A Brief Introduction to the European Balloon-borne Solar Telescope SUNRISE and Related Research Results: Postprint

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Abstract

Utilizing balloon-borne solar telescopes launched into the stratosphere to observe solar magnetic field evolution and monitor solar activity offers unique advantages. First, in the stratosphere, observations of the Sun by balloon-borne solar telescopes are not subject to interference from weather phenomena in Earth' s tropospheric atmosphere, and are conducted in an environment free from seeing effects. This provides superior conditions for acquiring high-quality solar images. Second, the atmospheric density in the stratosphere is extremely low, and absorption of ultraviolet radiation is significantly reduced. Balloon-borne solar telescopes can observe solar activity and eruptions in the near-ultraviolet band. Third, balloon-borne solar telescopes can reduce operational costs and improve telescope utilization through recovery, upgrading, and reuse, making them far more economical than space-based observations. The use of balloon-borne solar telescopes for solar observation research has a history of over half a century in Europe and America. This paper briefly reviews the development history of balloon-borne missions for solar observation, including the extremely rich experience accumulated during this period in instrument development and observation, provides a detailed introduction to the instrument payload of the European SUNRISE balloon mission, its vast amount of high-resolution observational data, and a series of high-quality scientific achievements completed on this basis, offering important reference for the development of balloon-borne telescopes in China.

Full Text

Preamble

Overview of the Balloon-Borne Solar Telescope SUNRISE and Related Research

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Abstract: Balloon-borne solar telescopes launched into the stratosphere offer unique advantages for observing solar magnetic field evolution and monitoring solar activity. First, in the stratosphere, balloon-borne solar telescopes operate free from interference by tropospheric weather phenomena, providing a seeing-free environment that enables acquisition of high-quality solar images. Second, the extremely thin stratospheric air significantly reduces ultraviolet absorption, allowing near-ultraviolet observations of solar activity and eruptions. Third, balloon-borne telescopes can be recovered, upgraded, and reused, substantially reducing costs and improving efficiency compared to space-based observations. Balloon-borne solar observations have a history spanning over half a century in Europe and the United States. This paper briefly reviews the development history of balloon-borne solar missions, including the extensive experience accumulated in instrument development and observations. We provide detailed descriptions of the SUNRISE mission's instrumentation, its vast high-resolution observational datasets, and the high-quality scientific results achieved, offering important reference for developing balloon-borne telescopes in China.

Keywords: balloon-borne missions; solar telescopes; high spatial resolution; high temporal resolution

0 Introduction

Balloon-borne solar telescopes launched into the stratosphere possess advantages unattainable by ground-based solar telescopes. On one hand, they avoid tropospheric atmospheric disturbances, enabling high-resolution observations; on the other hand, they can capture solar radiation characteristics in the near-ultraviolet and even far-ultraviolet bands. Since ultraviolet radiation reaching the ground is essentially completely absorbed by the dense atmosphere, ground-based solar telescopes cannot observe solar UV radiation. Additionally, balloon-borne solar telescopes have unique advantages over space-based solar telescopes: first, their development and launch costs are much lower than satellite-borne instruments; second, they can be recovered and reused with continuous upgrades, improving utilization efficiency; finally, successful balloon-borne telescope experience provides valuable reference for future space telescope programs.

Balloon missions for high-resolution solar observations have a long history (Table 1 lists all balloon-borne solar telescopes flown to date and their parameters). The earliest balloon-borne solar telescope was initiated by Princeton University Observatory. In 1957, they flew a balloon carrying a 12-inch (approximately 30.5 cm) aperture telescope to 80,000 feet (about 24 km) in near space [1]. The mission conducted flights on August 22, September 25, and October 17 of that year. The first flight failed to obtain good scientific data due to poor solar pointing. The second flight acquired 8,000 photographs, with 400 properly solar-pointed images, of which about 5 showed clear granulation. The third flight obtained more clear granulation images and also captured limb images. Two years later, after instrument improvements adding television visualization, telemetry, and remote control capabilities, another flight was conducted in 1959 [2], yielding high-resolution images of granulation, limb structure, and fine sunspot details that remain valuable references today. In 1975, they added a spectrograph for another flight, though unfortunately only granulation data were obtained [3-5].

The Soviet Stratospheric Solar Observatory conducted four flight experiments [6-8]. The first three flights used 0.5-meter telescopes, while the fourth used a 1-meter telescope. The third observation provided data on granulation and sunspots in Hα and its wing. By comparing dark mottles observed at Hα line center with photospheric granules observed in the wing, they found that mottle scales were several times larger than granules [7].

The Johns Hopkins University Applied Physics Laboratory launched a balloon carrying an 80-cm telescope equipped with a Fabry-Pérot magnetograph from Antarctica between January 7-26, 1996 [9]. Due to insufficient solar pointing stability, the image motion compensator could not keep image jitter within 0.1” , and issues with telescope focusing and subsequent image alignment resulted in relatively low resolution, yielding poor scientific data [10]. Addressing these problems, they improved the telescope [10,11] and conducted a 17-day observation in January 2000, acquiring monochromatic images, magnetograms, and Doppler images in the Ca I 6122.2 Å band, plus Hα monochromatic images. Among the 50,000 images obtained, the highest spatial resolution reached 0.5” [12].

The French National Space Research Center, in collaboration with the French Laboratory of Astrophysics of Marseille, flew balloons carrying a 20-cm telescope for ultraviolet observations on October 5, 1970, and June 24, 1971 [13]. They obtained observations in four bands: 2000 Å, 2100 Å, 3100 Å, and 4600 Å. Clear granulation and faculae were observed at 3100 Å and 4600 Å. They subsequently upgraded the instrument with a larger telescope aperture and successfully launched a 30-cm telescope to 38 km altitude on October 1, 1982 [14]. The data achieved 0.5” spatial resolution in the 1900 Å–3000 Å band. The telescope was equipped with a UV spectrograph that obtained high-resolution spectral data with 0.015 Å–0.02 Å resolution in wavelength ranges of 1900 Å–2130 Å and 2720 Å–2930 Å.

The Max Planck Institute for Solar System Research launched the “SUNRISE” balloon-borne solar telescope from northern Sweden on June 8, 2006, at 06:27 UT. The telescope conducted multi-band imaging observations of the quiet Sun at disk center and performed polarimetric measurements in the Fe I 5250.2 Å band [15,16]. A second balloon flight was conducted on June 12, 2013, targeting an active region [17]. Both missions obtained excellent scientific data and rich scientific output, producing approximately 50 research papers. A third balloon mission is currently in active preparation [18].

This paper focuses on introducing the SUNRISE mission’ s instrumentation and the scientific results from its two flights. Section 2 describes the SUNRISE instrumentation; Section 3 details the two flight missions; Section 4 presents the observational data from both flights; Section 5 summarizes the scientific achievements; Section 6 concludes with lessons from SUNRISE’ s success and prospects for future Chinese balloon missions.

1 SUNRISE Instrumentation

The SUNRISE instrumentation consists of a one-meter Gregory-type reflector telescope [19], a post-focus instrumentation platform (PFI) [20], and a gondola with pointing and tracking capabilities [21]. The one-meter Gregory reflector telescope has an effective focal length of 25 meters. A heat rejection wedge at the primary focus reflects 99% of incident sunlight, controlling thermal radiation passing through the primary focus to approximately 10 watts. The post-focus instrumentation includes a Sunrise Filter Imager (SuFI) [22], an Imaging Magnetograph eXperiment (IMaX) [23], an Image Stabilization and Light Distribution system (ISLiD) [22], and a Wave-Front Correction System (WCS) [21]. The gondola provides housing for the telescope, instruments, and power systems while ensuring telescope stability, tracking accuracy, and pointing precision. Figure 1 [Figure 1: see original paper] shows the SUNRISE balloon-borne solar telescope system before launch (left panel) and an overview of the telescope (right panel). Below we describe the telescope and these instrument systems in detail.

1.1 One-Meter Gregory Telescope

The SUNRISE balloon-borne solar telescope is a lightweight Gregory-type reflector telescope. The primary mirror M1 has a parabolic surface with an effective clear aperture of 1 meter. Figure 2 [Figure 2: see original paper] (left) shows the telescope optical path: parallel light from the Sun reflects off primary mirror M1 and focuses at first focus F1, forming a real solar image. A field stop at F1 allows a small fraction of light to pass to secondary mirror M2, reducing heat reaching M2 and subsequent optics. M2 has an effective diameter of 0.245 meters and focal length of 0.505 meters. Light reflected from M2 passes through two 45° mirrors (M3 and M4) and reconverges at second focus F2 located in the post-focus instrumentation platform above the primary mirror. A field stop at F2 further limits the field of view to within 180” .

Figure 2 (right) shows the overall telescope assembly structure. Yellow steel struts support and stabilize the telescope assembly and post-focus instrumentation by connecting the rear ring surrounding the primary mirror, the front ring surrounding the secondary mirror, and the central truss. Components surrounding the secondary mirror include the heat rejection wedge, octagonal front ring, heat rejection wedge radiators mounted on the front ring, the Lockheed Intermediate Sun Sensor (LISS), and the Full Range Elevation Device (FRED). LISS and FRED belong to the gondola system, with LISS assisting telescope pointing to the Sun and FRED tracking the Sun. The front ring and its components continuously face the Sun and receive high-temperature solar radiation. Radiators on the front ring and the heat rejection wedge at the primary focus are primarily responsible for cooling.

Components surrounding the primary mirror include mainly the rear ring, three plate baffles, and two 45° mirrors (M3 and M4). The rear ring primarily supports the primary mirror (Figure 2a). The outer surfaces of the plate baffles behind the primary mirror reflect well, protecting the mirror from ground infrared radiation and sunlight reflected from ground ice or ocean beneath the balloon, controlling primary mirror temperature. The front surface coating is aluminum, 100 nm thick. The mirror coating absorbs about 80 watts of solar radiation. M3 and M4 receive reflected light from M2 and redirect the optical path so the second focus falls above the primary mirror. Locating the second focus above the primary mirror enables compact integration of different functional instruments in a small space, greatly reducing the overall balloon payload volume.

Bearing interfaces (elevation axis) connecting to the gondola are installed on both sides of the central truss, aligned at the same height as the center of gravity of the telescope assembly and post-focus equipment. These bearings serve two main functions: connecting the telescope to the gondola and enabling telescope elevation angle adjustment through this transverse axis mechanism. Precise solar pointing is achieved primarily by adjusting the elevation angle. The front ring, rear ring, and truss are made of carbon fiber reinforced plastic composite materials, offering high strength, light weight, and low thermal expansion. The truss stiffness design ensures that lateral displacements of the front and rear rings under gravity loading are approximately equal, effectively maintaining instrument alignment. Even when relative lateral displacement occurs due to gravity load changes, the connecting structure maintains parallelism between major components and controls positional variations between M1 and M2 at the millimeter level.

Incident light reaching the primary mirror reflects and converges at F1 into a circular beam with 22 mm cross-section diameter and radiation power up to 1 kW. To prevent damage from such high energy concentration, effective cooling is required. As shown in Figure 3 [Figure 3: see original paper], a heat rejection wedge is installed at F1. This highly conductive cylindrical aluminum block has a wedge-shaped front surface coating (UV-reflection-enhanced) that reflects 99% of incident light from the primary mirror. Absorbed energy is transferred via heat pipes to radiators on the front ring, maintaining the wedge temperature below 25°C to prevent formation of image interference fringes and consequent wavefront deformation. The heat rejection wedge controls solar radiation power passing through the central aperture to approximately 10 watts.

Because extremely high energy concentrates around the first focus F1, uncontrolled beam paths could damage nearby structural components. A protective measure for such contingencies is a retractable curtain installed on the central truss plane facing the Sun. When accidents such as inaccurate sun sensor pointing occur, the curtain can shield the primary mirror. The curtain requires about 20 seconds to fully cover the primary mirror aperture, far less than the critical exposure time for components near the field stop. During flight, the retractable curtain is controlled by the computer pointing system. When pointing error exceeds \$±\$15 , the curtain enters shielding mode until pointing accuracy is restored to within \$±\$20" , effectively protecting primary mirror components.

1.2 Post-Focus Instrumentation Platform

The post-focus instrumentation platform is located above the telescope assembly (see Figure 2 right panel). Its width matches the telescope assembly at approximately 1.4 meters, with length about 2 meters–sufficient to accommodate required instruments–and height of 350 mm. This height considers two factors: minimizing the platform' s center of gravity and balancing increased bending and torsional stiffness with height changes. The platform houses a filter imager, magnetograph, image stabilization and light distribution system, and wave-front correction system. After integrating, aligning, and installing these independent modules, they are placed in their respective positions on the platform.

Designing these as independent modules offers advantages: each module achieves maximum internal stiffness, minimizing alignment errors within the post-focus platform due to gravity load changes. Additionally, it prevents mechanical tension within modules from differential thermal expansion between modules and the platform, maintaining horizontal alignment accuracy among modules within $±$0.2 mm in all directions. This alignment ensures maximum image shift at optical interfaces remains within tolerance. Module pointing errors relative to fixed points are controlled within 3 in all directions, with module displacements relative to the pupil kept within 5% of the pupil diameter. This maintains instrument calibration accuracy within $±$0.1 mm.

Figure 4 [Figure 4: see original paper] shows the post-focus instrumentation overview (left) and optical path (right). The platform houses mechanism controllers and the wave-front correction system, the magnetograph and filter imager, wave-front sensor electronics, and SuFI camera electronics, plus the image stabilization and light distribution system embedded in the platform and compatible with all device interfaces. The right panel shows the optical path: light enters the post-focus platform at M4 (blue line indicated by red arrow at M4), first converging at second focus F2, then redirected by an oblique mirror. Part of the light is allocated to the filter imager port, while another portion goes to the common port for the magnetograph and wave-front correction system, where radiation of corresponding wavelengths is further distributed to the magnetograph and wave-front sensor.

The platform bottom consists of two 10-mm-thick carbon fiber reinforced plastic composite plates joined together. These plates separate platform equipment from the telescope assembly while providing tensile strength to protect platform components. Overall, high stiffness-to-drag ratio is a prominent advantage of this platform structure. Using carbon fiber reinforced plastic composite plates further minimizes thermal expansion, ensuring that platform modules maintain good optical alignment under different thermal and mechanical loads during flight.

Cameras and electronic equipment installed in the post-focus platform require radiative cooling. Platform radiators maintain camera lenses (operating temperature 5°C–10°C) and nearby electronic components (operating temperature below 45°C) within acceptable ranges. Radiator dimensions and surface properties are determined based on flight conditions, required operating temperatures, and thermal performance analysis. Thermal stability is also critical: total temperature (including gradients) across the 2-meter platform must be maintained within 20$±$10°C. This ensures alignment of non-composite instruments like the magnetograph remains unchanged and optical polarization characteristics vary minimally.

1.2.1 Filter Imager The filter imager provides imaging observations in the violet and near-ultraviolet bands, including five wavelength bands: 2140 Å (passband 100 Å), 3000 Å (passband 50 Å), 3120 Å (passband 12 Å), 3880 Å (passband 8 Å), and 3968 Å (passband 1.8 Å). The filter imager employs a modified Schwarzschild microscope structure, commonly used in UV microscopes for their large numerical aperture and wide field of view coverage.

Figure 5 [Figure 5: see original paper] illustrates the optical design evolution from the Schwarzschild microscope principle to the filter imager. The original Schwarzschild configuration utilized only a small portion of the mirror surface. Figure 5b shows a decentered off-axis modification where object and image are displaced from the primary mirror optical axis. Building on this, Figure 5c adds a folding mirror to adjust the initial incident beam direction. This folding mirror, a plane mirror, also serves as an image motion compensator to stabilize the target image on the focal plane.

Further modification of Figure 5c yields the optical path used in the filter imager (Figure 5d). A dichroic beam-splitter plate is added in the exit beam path before imaging. This splitter reflects radiation shorter than 4500 Å while transmitting longer wavelengths. The selected beam ($\lambda < 4500$ Å) passes through two filters, a 45° mirror, and a phase diversity image doubler before detection by the CCD. Two filters are used to block stray light because UV intensity from the splitter is much weaker than longer wavelengths and easily overwhelmed by surrounding stray light. To prevent recontamination, the optical path from filters to CCD is enclosed, with the 45° mirror and phase diversity doubler sealed in a closed space.

1.2.2 Magnetograph The magnetograph primarily observes polarization information in the Fe I 5250.2 Å band (g = 3) with a field of view of 50" $×50".*ObservationsareconductedatseveralwavelengthpointsneartheFeI*5250.2*linecenterandatonenear*− *continuumwavelengthpoint*, *achievinganoiselevelof*10^{-3}$. Wavelength points refer to observation points offset from the line center by specific bandwidths, such as commonly used points at $±$80 mÅ, $±40*m*, *and* + 227*mfromlinecenter*.*Temporalresolutioncanbeadjustedbyvaryingthenumberofwavelengthpoints*(3*to*12)*and* *stateLiNbO*_{3}$ Fabry-Pérot etalon.

Figure 6 [Figure 6: see original paper] shows the magnetograph optical path and structure. Light enters the magnetograph at focus F4, first encountering a prefilter that only transmits light within 1 Å of the central wavelength, with the rest absorbed by a light trap. Although most UV photons are directed to the filter imager path [23], some residual UV remains. The prefilter protects liquid crystal variable retarders from any residual UV. Light from the prefilter passes through two liquid crystal variable retarders. The first retarder' s optical axis (along the light direction) is parallel to one linear polarization direction of the beamsplitter, while the second retarder' s axis is oriented 45° to the first.

Polarization modulation is achieved by driving retarders with specific voltages. The two retarders together can generate four linearly independent polarization states [I_1, I_2, I_3, I_4] (N =4) or provide two classic polarization states I+V and I-V for longitudinal polarization (N =2). Light passing through the retarders reaches a collimator doublet and first passes through a thermally stabilized enclosure. This enclosure provides a temperature-stable environment for internal components ($LiNbO_3$ F-P etalon), with fused silica windows at both ends. Light passes through the front window, the internal F-P etalon, and exits through the rear window, then encounters two 45° mirrors with aperture stops. After reflection, it passes through the $LiNbO_3$ F-P etalon again. Emerging light passes through a camera doublet, a 45° mirror, and a beamsplitter that divides it into two perpendicular beams: one to the CCD for imaging, the other through a phase plate to another CCD. Polarization state remains stable from retarders to beamsplitter.

Modern polarimeters (e.g., Hinode/SP) maintain high sensitivity through high signal-to-noise ratio (S/N), fast polarization modulation, and dual-beam configuration. S/N, the key parameter determining photometric and polarization sensitivity, is improved primarily through image accumulation. High S/N enables detection of the weakest photometric intensity δI and smallest polarization degree δp within telescope capabilities. The community consensus is that detecting weak polarization signals in quiet Sun network regions requires minimum S/N of 10^3. Measuring weak solar surface magnetic fields demands strict instrumental capabilities. Simulations of magnetoconvection in quiet Sun regions show magnetic field strength distributions increasing monotonically from 1 G to several kG. Detecting 1 G longitudinal fields requires detecting approximately 2$×10^{7}$ photoelectrons within a time period where the magnetic field itself does not change significantly. Current CCDs have full wells of about 10^5 electrons, meaning a single exposure detects only a small fraction of required photoelectrons. Therefore, single exposures cannot achieve the required photoelectron count for polarization sensitivity. Modern solar polarimeters introduce image accumulation during single exposures to increase photoelectron number N to achieve required polarization sensitivity or S/N. This approach has been successfully applied in advanced Stokes polarimeters [24], and the magnetograph uses this real-time exposure accumulation method to achieve S/N 10^3.

For spectral analysis, the magnetograph uses a combination of a 1 Å FWHM prefilter and a double-pass $LiNbO_3$ F-P etalon. While such interferometers have been used in solar physics [11], their application in the magnetograph is novel. The basic principle: the interferometer contains two parallel mirrors. When light enters, it undergoes multiple reflections between mirrors, creating modulation between transmitted and reflected beams. The emerging light produces a series of intensity peaks at given wavelengths, forming a spectrum. The instrument modulates spectral sensitivity primarily by adjusting mirror reflectivity, combined with S/N improvement to enhance spectral resolution.

1.2.3 Wave-Front Correction System The wave-front correction system consists mainly of a Shack-Hartmann wavefront sensor, high-speed camera (>1 kHz), and closed-loop control computer. Its primary function converts wavefront distortions measured by the Shack-Hartmann sensor into electrical signals that drive a fast tip-tilt mirror (operating at 1700 Hz) and slow secondary mirror M2 (operating at 0.1 Hz) [27,28] to make opposite corrections that cancel distortions. Thus, the system has two applications: as a fast wavefront sensor generating control signals to drive the tip-tilt mirror for image motion compensation, and as a slow wavefront sensor for active focusing of the telescope secondary mirror.

1.2.4 Image Stabilization and Light Distribution System When conducting multi-band observations, the SUNRISE balloon-borne solar telescope requires stable incident light and precise delivery of each band' s light to corresponding filter positions. To satisfy these requirements, a reliable image stabilization and light distribution system is mounted on the post-focus platform. This complex optical device must simultaneously perform different tasks: first, stabilize the incident beam to provide stable input for scientific instruments and the wave-front correction system; second, separate specific wavelength beams from incident light and deliver them to corresponding filters while transmitting remaining light to the wave-front correction system; third, transmit wavelength ranges covering all instrument requirements, providing matched optical interfaces at specified positions and orientations; fourth, ensure scientific instruments operate at diffraction limit under all conditions, including during balloon ascent; fifth, reduce residual pointing errors below a specific threshold to ensure image blur from residual errors does not affect image quality.

1.3 Gondola

The gondola hangs 100 meters beneath the balloon. With a payload of 1919.6 kg, it measures 5.5 meters in length and width, and 6.4 meters in height. It provides housing for the telescope, post-focus platform, power systems, and is responsible for accurate telescope orientation. The gondola autopilot maintains solar pointing accuracy within $±$45”. Within this range, the wave-front correction system and image stabilization system can compensate residual motion for continuous stable scientific observations. Gondola orientation control is accomplished through momentum transfer units at its top. Power is supplied by solar panels mounted on both sides of the telescope, with power control instruments on rear brackets. Two data storage units are safely loaded in a truss inside the upper core frame, providing data protection and facilitating post-landing data recovery. The gondola has a barrel-shaped appearance with a core structure of aluminum/steel tubing that is relatively lightweight yet provides required stiffness and high characteristic frequency (>10 Hz). This structure splits the telescope into upper and lower halves formed by two U-shaped components, facilitating scientific instrument integration and allowing elevation angle control from -5° to 50°.

Telescope azimuth is controlled by coarse and fine azimuth motors at the gondola top. Since balloon payloads rotate during ascent, the coarse azimuth motor primarily decouples the gondola from balloon rotation, while the fine azimuth motor rotates the gondola to specific orientations via acceleration and deceleration of a reaction wheel. The reaction wheel’ s rated speed is 10 r/min. Motor rotation provides gondola rotation torque proportional to motor frequency. Driving ranges are divided by frequency: the coarse motor compensates torque frequencies below 0.1 Hz, while the reaction wheel compensates 0.1–1 Hz.

Telescope elevation is adjusted primarily by a linear translation stage, a component of precision motion systems that restricts object movement to a single axis. The stage connects rigidly to the telescope central frame via a lever arm. Slight preloading of the lever arm minimizes elevation adjustment hysteresis. Several elevation drive modes were considered during early design, including torque motors, but the linear translation stage was selected for its high-precision elevation adjustment and ability to apply asymmetric loads to the telescope central frame. Due to its high-precision elevation adjustment, this drive mode can also serve as a lock during launch and landing.

The fine azimuth detector is fixed at the gondola top as a Precision Azimuth Sun Sensor (PASS), capturing azimuth within $±$3°. The Full Range Elevation Detector (FRED) locates telescope elevation as an intermediate-resolution device, searching for the Sun within $±$5° azimuth and $±$15° elevation. When the Sun’ s position exceeds this range, FRED provides a saturation signal indicating the Sun is above or below the telescope’ s maximum elevation. Both detectors have accuracy better than 10” . Highest-precision solar tracking is accomplished by the Lockheed Intermediate Sun Sensor mounted on the telescope front ring, with azimuth and elevation ranges of $±$3°. When temperature is stable and minimal, the Lockheed sensor achieves solar pointing accuracy of 1–2” .

2 Flights

SUNRISE’s first flight launched from Kiruna, northern Sweden, on June 8, 2009, at 06:27 UT, ascending to 37.2 km altitude and landing on a northern Canadian island on June 13, 2009, at 23:47 UT. The second flight launched from Kiruna on June 12, 2013, at 05:37:53 UT, reaching 37.1 km altitude and landing on a northern Canadian island on June 17, 2013, at 11:49:24 UT. During flight, the gondola pointing system activated first. The balloon payload rotated during ascent, exposing instruments to sunlight and heat, allowing the pointing system to debug parameters under different conditions. After parameter debugging, the gondola pointing system maintained extremely stable solar pointing throughout observations.

For thermal control, all instrument temperatures remained within normal ranges. For example, optics and mechanics on the post-focus platform stayed between 5°C–25°C. Some external component temperatures varied by $±$10°C, primarily due to telescope elevation changes and albedo flux variations from changing terrain. Albedo refers to the ratio of reflected solar radiation intensity to total solar radiation received at a surface.

Optical performance is evaluated through wavefront quality measured by correlation wavefront sensors, phase diversity, and reconstructed data. During observations, the main factor affecting optical performance is wavefront error, primarily caused by thermoelastic deformation of the optical system under daytime illumination and slight relative position changes between primary and secondary mirrors due to orientation changes relative to gravity. This wavefront error is measured by correlation wavefront sensors, with results used to adjust secondary mirror position to reduce error. During flight, only minor secondary mirror adjustments (100 m) were made in closed-loop to adjust focus position. Before adjustment, this slight defocus caused wavefront error of \$±0.5 \$ rms. The correlation wavefront sensor’ s sensitivity and secondary mirror adjustment precision achieved focus accuracy better than 0.01λ rms [22]. Alignment errors between correlation wavefront sensor focus and filter imager focus, and between wavefront sensor focus and magnetograph focus, were both within $\lambda/20$. However, post-processing revealed that the main factor affecting optical performance during observations was not wavefront error or optical components, but residual image smear from multi-frame 叠加 of moving images, reducing filter imager spatial resolution to 0.1” and magnetograph resolution to 0.15”-0.18” .

3 Observational Data

Both SUNRISE flights obtained excellent data. The first flight targeted quiet Sun regions at disk center, while the second focused on active regions. First flight data were obtained mainly on June 9, 11, and 13, 2009, including multi-band filter imager data at 2140 Å, 3000 Å, 3120 Å, 3880 Å, 3968 Å, and polarimetric data at 5250.2 Å. Total observation time was 130 hours. The longest continuous filter imager observation lasted 34 minutes, with 19 minutes at the shortest wavelength of 2140 Å, and the longest polarimetric observation was 32 minutes.

Figure 7 [Figure 7: see original paper] shows reconstructed monochromatic images from multi-band filter imager observations. The first row displays quiet Sun features near disk center (= 0.72), showing clear bright granules and photospheric bright points in dark intergranular lanes at 3000 Å, 3120 Å, and 3880 Å. At 2140 Å, bright granule boundaries are less distinct than in the other three bands, and dark intergranular lanes are no longer clearly visible. The leftmost panel in Figure 7a shows features near disk center in the Ca II H 3968 Å band, clearly revealing dark granules and bright intergranular lanes—the opposite of photospheric band observations. Features at 2140 Å appear intermediate between reversed and normal granulation. Figure 7b shows limb features, with spicules clearly observed above the limb.

Figure 8 [Figure 8: see original paper] shows reconstructed polarimetric data. The first row shows continuum image (left) and Doppler velocity map (right). The second row shows total linear polarization intensity normalized to continuum intensity Ic and circular polarization intensity normalized to Ic, defined as:

$$L_s = \frac{1}{4I_c}\sum_{i=1}^{4}\alpha_i\sqrt{Q_i^2+U_i^2}, \quad V_s = \frac{1}{4I_c}\sum_{i=1}^{4}\alpha_i V_i, \quad \alpha_i = 1, 1, -1, -1$$

where i = 1, 2, 3, 4 represent wavelength points near Fe line center. All parameters except Ls are reconstructed data. Observations near the continuum wavelength 5250.2 Å + 227 mÅ show granulation brightness contrast rms of 13.5%, indicating high-quality polarimetric images. The Vs profile in Figure 8' s lower right panel shows a network region with strong Stokes V signals. Most areas are internetwork regions with mixed-polarity magnetic fields. Magnetic elements in these internetwork regions have scales smaller than 1" , many approaching the telescope' s diffraction limit (0.15").

The second SUNRISE mission observed for 122 hours, with the filter imager acquiring 300 GB of data (60,806 images) and the magnetograph acquiring 68 GB (48,129 images). The longest continuous filter imager observation was 60 minutes, while the magnetograph' s longest continuous observation was 17 minutes. Pixel resolution varied by band but remained within 0.01983" -0.02069" per pixel. The magnetograph used multiple observation modes, primarily full Stokes parameter observations at 8 wavelength points on both sides of Fe I 5250.2 Å line center ($±$120 mÅ, $±$80 mÅ, $±40m, +227m), withtemporalresolutionof36.5seconds, pixelresolutionof0.05546", andfieldofviewof51"×$5
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Figures 9 [Figure 9: see original paper] and 10 [Figure 10: see original paper] show monochromatic and Stokes parameter intensity maps from the second flight. Figure 9(a) shows a 3000 Å filtergram normalized to IQS (quiet Sun intensity at 3000 Å). Photospheric bright points, faculae, and elongated granules are clearly distinguishable. Figures 9(b) and 9(c) show results with different passbands at the same line center (3968 Å). Despite different bandwidths, features are nearly identical. Observations near active regions in the Ca II H 3968 Å band (lower chromosphere) show clear fibril structures whose footpoints correspond to bright points in Figure 9a.

Figures 10a-10c show active region features at +227 mÅ, +0 mÅ, and +40 mÅ from Fe I 5250.2 Å line center. Figures 10d-10f show Stokes Q, U, V intensity distributions at +40 mÅ, all normalized to IQS. Details and features within active regions, particularly sunspot interiors, are identifiable—including pores, elongated granules, umbra, light bridges, some penumbral structure, and umbral bright points (see Figures 10a-10c). In Figure 10a, granules and umbral bright point outlines are very clear, corresponding to enhanced Stokes V signals at the same locations in Figure 10f, indicating strong longitudinal magnetic fields concentrated at umbral bright points. Surrounding areas show weaker Stokes V signals, implying non-uniform magnetic fields in sunspot umbrae with many smaller-scale, strong-field magnetic flux tubes.

4 Scientific Results

The first SUNRISE flight targeted quiet Sun regions near disk center. Scientific achievements focused on small-scale magnetic field emergence, flux tube-granulation interactions, flux tube configurations and characteristics, and wave propagation. Several new results were obtained that are difficult for ground-based telescopes to detect. For example, data revealed magnetic flux tubes for the first time, their interactions with granulation, the inclination angle of quiet Sun flux tubes from photosphere to chromosphere through multi-band observations, and supersonic blue-shift signals accompanying small magnetic elements emerging with granules—interpreted as photospheric magnetic reconnection. The second flight targeted active regions near disk center, with results focusing on magnetic flux emergence and cancellation near active regions, moving magnetic features, and fibril structures formed by strong fields extending to the chromosphere.

Both flights obtained high-quality data and fruitful scientific results. Here we summarize important achievements from both flights. The first flight’ s quiet Sun observations concentrated on convective motions and small-scale magnetic activity, including granulation, bright points in intergranular lanes, vortex motions in granules, and emergence of small magnetic elements on granules. These features are small-scale, short-lived, and require extremely high spatial and temporal resolution. Key first-flight results include:

- **First high-resolution observations of kilogauss magnetic flux tubes.** Lagg et al. [25] inverted SUNRISE/IMAX Stokes data with spatial resolution of 0.15”–0.18%. By analyzing temperature distributions at photospheric bottom, middle, and top layers in three regions with field strengths of 100 G, 500 G, and 1000 G, they found that kilogauss regions become progressively hotter than surroundings with increasing height, while weaker field regions show no significant temperature change, concluding that network regions consist of strong-field flux tubes with kilogauss strengths. Jafarzadeh et al. [26] constructed 3D magnetic field configurations of thin flux tubes, calculating an average inclination angle of $14° \pm 6°$ between the expanded and tilted flux tube from photosphere to low chromosphere and its original direction. Stangalini et al. [27] found 90° phase delay between horizontal motion speed of flux tubes and resulting longitudinal perturbation speeds inside them, suggesting small-scale horizontal motions can generate longitudinal waves.
- **First discovery of ultraviolet bright point brightness contrast up to 2.31.** Riethmüller et al. [28] studied brightness contrast of bright points in UV and visible bands to examine their contribution to solar irradiance. They found average brightness contrast of bright points at 2140 Å reached 2.31, with contrasts at other bands (3000 Å, 3120 Å, 3880 Å, 3968 Å, 5250 Å) being 1.52, 1.35, 1.60, 1.89, and 1.11 respectively. Hirzberger et al. [29] found quiet Sun intensity contrast at 2140 Å reached 32.8%,

higher than other bands. Using the same data, Kahil [30] studied the relationship between line-of-sight magnetic field strength and intensity at different wavelengths, finding different logarithmic relationships between intensity and field strength for each band.

- **Discovery of small-scale magnetic elements emerging with granules and accompanying supersonic blue-shift phenomena.** Borrero et al. [31,32] studied polarization signals within granules, finding supersonic blue-shift polarization signals in one granule. The granule emergence rate was 1.3×10^{5} arcsec^{-2}s^{-1}, area about 0.046 arcsec^{2}, and duration 80 seconds. These supersonic polarization signals accompanied emergence of opposite magnetic polarity signals. They further found these events often accompanied by opposite polarity fields and spectral line blue- and red-shifts, inferring possible magnetic reconnection between opposite polarity fields [33]. Palacios et al. [34] studied a magnetic emergence event with a granule. The newly emerged field initially had ~100 G strength at the granule top, then split as the granule divided. Later, an opposite polarity field emerged and both converged in the intergranular lane. Requerey et al. [35] found plasma downflow regions in convective motions with density 6.7×10^{-2} Mm^{-2}, appearing at mesogranular boundaries with strong longitudinal fields. About 40% of downflow region area contained fields stronger than 500 G. Steiner et al. [36] found bright structures at granule edges moving toward granule centers, with dark structures following. Numerical simulations showed this resulted from collisions between twisted flux tubes in intergranular lanes and granules.

- **Updated conclusions on vortex motion number density in intergranular lanes.** Bonet et al. [37] found vortex motion number density of 3.1×10^{-3} Mm^{-2} min^{-1}. SUNRISE’ s high spatial resolution polarimetric and imaging data detected 1.7 times more vortices than previous observations. Observed vortices lasted 7.9 ± 3.2 minutes, with multiple occurrences at the same location and both clockwise and counterclockwise rotations.

- **Relationship between strong linear polarization regions and transverse magnetic fields.** Danilovic et al. [38] tracked strong linear polarization signal regions, finding transverse field occurrence frequency density of 7×10^{-4} arcsec^{-2}s^{-1}, 1-2 times higher than previous results [39-42]. These strong linear polarization signals showed no clear pattern in lifetime or area, often appearing at granule edges, mostly with red-shifts though some showed only blue-shifts throughout their lifetime. Kianfar et al. [43] further studied quiet Sun linear polarization features. With $S/N > 4.5$, 26% of the studied region was covered by linear polarization signals occupying 10% of the area. Occurrence frequency density was 8×10^{-4} arcsec^{-2}s^{-1}, scales 0.1”-1.5” , lifetimes 30-300 seconds, field strengths of a few hundred gauss, and horizontal speeds ~1.2 km/s. These regions were uniformly distributed in red- and blue-shift areas with higher brightness contrast than surroundings. Quintero Noda et al. [44] found linear polarization signals appeared ~84$±$11 s before strong Doppler velocities. About 80% of strong Doppler signals occurred near neutral lines between emerging and pre-existing fields, interpreted as magnetic reconnection. The remaining 20% showed no clear proximity to pre-existing fields, suggesting possible geometric complexity.

- **Magnetic diffusion causes flux decay following exponential curves.** Guglielmino et al. [45,46] analyzed a bipolar magnetic element from emergence to disappearance, calculating total flux of 6$×10^{17}$ Mx and emergence rate of 2.6$×10^{15}$ Mx/s. During evolution, the bipole axis orientation changed by 90°, suggesting writhe. During decay, footpoints split into smaller elements that canceled with surrounding fields while magnetic diffusion accelerated decline. They found exponential flux decay with diffusion coefficient (8$×10^{2}$ km^2/s) consistent with large-scale magnetic diffusion in flux transport models. Martínez González et al. [47] found periodic shape deformations of magnetic structures from circular polarization data. They noted stable flux structures oscillated with periods comparable to granule lifetimes, inferring compression by granule convection. Three magnetic structures near one granule oscillated in phase, suggesting interference could increase amplitude to 1,600 km.
- **Energy release occurs primarily in the lower atmosphere.** Chitta et al. [48] used SDO/HMI and Sunrise/IMaX magnetograms as boundary conditions to simulate magnetic field configurations and evolution, studying energy release processes. They found energy release mainly occurred in atmospheric layers below 2,000 km, suggesting chromospheric magnetic fields may play important roles in coronal heating.
- **Characteristics of low chromospheric bright points in quiet regions.** Jafarzadeh et al. [49] calculated horizontal velocities, equivalent diameters, intensities, and lifetimes of chromospheric bright points, finding average horizontal speed of 2.2 km/s, equivalent diameter 0.2", average intensity 1.48 times background brightness (<I_{Ca}>), and average lifetime 673 seconds (<I_{Ca}> is quiet Sun average brightness in Ca II H). They estimated kink wave power density transmitted to higher atmosphere as 310 W/m^2 for bright points with speeds reaching 15 km/s. Subsequent studies [50] calculated diffusion factor $\gamma = 1.69 \pm 0.08$ and diffusion coefficient $D = 257 \pm 32$ km^2/s. Using both SUNRISE flights' data, they studied horizontal motions and diffusion characteristics of magnetic structures in quiet and active regions [51]. Diffusion factors >1 (super-diffusive) were found in all six studied regions (quiet Sun internetwork, network, active region internetwork, network, plage with pores, and sunspot regions), except quiet Sun network which showed random motion ($\gamma = 1$). They attributed super-diffusion to surrounding granule convection and small-scale perturbations within intergranular lanes.

The second flight targeted small-scale, short-lived magnetic structures near active regions, such as flux emergence and cancellation near sunspots, and fibril structures formed by small-scale strong fields above active regions. Large-scale, long-lived structures like sunspots and pores were not primary targets. Key second-flight results include:

- **First high-resolution study of slender Ca II H fibril characteristics.** Jafarzadeh et al. [52] reconstructed magnetic field configurations of slender Ca II H fibrils through extrapolation and numerical simulation, finding footpoints rooted in field-concentrated regions and fibril tops overlapping simulated small-scale magnetic loops. Gafeira et al. [53] statistically studied 38 such fibrils, finding average width 180 km, length 500–4,000 km, and average lifetime ~2,000 s (~33 min). Jafarzadeh et al. [54] found transverse oscillations with speeds 2.4 ± 0.8 km/s, periods 83 ± 29 s, upward propagation phase speeds 9 ± 14 km/s, and energy flux ~15 kW/m^2. Gafeira et al. [55] studied width and intensity perturbations, finding periods of 32 ± 17 s and 36 ± 25 s, with propagation speeds 11 km/s and 15 km/s, likely caused by fast sausage mode waves.
- **First high-resolution multi-band oscillation and motion characteristics of magnetic structures.** Jafarzadeh et al. [56] analyzed simultaneous co-spatial observations of magnetic structure oscillations in 3000 Å continuum and 3968 Å Ca II H line. The magnetic structure was traced by bright points. Phase differences between photospheric and low chromospheric oscillations revealed high-frequency waves (up to 30 MHz) propagating upward along the flux tube, plus downward propagating waves and standing waves. They estimated height difference between structures at the two wavelengths as 450 ± 100 km, and phase speeds of transverse and longitudinal waves along the flux tube as 29 ± 2 km/s and 31 ± 2 km/s respectively.
- **More precise extrapolation of 3D magnetic field structure from photosphere to mid-chromosphere in active regions.** Wiegelmann et al. [57] used second-flight magnetic data as boundary conditions for a magnetostatic model to extrapolate 3D field structure. High S/N polarimetric data enabled determination of free parameters in linear magnetostatic models using transverse field measurements. High spatial resolution permitted non-force-free field models between photosphere and mid-chromosphere.
- **Studies of flux emergence.** Smitha et al. [58] calculated flux emergence rates (FER), tracking emergence processes with fluxes of 10^{15}–10^{18} Mx, finding occurrence frequency of 1,100 Mx cm^{-2} d^{-1}, with single emergences $<10^{16}$ Mx contributing most to atmospheric flux increase. Centeno et al. [59] studied a dipole emergence event in an active region. When polarization data detected the emergence, corresponding chromospheric magnetic structures extended above it, showing details of field-granulation interaction and plasma being dragged upward into magnetic

channels. Plasma on the structure formed a material flow channel falling to footpoints, fixing the structure' s geometry through gravity while the structure oscillated. Finally, magnetic reconnection changed the structure, allowing part to extend to higher atmospheric layers, releasing energy that heated filament material.

- **Studies of flux cancellation.** Chitta et al. [60] combined SUNRISE second-flight magnetic data with simultaneous SDO data, finding coronal loops often rooted in photospheric regions with obvious dipole fields where small-scale fields continuously cancel. During cancellation, inverted Y-type jets appeared in the low chromosphere, suggesting low-atmosphere cancellation or reconnection may be important contributors of mass and energy to the corona. Kaithakkal et al. [61] studied 11 cancellation events near active regions, finding flux decay rates of $3.3\$\times10^{\{15\}-0.24\times10}\{15\}\$$ Mx/s. They classified events into two types: cancellation between pre-existing and newly emerging fields (6 events) and between two pre-existing fields (5 events). The first type showed Doppler shifts changing from blue to red, while the second type remained red-shifted, suggesting partial field submergence or reconnection-driven submergence.
- **Studies of Moving Magnetic Features (MMFs) near pores.** Kaithakkal et al. [62] studied MMFs near a pore, finding sub-arcsecond scales all moving away from the pore. MMFs with same polarity as the pore moved at 1.3 km/s, while opposite polarity MMFs moved at 1.2 km/s, suggesting same-polarity MMFs have faster horizontal speeds. Same-polarity MMFs showed no clear red- or blue-shifts, while opposite-polarity MMFs showed clear blue-shifts.
- **Comparison of Mg II k and Ca II H observations.** Danilovic et al. [63] compared active region observations in Mg II k and Ca II H bands with passbands of 4.8 Å and 1.1 Å respectively. Features were similar during flares, but Mg II k showed 1.4–1.7 times higher brightness contrast and smoother, more blurred images despite longer exposure times (100× Ca II H). The contrast difference also resulted from different formation heights of the two lines.
- **Ellerman bomb simulations.** Danilovic et al. [64] compared second-flight Ellerman bomb observations with numerical simulations, revealing complex physics and observational limitations in determining reconnection heights.

Analysis of both SUNRISE flights yielded 24 scientific results. First-flight results focused on small-scale quiet Sun magnetic structures, while second-flight results concentrated on active region structures like flux emergence, cancellation, and low chromospheric fibrils. These achievements are significant for both technical development and basic research. Technically, they help determine required spatial and temporal resolutions for studying small-scale magnetic structures in the lower solar atmosphere and provide references for future large-aperture solar optical telescope development and science goal definition. Scientifically, they provide rich information for studying small-scale magnetic field characteristics, flux emergence/cancellation, convection-field interactions, wave excitation/propagation, and solar atmospheric radiation characteristics, offering observational basis for solving fundamental problems like lower atmospheric energy conversion/transport and solar magnetic field origin.

5 Summary and Outlook

SUNRISE’ s instrumentation is complex and extremely precise, with several outstanding characteristics:

1. **Large-aperture telescope.** This was the first balloon mission carrying a 1-meter optical telescope. At 37 km altitude in the stratosphere, observations are free from ground atmospheric effects and seeing fluctuations. The large aperture enables near-diffraction-limited high-resolution multi-band observations, particularly in the near-ultraviolet—an unattainable advantage for current ground-based large telescopes. SUNRISE thus obtained the best international high-resolution multi-band observations of the lower solar atmosphere.
2. **Excellent optical performance.** SUNRISE has a complex optical path. To simultaneously satisfy multi-band imaging, polarimetric imaging, spectroscopic observations, and high-precision tracking requirements, the image stabilization and light distribution system uses tip-tilt mirrors to stabilize beams and beamsplitters to precisely allocate different wavelengths to corresponding optical exits while meeting interface requirements. The wave-front correction system measures wavefront distortion and provides feedback to the stabilization system, enabling tip-tilt mirrors to precisely cancel optical path jitter and ensure high stability.
3. **High-precision solar tracking.** Solar tracking uses combined coarse and fine azimuth detectors to determine solar azimuth within $±$3°. The Full Range Elevation Detector determines solar elevation within $±$5° azimuth and maintains $±$3° elevation accuracy. When both azimuth and elevation are within $±$3°, the Lockheed Intermediate Sun Sensor further refines pointing to 1”-2” . Final beam stabilization achieves 0.04” (rms) precision.
4. **Continuous stable thermal control.** From ground to stratosphere, and from night to daytime solar exposure, thermal radiation varies significantly. Optical components are vulnerable to damage and deformation from varying radiation intensity, causing alignment degradation. Therefore, maintaining stable operating temperatures is crucial. Post-focus platform thermal control requires temperature stability within 20 ± 10°C under all conditions. During observations, thermal control around the primary mirror is critical. The wedge surface coating at the first focus reflects 99% of radiation from the primary mirror, controlling radiation

power near the first focus to ~10 watts via the field stop. Three heat shields on the primary mirror rear ring reflect ground-reflected light to protect the mirror.

5. **High-stiffness, low-weight, low-expansion support materials.** Materials connecting the primary and secondary mirrors and post-focus platform, and plates encapsulating the platform, feature high stiffness, light weight, and low expansion. This ensures frames don' t deform under different gravity and thermal loads, while low weight reduces balloon payload burden.
6. **High-resolution polarimetric/spectroscopic capability.** The post-focus magnetograph uses fast polarization mode with two liquid crystal variable retarders, image accumulation, and dual-beam polarization to achieve 0.1% polarization sensitivity. Reconstructed polarimetric data have spatial resolution of 0.15" -0.18" , longitudinal field measurement accuracy of 4 G, and transverse field accuracy of 80 G. Line-of-sight velocity errors range 5-40 m/s. For spectroscopy, a narrowband prefilter and dual-channel F-P etalon achieve 85 mÅ spectral resolution.
7. **High-resolution imaging capability.** Shorter wavelengths yield weaker light intensity, and short-wave UV light is easily contaminated. To obtain high-resolution UV imaging, after wavelength allocation by the light distribution system, incident light passes through two filter wheels to exclude out-of-band stray light. The optical path from filter wheels to CCD is enclosed in a tube to prevent UV contamination and noise 淹没. This enables diffraction-limited spatial resolution across multi-band imaging.

SUNRISE' s two scientific flights yielded remarkable results, focusing on small-scale magnetic fields in quiet Sun regions (first flight) and active regions (second flight). These achievements highlight that solving fundamental physical problems like coronal heating and magnetic field origin requires larger-aperture solar optical telescopes and excellent seeing conditions or seeing-free environments. SUNRISE' s two flights were undoubtedly successful and highly instructive.

Currently, China still lacks balloon-borne and space-based solar telescopes. The necessity and urgency for developing balloon-borne solar telescopes in China are evident, both for solar physics development and for China' s international standing in solar research. High-resolution balloon-borne observations can lay foundations for solving coronal heating problems, exploring the physical nature of solar eruptions, and provide references for future Chinese space-based telescopes.

In early 2018, the Chinese Academy of Sciences launched the "Near Space Scientific Experimental System" project, also known as the "Honghu Project." This project aims to "develop heavy-lift airships, persistent ultra-pressure airships, reusable powered airships, balloon-borne near-space solar UAV systems, and near-space middle-upper atmosphere scientific detection platforms—three categories and five types of experimental platforms.” By establishing China’ s first near-space scientific experimental system, it aims to “deeply characterize near-space weather, electromagnetic environment, and radiation environment; investigate near-space biodiversity; explain biological effects of key environmental factors; and conduct near-space scientific research.” The project successfully completed comprehensive verification tests for biological atmospheric payloads from May 13 to June 7, 2019, including all flight operations and test subjects. In July-August 2019, the Honghu Project completed its first flight experiment—an excellent opportunity for developing China’ s balloon-borne solar telescope.

Yunnan Observatories, Chinese Academy of Sciences, undertakes the “Coronagraph Near-Space Payload Experiment” sub-project, combining coronagraph and balloon-borne solar telescope advantages to target: (1) large-scale coronal mass ejection structure and propagation; (2) observing fine current sheet structures in limb corona to test and improve solar eruption models; (3) diagnosing solar eruption processes and low atmospheric magnetic reconnection using near-UV lines Mg II k 2796 Å and Mg II h 2803 Å for high chromospheric radiation detection. Balloon-borne solar telescopes have great development potential for solar activity observation and monitoring from optical to radio bands. This paper aims to provide valuable reference for China’ s balloon-borne solar telescope development, particularly for Yunnan Observatories’ “Coronagraph Near-Space Payload Experiment” project.

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