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

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ABSTRACT

SUNRISE is a balloon-borne solar telescope with an aperture of 1 m, working in the UV/VIS optical 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 diffraction-limited images of the photosphere and chromosphere with an unpredecented resolution down to 35 km at wavelengths around 220 nm. Focal-plane instruments are a spectrograph/polarimeter, a Fabry-Perot filter magnetograph, and a filter imager. The first stratospheric long-duration balloon flight of SUNRISE over Antarctica is planned in winter 2006/2007. SUNRISE is a joint project of the Max-Planck-Institut für Sonnensystemforschung (MPS), Katlenburg-Lindau, 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, La Laguna, Tenerife.

In this paper we will present an overview on the mission and give a description of the instrumentation, now, at the beginning of the hardware construction phase.

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. The wealth of fine-scale structure in the solar photosphere is illustrated in Fig. 1.

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

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Sunrise aims to observe manifestations of small-scale magnetic structure on a spatial scale of 35–100 km, which corresponds to a maximum angular resolution of 0.05 arcsec. Magnetic structures at such fine scales are seen in the simulations of Vögler & Schüssler [2]. Sunrise also aims to follow the evolution of the magnetic structures on the relevant time scales, ranging from seconds (Alfvén crossing time) over roughly a day, 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 [3] 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 [4], and for the larger variations at short wavelengths affecting the Earth's upper atmosphere (e.g. [5]), since the uncertainties in our knowledge of the thermal structure and radiative properties of the magnetic elements constitute a major uncertainty for the quantitative modelling of solar irradiance.

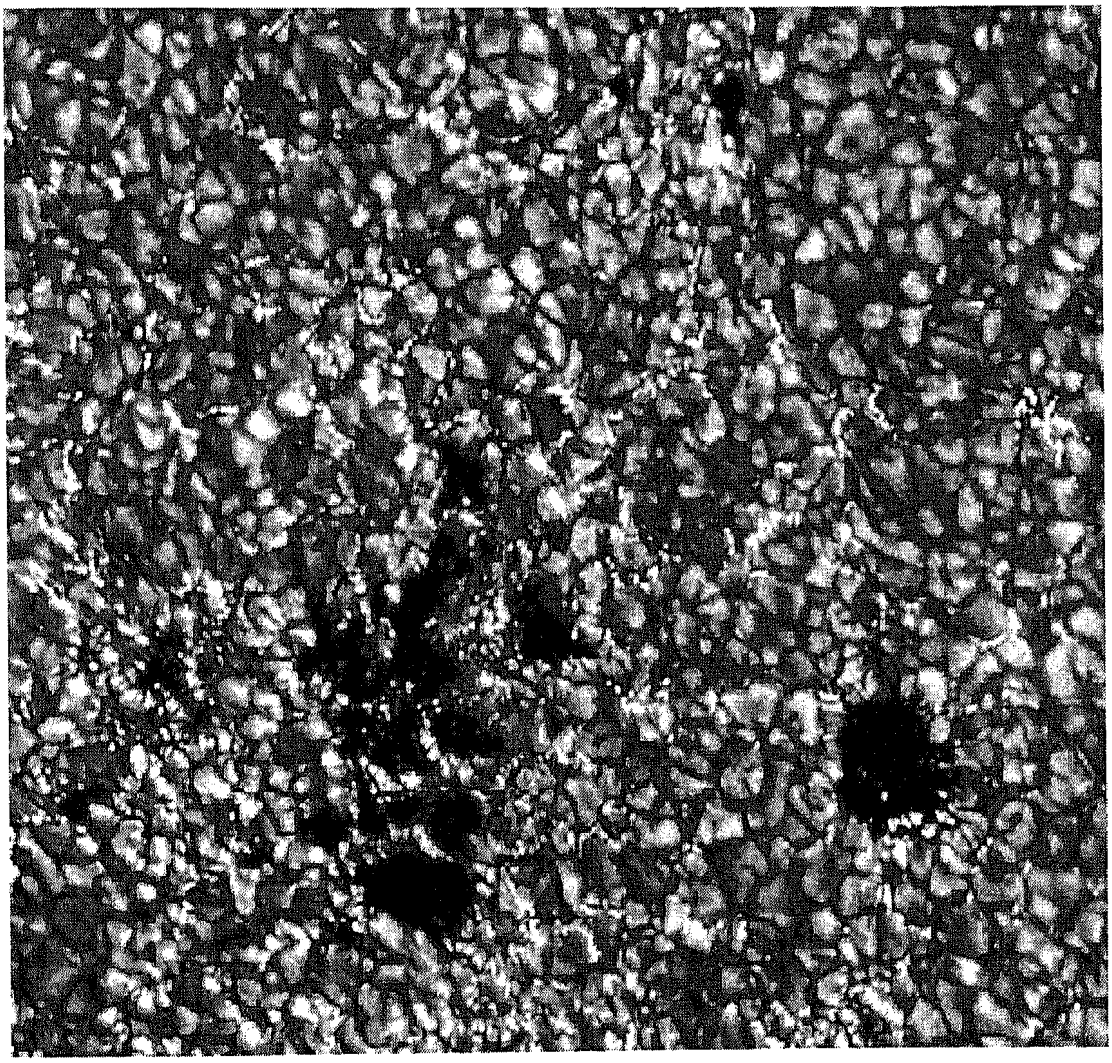

Figure 1. Granulation, pores, and magnetic elements in the solar photosphere as visible in the Fraunhofer G band at 430.4 nm, a wavelength range dominated by lines formed by the CH molecule. The magnetic flux outside the pores resides in tiny field elements located in the dark intergranular lanes. Their actual size is below the $\simeq 150$ km resolution of the 50 cm telescope. The field of view is about 40 Mm×35 Mm on the Sun (image taken by G. Scharmer with the old 50 cm Swedish Vacuum Solar Telescope on La Palma, Spain)

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 [6]. 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 or local dynamo action [7].

2. SCIENCE REQUIREMENTS

The resulting science requirements for the SUNRISE instruments are that they 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 $\simeq 35\,\mathrm{km}$ on the Sun,
- ...on a sufficiently large field of view to cover the magnetic connectivity in the solar atmosphere ($\simeq 30\,\mathrm{Mm}$),
- ...over a sufficiently long time to follow the evolution of magnetically active regions (i.e., days to weeks), 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 $\simeq 220\,\mathrm{nm}$), 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. Observations from above the ground are mandatory in order to avoid the image deterioration by turbulence in the Earth's atmosphere and to gain access to the solar UV radiation between 220 and 370 nm.

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 simultanous 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 will contain a fast tip-tilt mirror, which will be controlled by a correlating wavefront sensor (CWS), which will also 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, simultanous 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 four 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 [8]. 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 [9].

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 magnetic field measurements (polarimetric branch) and diagnostic spectroscopy (diagnostic branch). SUPoS is based on an all-mirror scanning Echelle spectrograph in a modified Littrow configuration, similar to the POLIS instrument [10], [11], now installed at the German Vacuum Tower Telescope (Teide observatory, Tenerife/Spain).

The polarimetric branch of SUPoS 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 Mg II K line at 279.6 nm is an excellent diagnostics tool for the temperature structure in the chromosphere.

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 FeI (neutral iron) at 525.06 nm.

4. INSTRUMENT DESCRIPTION

4.1. Main Telescope

The SUNRISE main telescope is a light weight Gregory-type reflector with 1 m clear aperture and 25 m effective focal length. The system is based on a monolithic 1 m C/SiC mirror with a parabolic surface and focal length of 2.5 m. The main mirror is currently being manufactured under responsibility of ASTRIUM, Friedrichshafen, Germany, under contract with the Lockheed Martin Solar and Astrophysics Laboratory, Palo Alto, USA. The development is funded by NASA in the framework of the Solar Lite program. The telescope will be built by an industrial contractor under supervision of the Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany.

In the real 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 covering the telescope structure with MLI from both inside and outside, by a set of baffle rings, and by a conical 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 focussing. The telescope will be built by Kayser-Threde (Munich) under supervision of the Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany. Recently, the Phase-B study for the telescope has been finished by Kayser-Threde. The start of Phase C/D has been taking place in the beginning of 2004. A detailed description of the telescope can be found in paper 5489-126 by Bittner at al. in these proceedings.

4.2. Image Stabilization and Light Distribution System: ISLiD

ISliD is a 1:1 relay optics, which reimages the telescope secondary focus on the entrance slit of the SUPoS spectrograph. The optical configuration is of Czerny-Turner type with a 1250 mm collimator, that images the telescope's pupil onto a fast tip-tilt mirror used for image stabilization to 0.05 arcsec at 100 Hz. Near the pupil the scanning mirror is placed, which moves the solar image in a direction perpendicular to the SUPoS entrance slit. A 1250 mm camera mirror reimages the solar image onto the slit. Between the tip-tilt mirror and the scanning mirror two dichroic beam-splitters are placed, which take out the wavelength bands for SUFi, IMaX, and for the CWS. The first beam-splitter reflects all wavelengths below 400 nm except a 10 nm notch centered around 279 nm, which is passed to the SUPoS spectrograph. The second beam-splitter reflects a wavelength band between 420 nm to 800 nm to IMaX and the CWS, except a narrow notch centered around 630 nm, which is also passed to SUPoS. Wavelength separation between ImaX (525 nm) and the CWS is achieved by a third beamsplitter in the ImaX/CWS common part of their optical feed path. The stringent requirements are met by state-of-the-art multilayer technology. The coating design has not only to ensure the required wavelength separation, but simultanously minimize the polarisation at 630 nm and 525 nm. All coatings have been designed and deposited in IAD (ion assisted deposition) technique by mso-jena.

4.3. Correlating wavefront sensor: CWS

The CWS is used in two ways, for precision images 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.

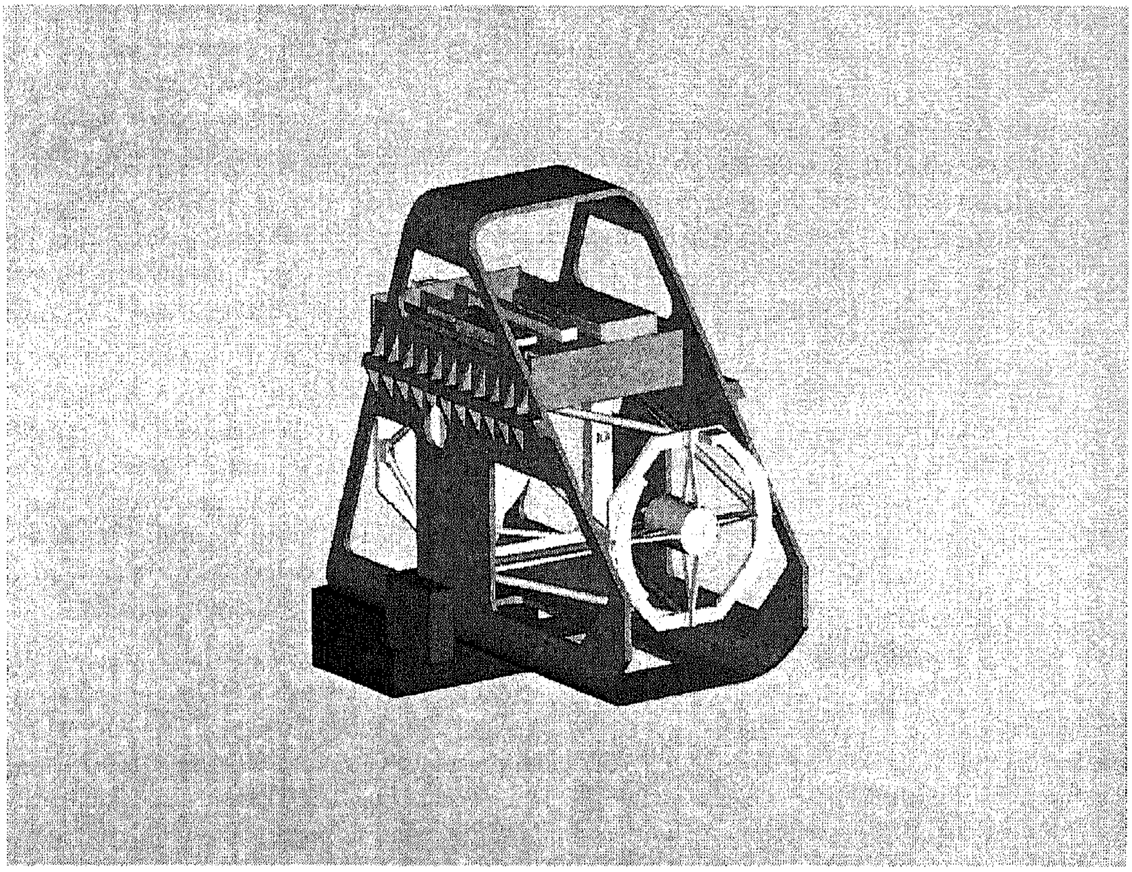

Figure 2. Sketch of the telescope in the gondola in landing position at zero elevation. The instrument platform is attached to the telescope central frame on top of the telescope. The instrument platform houses all three science instruments (SUPoS, SUFi, and IMaX) as well as the Image Stabilization and Light Distribution system (ISLiD) and the Correlating Wavefront Sensor (CWS).

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, 18 subapertures sense the local wavefront tilt in two zones of the pupil. The information derived from the 18 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. For details we here refer to paper 5489-140 by Schmidt et al. in these proceedings.

4.4. SUNRISE Polarimetric Spectrograph: SUPoS

SUPoS is a high resolution spectrograph feeding two CCD cameras working in two distinct spectral bands. The overall optical configuration is a combination of a Czerny-Turner arrangement with an echelle grating in a modified Littrow configuration. This concept has been first used in the POLIS spectropolarimeter [10], [11] now installed at the German Vacuum Tower Telescope (Teide observatory, Tenerife/Spain). The instrument works as a pure spectrograph in the so-called diagnostic branch for detailed line profile measurements in the Mg II K line at 279.6 nm. This line is particularly suited for diagnostics of the temperature structure in the chromosphere.

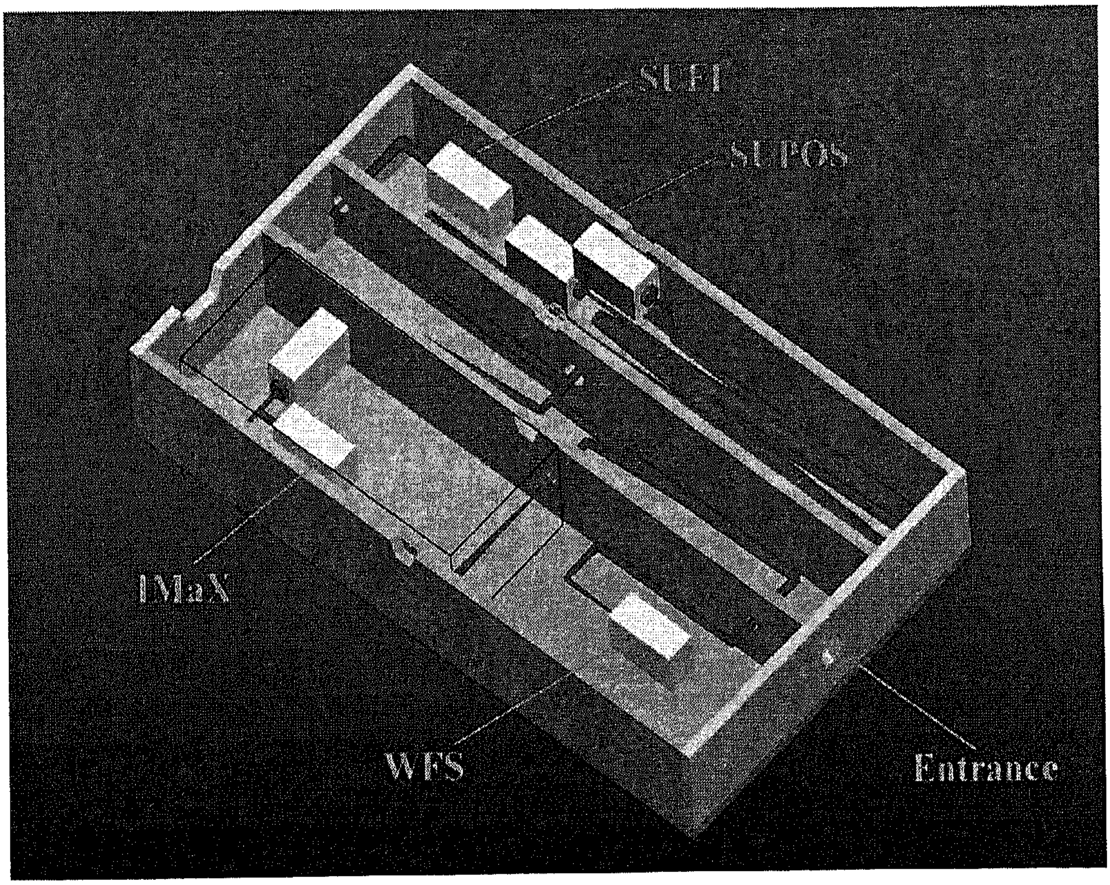

Figure 3. Sketch of the arrangement of the postfocus instrumentation on the instrument platform. The envelope of the optical light paths is visible. Individual optical components are omitted in this picture. The CCD cameras of the three science instruments and the CWS wavefront-sensor camera are shown. Light from the main telescope enters from the right, as indicated.

In the polarimetric branch a dual-beam system with a rotating modulator and a polarizing beam splitter mounted in front of the corresponding CCD is used.

The echelle grating is used in 41st order for the 279.6 nm channel and in 18th order for 630.5 nm. The red and the UV channel fall on seperate camera mirrors which image the spectra on two CCDs. Narrowband interference filters act as order sorters in both channels. Due to the limited photon flux in the core of the Mg II K line and the reduced efficiency of the CCD in the UV, the 279.6 nm channel will be purely spectroscopic. In the red channel a polarising beamsplitter is placed, which acts as an analyser for the polarisation modulator. The modulator is similar to the POLIS modulator and is placed between the scanning mirror of ISLiD and the ISLiD reimaging mirror. A rotating set of SiO_2/MgF_2 waveplates modulates the polarisation with the same efficiency for 630 nm and 279.6 nm. This is achieved by careful choice of the optical retardation. However, as indicated above, in the first flight only the polarisation at 630 nm will be analysed. Therefore the grating must be polarisation-free at this wavelength.

4.5. SUNRISE Filtergraph: SUFi

The SUFi instrument is designed as a phase diversity imager for observations at highest angular resolution in different wavelength bands. It is fed by ISLiD beam-splitter BS1, which reflects all light below 400 nm to SUFi, with the exception of a 10 nm notch transmitted to SUPoS. The SUFi imager works at 4 wavelengths: 225 nm (FWHM 20 nm), 300 nm (FWHM 1 nm), 313 nm (FWHM 0.8 nm), and 388 nm (FWHM 0.8 nm). The filters are designed and produced by Barr (USA) as IAD coated metal/dielectric multilayer stacks. To ensure appropriate blocking of unwanted broadband radiation the filters will be used in tandem configuration, mounted in two seperate filter wheels. The two wheels are driven by the same step motor, but rotate in opposite directions. This eliminates any residual torque on the instrument platform during rotation when changing wavelength. Achromatic reimaging of the telescope secondary focus onto the SUFi CCD (2048 squared 12 μm pixels back-thinned SiTe sensor) is done by two achromatic doublets made by Halle (Berlin) from synthetic quartz and MgF_2. A special beam splitter, placed immediately before the CCD, doubles the image: one image falls onto the CCD in optimum focus position, while the other image is formed with a fixed amount of defocus. Both images are required for phase diversity restoration of the real solar image.

4.6. Imaging Magnetograph eXperiment: IMaX

IMaX is a polarisation sensitive filtergraph developed for observations of Doppler shifts and polarisation in a Zeeman sensitive spectral line (Fe I 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).

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 Andalucia, Granada, the Instituto Nacional de Tecnicas Aeroespaciales, Madrid, and the Grupo de Astronomia y Ciencias del Espacio, Valencia.

For more detailed information on the ImaX instrument we here refer to paper 5487-54 by Martinez-Pillet in these proceedings.

Telescope	primary focal length	2.5 m
	effective focal length	25 m
	image scale	8.25 arcsec/mm
Correlating wavefront sensor	wavefront sensor	128 × 128 CCD
	pointing accuracy	$\leq$ 0.01 arcsec
	dynamic range	40 Hz minimum
	number of elements	7
	No. of Zernike terms	5
Spectrograph	focal length	1250 mm
— Scanning unit	step width	0.05 arcsec
	total range	± 60 arcsec
— Main disperser	grating	158 grooves / mm
	spectral resolution	2.7 pm (near 500 nm)
	dispersion	12.6 pm / mm (near 630 nm)
— Polarimetry unit	dual beam system	polarizing beam splitter
	retarder	rotating wave plate , 1 Hz
— CCD cameras	format, speed	652 × 488, 16 frames/s
	pixel size	12 × 12 μm^2
	CCD I FOV	65 arcsec × 0.26 nm
	spectral line	630.2 nm (Fe I)
	CCD II FOV	65 arcsec × 0.24 nm
	spectral line	279.6 nm (Mg II K)
SUFi	phase diversity imager	
— CCD camera	format	2048 × 2048
	pixel size	12 × 12 μm^2
	FOV (3 pixel sampling)	40 × 80 arcsec^2
— phase diversity	beam-splitter, 1 CCD	
— Filter wheel	4 positions	220 nm (continuum)
		300 nm (continuum)
		313 nm (OH molecular band)
		388 nm (CN molecular band)
IMaX	polarimetric narrowband imager	
— filter unit	prefilter	narrowband interference filter
	main filter	$\mathrm{LiNbO_3}$ Fabry-Perot etalon in double pass
	spectral resolution	4 pm
	spectral line	525.06 nm (Fe I)
— polarimetry unit	polarization modulator	2 nematic liquid crystals, 15 Hz
— Camera	2 CCDs	1024 × 1024
	pixel size	12 × 12 μm^2
	FOV	60 × 60 arcsec^2
— phase diversity	2 seperate CCDs	

Table 1. Design parameters of the post-focus instrumentation

5. 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 gondola and the gondola systems (MTU, elevation drive, power supply, coarse pointing, etc.) are responsibility of the the High Altitude Observatory, Boulder, USA.

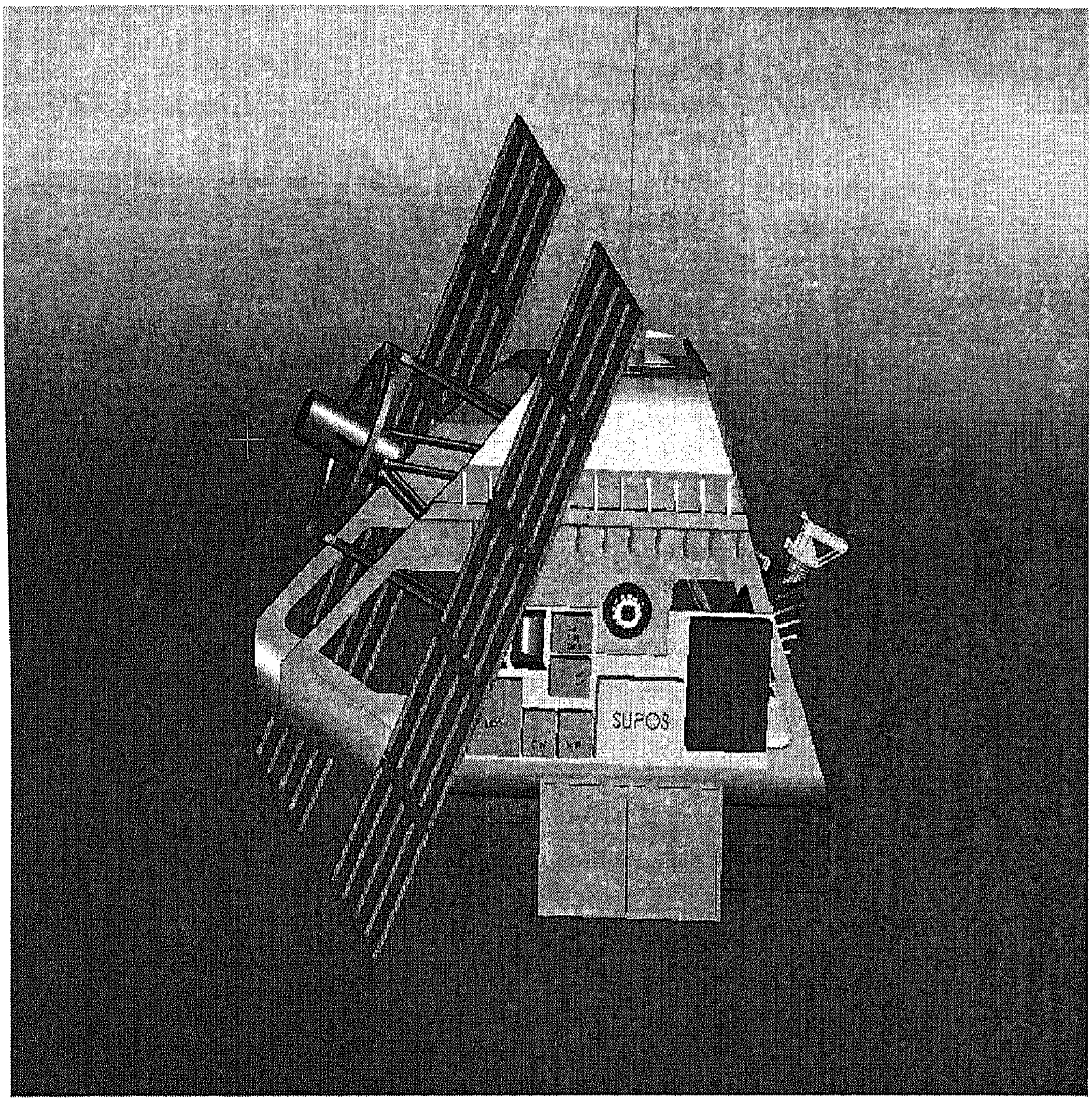

Figure 4. Sketch of the complete gondola. The telescope with the instrument platform can be seen. At the side of the gondola the electronics boxes of the system subunits and the science instruments are visible. Also the solar panels on both sides of the gondola are depicted.

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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