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Z-HELIOS SOLAR OPTICAL TELESCOPE FOR SPECTROHELIOGRAPH APPLICATION

Svetoslav Zabunov, Garo Mardirossian

Space Research and Technology Institute — Bulgarian Academy of Sciences
e-mail: s14@ialms.net, garo.mardirossian@gmail.com

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Abstract

The current article focuses on the Z-Helios refractor solar optical telescope as a critical component within a novel, automated spectroheliograph system developed at the Space Research and Technology Institute – Bulgarian Academy of Sciences. The telescope is specifically engineered to provide a stable, high-resolution solar image to the spectrographic apparatus. This paper details the telescope's optical, mechanical and electronic specifications, its integration within the spectroheliograph system, and its specific features and design enabling high-resolution, narrowband solar observations in the range of 360 nm to 830 nm wavelengths.

The benefits of the proposed instrument are disclosed in favor of system mobility, low cost needed for hardware acquisition and maintenance and ease of use – the telescope and the whole optical system requires minimum operator involvement during the observation process, data acquisition and data processing operations.

Introduction

Detailed observations of the solar disk in narrowband light across the visible, near infrared, and ultraviolet spectrum are essential for scientific studies of the Sun. The aim is to observe, research and analyze the processes taking place in the solar atmosphere. The latter extends from the end of the convection zone to the inner boundary of the heliosphere. The solar atmosphere consists of three layers: the solar photosphere, the solar chromosphere, and the corona. The photosphere is made of convection cells called granules and is slightly less opaque than air on Earth. The layer below the photosphere is opaque to visible light. The higher region of the photosphere is not as hot as its lower part. Hence, an image of the Sun disk becomes visually brighter moving from the limb to the center. This phenomenon is known as limb darkening. The photosphere is only partially ionized – about 3%, thus having most of the hydrogen in atomic form. Extending to about 500 km above the photosphere, there is found the coolest layer of the Sun – a temperature minimum region about 4100 K. In this layer the low temperature allows for the existence of carbon monoxide, water and other simple molecules. Above the temperature minimum layer we find the chromosphere – a layer about 2000 km thick having inherent spectrum emission and absorption lines. Its name is derived from the Greek ‘chroma’, meaning color, due to its visible colored flash at the beginning and end of total solar eclipses. The temperature of the chromosphere increases with altitude and reaches 20000 K near its top. In the highest region of the chromosphere helium gets partially ionized [1].

At the end of the chromosphere, just before the corona, there is a thin layer (200 km thick). This layer is a transition characterized with pronounced temperature gradient – temperature rises from 20000 K in the top chromosphere to 1000000 K at the beginning of the corona. At the start of the corona we observe full ionization of helium that significantly decreases radiative plasma cooling. The transition region is not smooth, but acts as a nimbus around chromospheric irregularities such as spicules and filaments thus being in continuous chaotic motion [2].

The solar magnetic field bears various effects collectively called solar activity. For example, solar flares and coronal mass ejections often occur at sunspot groups. High-speed streams of solar wind are slowly changing. They are emitted at the surface of the photosphere from coronal holes. Both high-speed streams and coronal mass ejections of solar wind carry plasma outward into the Solar System. The solar activity affects Earth invoking auroras at moderate to high latitudes, and stronger activity may induce disruption of radio communications and electric power [3, 4].

Solar activity changes according to the 11-year solar cycle. The sunspot number is correlated to the solar cycle [5]. In history there were periods during which the solar cycle has stopped completely for a few decades (during the 17th century). This period is known as the Maunder minimum. It is characterized with an era known as the Little Ice Age. Then, Europe lived through abnormally cold temperatures.

The first technology to offer capabilities for observing the solar atmosphere was the spectroheliograph instrument (SHG), developed concurrently and independently in 1892 by two scientists: the prominent French astronomer Jules Janssen's colleague Henri Deslandres at the Meudon Observatory and George Hale in Kenwood, USA [6, 7]. Deslandres later became the Director of the Meudon Observatory from 1907 to 1909. He developed two primary types of spectrographs: the *spectrohéliographe des formes*, a narrow-bandpass instrument which revealed structures in the chromosphere such as filaments and active regions, and the *spectrohéliographe des vitesses*, used to record line profiles of cross sections of the Sun to measure Doppler shifts of dynamic features. Deslandres finished his large quadruple spectroheliograph in 1908, initiating systematic observations of the Ca II K line that continue to this day, with Hα observations following in 1909. This continuous data collection has accumulated over 100 000 observations spanning more than 10 solar cycles. Optical and mechanical redesigns were carried out in 1989, and digital technology was implemented in 2002 [8].

The spectroheliograph system is primarily utilized today to observe the Fraunhofer lines in the solar spectrum. These absorption lines appear as dark spectral lines within the continuous spectrum of the Sun (Fig. 1) and were first observed in 1814 by German physicist Joseph von Fraunhofer [9, 10]. The lines are formed when specific elements in the cooler solar atmosphere absorb light emitted by the hotter underlying photosphere. The SHG delivers super-high contrast with an ultra-narrow bandpass. While a top-notch etalon filter may achieve around 0.5 Å (Angstrom) per pixel spectral resolution, the SHG easily reaches 0.06 to 0.1 Å. The etalons having 0.3 Å have prohibitive cost in most scenarios. SHG delivers exceptionally high contrast images without parasitic light leaks originating from the photosphere innate to single stack etalons.

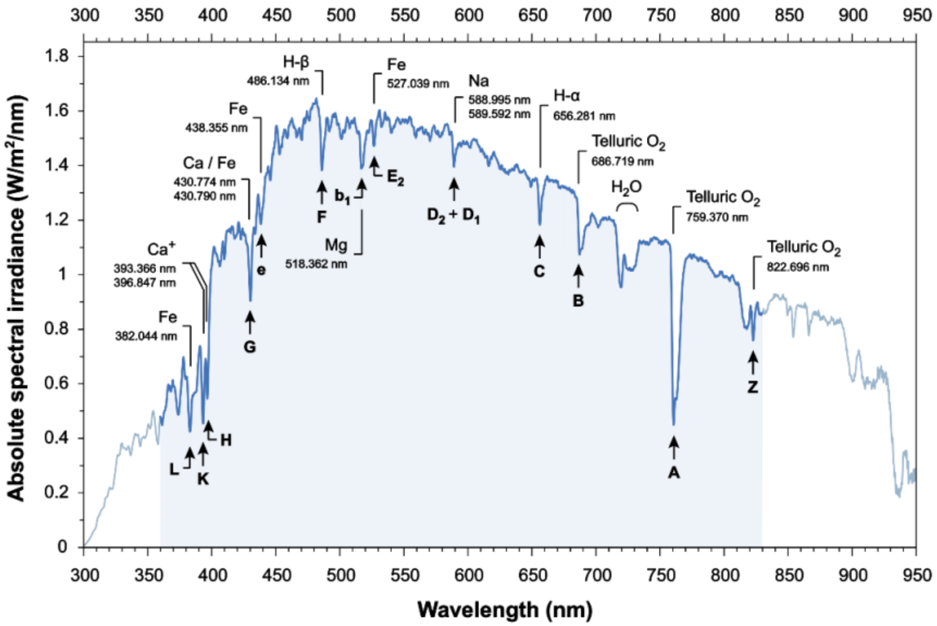

Fig. 1. Sun spectral irradiance measured with a calibrated spectrometer (Flame S-XR1-ES, Ocean Insight). The measurement was made on a sunny day on 13th of June 2022 at noon from Hauterive, Switzerland (47°01'N 6°58'E). For photometry and colorimetry, standard measurements are usually carried out in the range 360–830 nm (highlighted area). Correlated color temperature (CCT): 5470 K. Image Author: Cyamahat (on wikipedia.org) licensed under the Creative Commons Attribution-Share Alike 4.0, CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/deed.en).

The Spectroheliograph

The spectroheliograph is an optical instrument that comprises an optical telescope (refractor or reflector), a narrow slit located on the telescope focal plane, a collimator lens, a prism or diffraction grating, an imaging lens (camera lens) and an imaging screen, photographic plate, photographic film or camera.

The whole instrument is mounted on an astronomical telescope mount in order to be directed towards the Sun [11]. Another approach with large and heavy spectroheliograph devices is to utilize a mirror system that directs the solar beam towards the instrument instead of rotating the latter. The telescope focuses the solar image onto the focal plane where the slit is placed. The circular image of the Sun, covers the slit and only a single line (a stripe) passes through the slit at a time. By scanning the solar disk stripe by stripe the device is later capable to reconstruct, either on photographic plate or digitally using a camera and a computer, the whole solar disk image.

After passing through the slit, the light enters a collimator lens. The purpose of the latter is to make the light rays parallel. These parallel light rays reach the prism or diffraction grating and are dispersed in relation to their wavelength. The dispersed light is focused by means of a camera lens onto a photographic plate or digital camera sensor. When a camera is used, the image of a single stripe of the solar disk is digitized and recorded by the computer controlling the camera. Then the next stripe is stored and so on. The final image is reconstructed out of the stored stripes. Due to the light dispersion, only a narrowband light is recorded at the desired wavelength. General optical lenses and telescopes are used for the light spectrum between near infrared light and low frequency ultraviolet light. For wavelengths outside this region special optics are needed.

Innovative Spectroheliograph

The described telescope within the current paper is part of an innovative spectroheliograph being under development at the Space Research and Technology Institute – Bulgarian Academy of Sciences. It is expected to be tested soon. The SHG component and functional diagram is shown in Fig. 2. The instrument relies on a refractor optical telescope with absolute aperture in the range of 80 mm to 125 mm. A telescope with smaller aperture would yield low angular resolution while larger aperture beyond 125 mm would render the telescope too heavy and cumbersome for portable applications, while yielding unnoticeable improvement in resolution. Larger telescopes are useful in situations with low atmosphere distortions – not the general case when observing from low to medium altitudes. The slit is within 7 to 10 microns of width – either made of quartz glass or stainless steel to be able to resist the significant heat dissipated in it from the projected sunlight. Suitable slits may be readily purchased from optics vendors. The employed collimator lens is a photographic objective lens. This approach delivers much better resolutions and minimized aberrations in comparison with simple achromatic doublets. The spectroheliograph is employing reflecting diffraction grating – those are available from optics manufacturers. The camera lens used is a high quality photographic lens either the standard component for the implemented camera or general purpose photographic lens. The requirements for the camera are lower in comparison with tasks in astrophotography – there is enough light and the resolution is significantly restricted by the seeing conditions to few megapixels (2 megapixels in most scenarios). The apparatus comprises also a filter wheel installed in front of the camera lens. Its goal is to eliminate the dispersion of other wavelengths from higher diffraction orders. The innovative SHG is computer controlled.

Telescope Specifications and Optical Design of Z-Helios

Refractor telescopes have a long history, dating back to Galileo's first astronomical uses in the 17th century. A refractor uses a primary objective lens at the front of the tube to collect light and bring it to a point of focus. A second lens system then magnifies this image for observation or projection onto a sensor. This design is robust and seldom requires collimation in contrast to reflector telescopes. Key parameters of refractor telescopes are aperture, focal length, number of optical elements, focusing mechanism, etc.

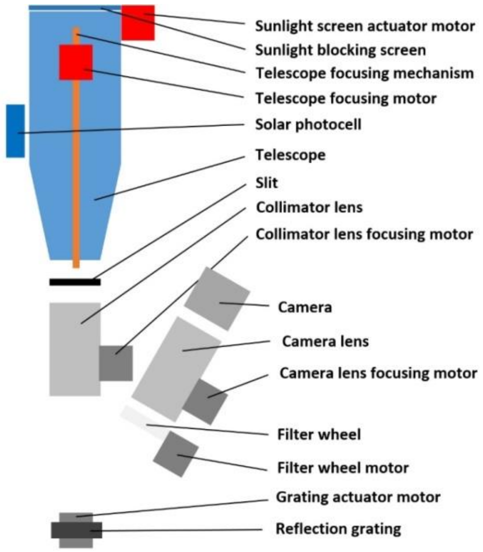

Fig. 2. Innovative computer controlled refractor optical telescope Z-Helios as part of a spectroheliograph system. The components of the system not part of the telescope are shown in gray shades.

The Z-Helios telescope was specifically developed to be implemented in the innovative spectroheliograph. As mentioned above, the absolute apertures suitable for portable spectroheliograph systems range from 80 to 125 mm in diameter. Z-Helios was chosen in between of these numbers with 100 mm aperture. Thus a compromise between portability, cost, weight and resolution was achieved. Because the spectroheliograph instrument performs monochromatic very narrowband imaging (less than 0.3 Å bandwidth) the telescope does not require the complex multi-element apochromatic design typically used in broadband imaging telescopes. The Z-Helios telescope is based on an objective lens achromatic doubled with maximum diffraction limited resolution in the center of the image and minimal corrections near the end of image circle aberrations due to high magnification required. The instrument involves solar protection – a motorized sunscreen actuator motor. The sunscreen is automatically opened only when direct sunlight is registered by an external optical sensor, thus preventing damage to internal parts from angled solar rays (Fig. 2). The telescope focusing mechanism, the sunscreen function are controlled by the main computer of the spectroheliograph system. In Fig. 2 the reader may observe the components of the whole spectroheliograph system and the telescope in particular. The parts belonging to the telescope are shown in color while all other components of the spectroheliograph are visualized in gray shades. The solar photocell is also part of the telescope and is directly connected to the computer governing the functions of the spectroheliograph system.

Conclusion

The Z-Helios telescope is part of an automated spectroheliograph system controlled by a computer module. The computer component controls all actuator motors, received data from all sensors and carries out the data acquisition process, then processes the data and creates the images. The Z-Helios telescope provides the necessary optical stability and resolution for the innovative spectroheliograph developed at the Bulgarian Academy of Sciences. Its robust design, suitable aperture, and automated focusing mechanisms make it an ideal front-end for a small-scale, mobile, and highly versatile solar observation system. The system design ensures minimal operator involvement in the acquisition process freeing its users to engage with different scientific tasks.

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Z-HELIOS СЛЪНЧЕВ ОПТИЧЕСКИ ТЕЛЕСКОП ЗА ИЗПОЛЗВАНЕ В СПЕКТРОХЕЛИОГРАФ

С. Забунов, Г. Мардиросян

Резюме

Настоящата статия разкрива детайли относно иновативния слънчев оптически рефракторен телескоп Z-Helios. Последният се явява важен компонент от автоматизиран спектрохелиограф, разработен в Института за космически изследвания и технологии при Българска академия на науките. Телескопът е конструиран за да осигури стабилно и ясно изображение на слънчевия диск. В статията са показани детайлите относно оптичните, механичните и електронните особености на телескопа. Също така се разкрива общата функционалност и схема на спектрохелиографа, от който телескопът е неразделна част. Описани са характеристиките на телескопа, които са определящи за успешното функциониране на спектрохелиографа в честотния диапазон на електромагнитните вълни с дължини от 360 nm до 830 nm.

Предимствата на предложения 9телескоп са разкрити по отношение на стабилност на системата, цена на хардуера за придобиване и поддръжка, ниска сложност на експлоатация и намалена ангажираност на персонала с функциите на системата по наблюдение на Слънцето, събиране на данни и тяхната обработка.