the telescope structure and consists of the science instruments and the wavefront sensor/correlation tracker unit. A tip-tilt steering mirror is controlled by the correlation tracker and provides precise pointing and guiding. Stray light is minimized by the field stop in F1, by covering the telescope structure with MLI from both inside and outside, by a set of baffle rings, and by an inner primary-mirror-bore baffle.
The optical system of the SUNRISE telescope is semi-active: relative alignment of M2 to M1 is controlled by low order wavefront sensing in the science focus and passing control signals to the M2 mount. This technique is also used for focusing. The telescope will be built by Kayser-Threde (Munich) under supervision of the Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany.

4.3 Image Stabilization and Light Distribution System: ISLID

ISLID performs two main tasks: First, it forms a real image of the telescope aperture on a fast tip-tilt mirror, which is used to stabilize the image and compensate for residual image motion due to gondola shake and vibrations within the system. This is done with a field lens in the telescope's secondary focus. In order to allow for the UV part of the solar spectrum to be transmitted the lens is made from fused silica and is uncoated. Reimaging is achieved with a two mirror arrangement (for SUFI) and additional refractive optics for SUPOS, IMaX, and CWS.

The second task of ISLID is the light distribution to the different post-focus instruments in a most photon efficient manner by guiding only the dedicated wavelength bands of the instruments by the use of dichroic beam splitters.

4.4 Correlating Wavefront Sensor: CWS

The CWS is used in two ways, for precision image stabilization and guiding, and to control proper alignment of the telescope.
Guiding is performed in a closed-loop servo system that consists of a correlation tracker (CT) to provide the error signal and a tip-tilt mirror performing the correction.
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 and align the secondary mirror, M2.
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, 7 subapertures sense the local wavefront tilt in two zones of the pupil. The information derived from the 7 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.
The correlation tracker/wavefront sensor unit including the tip-tilt mirror and the control software is developed by the Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany.

4.5 SUNRISE Polarimetric Spectrograph: SUPOS

The spectropolarimeter SUPOS has undergone a considerable design change and is now designed as a single spectral line high resolution grating spectrograph working at a wavelength around 854 nm. Here a chromospheric line of singly ionized calcium allows for simultaneous magnetic field diagnostics due to its Zeeman splitting. The line is formed in different layers, spanning from the photosphere to the chromosphere. While the interpretation of the data is more demanding as compared to purely photospheric lines, the advantage of having access to chromospheric magnetism more than compensates for this. The full polarisation state of the spectral line will be detected using 2 nematic liquid crystal variable retarders followed by a polarizing beam splitter. The CCD camera is read in synchronism with the electrooptical modulation in order to demodulate the polarization signal.

4.6 SUNRISE Filtergraph: SUFI

The SUNRISE filter imager (SUFI) is the instrument allowing for the highest angular resolution of down to 0.05 arcsec. This corresponds to the diffraction limit of the 1m mirror for a wavelength of 225 nm. In order to achieve near diffraction limited imaging, a phase-diverse imaging technique is used by splitting the image in front of the CCD detector: half of the CCD area collects the focused image, while a special optical arrangement forms a second image of the same scene on the second half of the CCD, now with a defocus of one wave. Postfacto restoration of the image free from static aberrations of the optical path can be achieved. The optical arrangement is a Schwarzschild system to magnify the telescope secondary focus scale by a factor of 5 onto the CCD. SUFI works in distinct wavelength bands in the near UV between 220 nm and 390 nm, which are selected by IAD coated interference filters sitting in a double filter wheel to ensure sufficient blocking against the strong visible and near infrared parts of the solar irradiance.

4.7 Imaging Magnetograph eXperiment: IMaX

IMaX is a polarisation sensitive filtergraph developed for observations of Doppler shifts and polarisation in a Zeeman sensitive spectral line of neutral iron at 525.06 nm.
A tunable $LiNbO_3$ solid state Fabry-Perot etalon is used in double pass. This configuration significantly saves mass and power and relaxes the demanding requirements on passband stability. Since the free spectral range of such a system is quite small, a narrowband interference filter (FWHM 0.1 nm) must be used. Both, prefilter and etalon must be thermally stabilized.
Imaging is done with two synchronised CCD cameras for phase diversity reconstruction.
Polarimetry is done with two nematic liquid crystal modulators. Four switching states are needed for full Stokes vector polarimetry. A two-state observing mode is foreseen for longitudinal magnetometry (only circular polarisation) at high cadence.

IMaX is being developed by a Spanish consortium led by the Instituto de Astrofísica de Canarias, La Laguna (Tenerife), in cooperation with the Instituto de Astrofísica de Andalucía, Granada, the Instituto Nacional de Tecnicas Aeroespaciales, Madrid, and the Grupo de Astronomía y Ciencias del Espacio, Valencia.

5 Schedule

SUNRISE plans to conduct a continental U.S. test flight with the gondola, main parts of the electronics and a dummy telescope in October 2007. The telescope delivery to MPS is expected early 2008. Assembly, alignment and calibration of telescope and postfocus instrumentation, the system integration and testing with the refurbished gondola are planned until end of 2008. Mission preparation and shipping to ESRANGE will be beginning 2009, aiming at a launch during the May/June 2009 launch window.

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