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SUNRISE
Impressions from a successful science flight

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SUNRISE is a balloon-borne telescope with an aperture of one meter. It is equipped with a filter imager for the UV wavelength range between 214 nm and 400 nm (SUFI), and with a spectro-polarimeter that measures the magnetic field of the photosphere using the Fe I line at 525.02 nm that has a Landé factor of 3. SUNRISE performed its first science flight from 8 to 14 June 2009. It was launched at the Swedish ESRANGE Space Center and cruised at an altitude of about 36 km and geographic latitudes between 70 and 74 degrees to Somerset Island in northern Canada. There, all data, the telescope and the gondola were successfully recovered. During its flight, Sunrise achieved high pointing stability during 33 hours, and recorded about 1.8 TB of science data. Already at this early stage of data processing it is clear that SUNRISE recorded UV images of the solar photosphere, and spectropolarimetric measurements of the quiet Sun's magnetic field of unprecedented quality.

1 Introduction

The SUNRISE telescope is the largest solar telescope that was flown on a stratospheric balloon. With its aperture of 1 meter it is actually one of the world's largest solar telescopes, and it is the telescope with the best spatial resolution, thanks to its UV capabilities. SUNRISE is an international program led by the Max-Planck-Institut für Sonnensystemforschung (Katlenburg-Lindau), and with the High Altitude Observatory (Boulder, U.S.), the IMaX consortium (Teneriffa, Granada, Madrid), the Lockheed-Martin Solar and Astrophysics Laboratory (Palo Alto, U.S.), and the Kiepenheuer-Institut für Sonnenphysik (Freiburg) as partners.

The main scientific goals of the SUNRISE mission are the exploration of physical processes in the solar photosphere and lower chromosphere at high spatial resolution. The magnetic field is the source of the solar activity, it causes the variability of the solar irradiance, and influences the space environment outside the Earth atmosphere. The variability of the Sun influences the state of the Earth atmosphere which in turn may be an important driver for our climate. In the photosphere of the Sun, the magnetic field interacts strongly with the convective motion. This leads to the formation of magnetic flux concentrations with sizes around 100 km or below which influence all layers of the atmosphere and are crucial for its energy balance and dynamics. The general goals are structured along the following science questions:

– What are the origins and the properties of the intermittent magnetic structures and the turbulent magnetic field?
– Are there different dynamos acting in the Sun?
– How is the magnetic flux brought to and removed from the solar surface?
– How much magnetic flux is there in the quiet Sun?
– How does the magnetic field transport momentum and energy to the outer solar atmosphere?
– What is the physics of solar irradiance variability?
– What is the nature of the solar chromosphere?

2 Instrumentation

The SUNRISE balloon payload consisted of the gondola system, the telescope, a focal plane instrument package, a data processing unit, and 4 TB of disk space for the science data. The gondola was built at the High Altitude Observatory (HAO) in Boulder (CO, USA), with financial support from NASA. The gondola provided the coarse pointing of the telescope and included the general power supply system. The pointing signal was produced by a Lockheed Intermediate Sun Sensor (LISS). This sensor was provided by the

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Fig. 1 (online colour at: www.an-journal.org) The SUNRISE solar telescope in midnight sunlight during the flight readiness test. Mounted to the top part of the telescope's front ring, the sensor for the coarse pointing is visible. The telescope is pointed to the Sun, as can be seen from the shadow of the secondary mirror on the cover of the primary. The shiny (light blue, due to reflection of the sky) wedge-shaped plates on top of the front ring are radiation coolers for the prime focus field stop.

Lockheed Martin Solar and Astrophysics Laboratory (LMSAL) in Palo Alto.

The telescope (Fig. 1) was designed and built at Kayser Threde (Munich) under the leadership of the Max-Planck-Institut für Sonnensystemforschung (MPS) at Katlenburg-Lindau. It is a Gregory configuration with a 1 m primary, and an effective focal length of 25 m (Barthol et al. 2010). The focal plane instrument box was built at the MPS. It contained a light distribution unit that fed all instruments simultaneously, a wave-front correction unit (Fig. 3), and two science instruments (Gandorfer et al. 2010).

For real-time correction of low-order aberrations (image shift, focus and coma), a Correlating Wavefront Sensor (CWS) was developed at the Kiepenheuer-Institut für Sonnenphysik (KIS, Freiburg). Starting from the coarse telescope pointing of about ±45 arcsec, the CWS provided image stabilization down to 0.04 arcsec with a closed-loop bandwidth of about 60 Hz. The diurnal focus shift due to temperature changes was of the order of 0.5 waves. The in-flight correction of the CWS reduced this effect down to 0.01 waves (Berkefeld et al. 2010).

2.1 Science instruments

A photometric filtergraph (SUFI) was used for imaging of the photosphere and the lower chromosphere in five wavelength bands between 214 nm and 397 nm (see Table 1). A detailed description of the SUFI instrument can be found in Gandorfer et al. (2010). SUFI is capable of providing high-quality diffraction-limited images with a field of view of about 20×40 arcsec^2. The finally achieved spatial resolution was limited by high-frequency jitter at frequencies around 100 Hz, that could not be corrected by the CWS. The

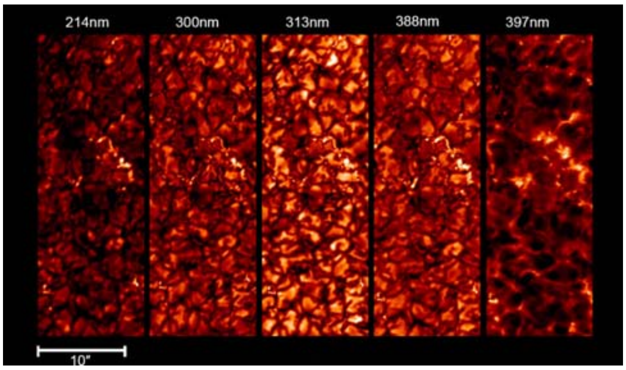

Fig. 2 (online colour at: www.an-journal.org) UV images of solar granulation (post-processed using a phase-diversity algorithm) taken with the photometric filtergraph.

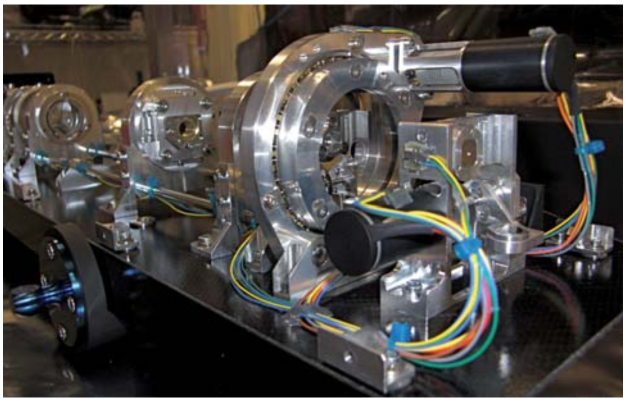

Fig. 3 (online colour at: www.an-journal.org) Wave-front sensor of SUNRISE. The picture shows, from *right to left*, the (motorized) focal plane unit of the CWS, the (motorized) neutral density wheel and the mount for the micro-lens array, together with some re-imaging lenses.

instrument is equipped with a *Phase-diversity sensor* that allowed removing residual fixed aberrations of the telescope and instrument package, and to correct any differential defocus caused by thermal effects during the flight. This image reconstruction capability is very important, because aberrations that are negligible at 520 nm need to be corrected at SUFI wavelengths of 300 nm and below. The integration time for all bands, except 214 nm, was between 100 and 300 ms. With four bands, the cadence for the full sequence was 8 seconds. The 214 nm band could only be observed with the Sun at high elevation angles, owing to the strong ozone absorption in the Earth atmosphere above the 36 km float altitude of SUNRISE. Even then, an integration time of about 30 s was needed to record UV images at 214 nm.

The magnetic field of the solar photosphere was measured with the IMaX instrument, a two-dimensional filter spectrometer that was operated at the Fe I 525.02 nm line with a strong magnetic sensitivity (Fig. 4). The instrument is based on a LiNb Fabry-Perot Etalon, used in double path, and LCVR modulators. Depending on the specific observing target, the spectral line can be sampled at 2, 5, 10, or 12 spectral positions. The field of view is about 60

Table 1 Wavelength bands of the SUFI instrument.

Wavelength [nm]	Origin
214	”Continuum”
300	”Continuum”
313	”Continuum”
388	CN
396	Ca II

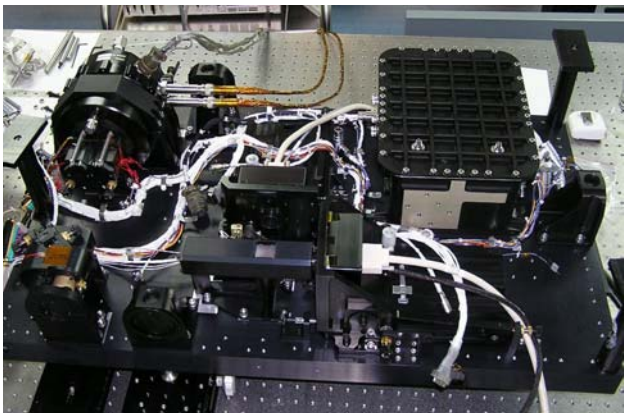

Fig. 4 (online colour at: www.an-journal.org) IMAX spectropolarimeter during assembly in Madrid. The LiNb etalon is in the upper left corner of the picture. The two CCD detectors are at the center (facing left and down), and the box on the upper right contains the electronics for the etalon.

Fig. 5 (online colour at: www.an-journal.org) Launch of Sunrise at ESRANGE in the morning of 8 June 2009. The gondola with the telescope stowed in horizontal position has just been released from the launch vehicle. The solar panels for the science payload are mounted on both sides of the telescope. The small solar panels below the telescope are used for the telemetry system.

arcsec squared. The IMaX instrument took magnetic field measurements by measuring the Stokes profiles at a noise level of 10^{-3} of the continuum intensity, and a resulting cadence of 30 s. IMaX also was equipped with a Phase-Diversity system that allowed for post-facto correction of image degradation caused by residual telescope aberrations. More details are given by Martínez Pillet et al. (2010).

3 Science flight

SUNRISE was launched on 8 June 2009, at 8:26. The launch operation was carried out by the Columbia Scientific Ballooning Facility of NASA, at the ESRANGE space center in Kiruna, Sweden. Launch operation and flight control was supported by ESRANGE staff. Although SUNRISE was a very heavy balloon payload, with a total weight of more than 6000 kg (including the balloon), the launch (Fig. 5) was very smooth, and the balloon with a (final) volume of more than 1 000 000 m^3 reached its float altitude of 36 km after about 2.5 hours. During ascent all instruments had been switched on in order to provide internal heating during the passage through the cold tropopause with temperatures below –50 °C. Once the float altitude was reached, the gondola was pointed to the Sun, and electric power was provided by the photovoltaic arrays. The next hours were scheduled for instrument commissioning. This procedure became very tedious when the line-of-sight communication was lost after only five hours. Science observations were carried out whenever the pointing stability was good. High-quality observations were performed during a total of 33 hours, divided into many intervals with durations up to 43 minutes. About 1.8 TB of raw data were stored on the onboard disks.

After launch, the balloon slowly drifted toward the Northern Sea, crossed the ocean, then Greenland, and approached Canada at a latitude of 74°, close to the famous North-West Passage. The descent and landing was initiated on June 14 by disconnecting the balloon from the gondola. The gondola and telescope landed on Somerset Island, an unpopulated island not too far away from Resolute Bay, a small air base. From there, the recovery operation was started and gondola, telescope, instruments and the data disks were successfully recovered. Figure 6 shows members of the recovery team after the de-installation of the primary mirror, happy to find it intact. The data disks were brought to the MPS as fast as possible, to verify the readability of the science data. The gondola was returned to the HAO, while the telescope and the instruments were shipped to the MPS, where a thorough inspection of the state of all components was carried out. More details of the science flight are provided by Barthol et al. (2010).

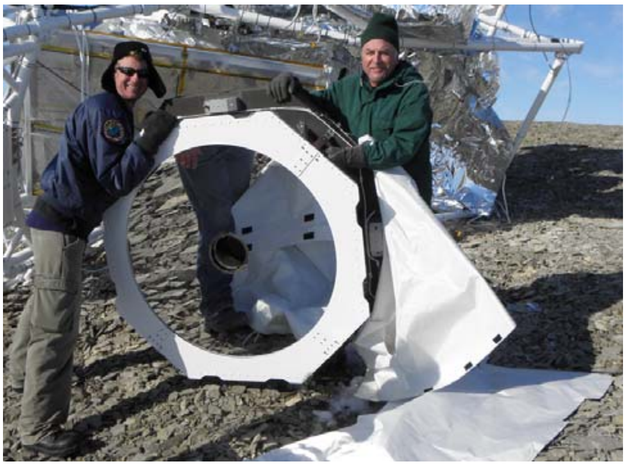

Fig. 6 (online colour at: www.an-journal.org) Recovery of Sunrise on Somerset Island. The telescope including the precious primary mirror survived a rough landing.

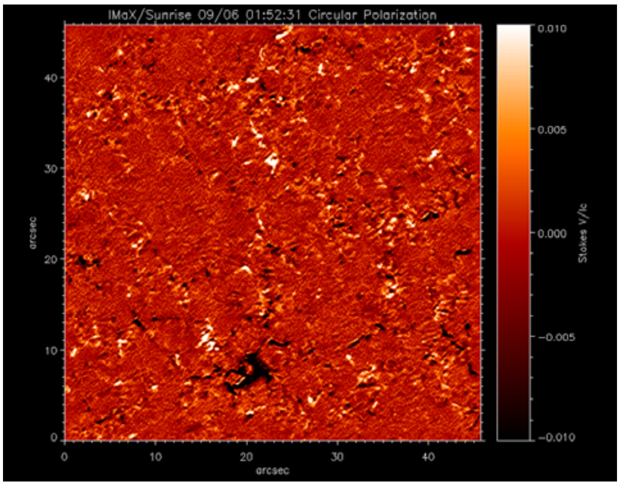

Fig. 7 (online colour at: www.an-journal.org) Circular polarization measurement with the IMaX instrument. The color coding gives the strength of Stokes V which reflects the line-of-sight component of the magnetic field. A preliminary image reconstruction has been performed. The image has been taken in a magnetically quiet region at disk center.

4 Data processing and first results

At the time when this article was written, the processing of the imaging and the spectro-polarimetric data was still underway. From the first examples of fully processed data we conclude that the SUNRISE mission was successful and will provide new insights to the dynamics and magnetism of the quiet Sun. Due to the lack of strong magnetic activity, no data concerning sunspots could be taken. The quiet Sun data taken by the IMaX instrument (see Fig. 7) are of unprecedented quality, thanks to the combination of high spatial resolution (0.1 arcsec) over the full field of view and temporal resolution (30 s). During the flight, several data sets with duration of more than 30 min were obtained. Most of the observations were made at disk center, complemented by measurements of the center-to-limb variation.

A quick comparison with spectro-polarimetric data from the Hinode satellite shows the superiority of the IMaX data as far as spatial and temporal resolution is concerned. With IMaX data studies of the generation, evolution and disappearance of small scale magnetic flux in the solar photosphere will be performed. The SUFI UV images show high intensity contrast values (see Fig. 2). The SUNRISE telescope has a very low level of internal stray light, thanks to its excellent optical performance, and external atmospheric stray light is virtually absent, thanks to the cruising altitude of 36 km, so that the contrast measurements, taken at different wavelengths, can be used to test predictions from numerical simulations.

Once the data processing is completed, the participating institutes will proceed with the scientific data analysis. All data will be available to all interested scientists six months after data processing is finished.

Based on the success of the first science flight, the Sunrise teams intend to seek financial support for a second mission, with improved instrumentation, and, funds permitting, a third science instrument for magnetic field measurements in the solar chromosphere.

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