DATABASE OF SOLAR OBSERVATIONS IN THE NEAR-INFRARED REGION OBTAINED WITH THE BST-2 TELESCOPE OF CRAO

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Systematic observations in the near-infrared region at the Tower Solar Telescope BST-2 of the Crimean Astrophysical Observatory began in 1999 and continue to this day. During this time, a unique observational material has been accumulated, allowing the analysis of the evolution of coronal holes, filaments, and active regions. Due to the fact that during this period the observational process has been repeatedly modernized with varying degrees of complexity and changes were made to the processing programs, we have developed several series of spectroheliograms of different types. The latest stage of modernization, in particular, concerned the creation of new software with the capability of streaming processing of observational results. This allowed us to systematize work on unifying the presentation of our data. In this paper, an updated database is proposed. The structure of the database, access to its elements, and examples of comparing solar disk maps from our database with solar images in other spectral lines and those synthesized by various algorithms are considered. The unified database is a convenient tool for uniform visualization of observational material obtained over more than two solar cycles. It can be useful for scientific research in studying the nature and evolution of coronal holes and their connection with other structures on the Sun.

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1. INTRODUCTION

The infrared solar spectrum contains a wealth of physical data about the Sun and is studied using modern detectors and technologies of ground-based solar telescopes. Spectroscopic observations in the He I 10830 Å (He I) line provide important diagnostic information about the structure and dynamics of the chromosphere and the overlying corona.

While the element helium was discovered by its yellow line in the visible spectrum during a solar eclipse [Janssen, 1869], studies of the infrared spectral line only began after film became regularly used. Spectra obtained at the McMath-Hulbert Observatory *English* McMath-Hulbert Observatory *)* in Michigan [Mohler and Goldberg, 1956] showed that the line has a large width corresponding to a kinetic temperature of 50,000 K, and thus it likely originates in hot regions of the solar chromosphere. The He I line according to Belenko [2001] forms in the upper chromosphere at a height of ~2000 km and is excited by ultraviolet radiation. The He I absorption line is within the transmission range of conventional refractive optics and at the long-wavelength boundary of silicon CCD detector sensitivity [Penn, 2014]. Many combinations of telescopes, instruments, and detectors have been used to observe this spectral feature. The discovery of the He I absorption line on the solar disk was made at the Mount Wilson Observatory (*English* . Mount Wilson Observatory) using film [Babcock and Babcock, 1934], and then the line was observed at the same location but with an ITT FW-167 infrared image converter tube [Zirin and Howard, 1966]. Full-disk observations were conducted for many years using silicon detectors on the VST vacuum telescope [Livingston et al., 1976; Jones et al., 1992] and continue with SOLIS VSM and FDP instruments at the Kitt Peak National Observatory (*English* . Kitt Peak National Observatory) [Keller et al., 2003]; infrared array detectors [Penn and Kuhn, 1995; Schad et al., 2013]. Vector magnetic measurements of the full disk using He I are conducted at the Solar Flare Telescope of the National Astronomical Observatory of Japan (*English.* National Astronomical Observatory of Japan) approximately since 2010 [Hanaoka et al., 2011]. Although the He I line is accessible through various telescopes and detectors, its precise spectral analysis is a challenging task. The absorption line is usually very weak, reaching a depth of only a few percent of the quiet Sun continuum intensity, but it can become very dark in filaments or active regions (AR) of the Sun, where its absorption increases tenfold. For analysis and scientific purposes, it is best to observe a large spectral region surrounding the line center [Malanushenko and Jones, 2004]. Comparing observations from the Skylab X-ray telescope (*English* . sky laboratory Skylab) with He I spectroheliograms, Harvey et al. [1975] discovered that coronal holes (CH), visible in X-ray data, also demonstrate a lack of He I absorption on the solar disk. It is in this line that it is possible to observe CHs from Earth.

2. OBSERVATIONS IN THE HE I 10830 Å LINE AT THE TST-2 TELESCOPE OF CRAO

In the second half of the 1980s, at the Crimean Astrophysical Observatory (CrAO, English: Crimean Astrophysical Observatory (CrAO)) on the Tower Solar Telescope-2 (TST-2, *English.* Tower Solar Telescope-2 (TST-2)), work began under the leadership of N.N. Stepanyan to prepare technical capabilities and software for observations in the He I line. Also under her guidance, a system for conducting observations and image processing was developed, and daily monitoring and operational presentation of observational data on the Internet were organized. This allowed CrAO to participate in national and international observational programs like "Solar Service," "SpaceWeather," and others. Creating a complete catalog of observations or a unified database (DB) was also her idea and was repeatedly discussed by us.

Regular observations in the He I line at CrAO have been conducted on the TST-2 telescope with a diffraction spectrograph and universal spectrophotometer from 1999 to the present. During this period, over 4500 maps of the full solar disk in the He I line have been obtained. However, due to the fact that during this time the observation process has repeatedly undergone modernization of varying complexity and changes were made to processing programs, we have several series of spectroheliograms of different types (Fig. 1 , left panel). In this regard, there was a desire to create a unified standardized database, convenient for visualization and analysis of solar disk maps.

3. FORMATION OF A UNIFIED DATABASE

This work is a continuation of a series of papers [Andreeva and Malashchuk, 2021; Andreeva and Malaschuk, 2022; Andreeva et al., 2023a, b] on the formation of a unified database of solar observations in the near-infrared region, obtained with the BST-2 telescope of CrAO from 1999 to the present. The first two works initiated the formation of a unified database for 1999-2018. The paper [Andreeva et al., 2023a] presents the technical characteristics of the BST-2 telescope, its optical scheme, and also examines the stages of modernization of the observation process in the He I line and processing programs for solar disk maps. There were three of them, and they are described in detail in the works [Bukach et al., 1990; Stepanyan et al., 2000; Semenov et al., 2021]. The last stage was in 2019 . It concerned the spectrophotometer control system; completely new software was developed to accompany the scanning process , and a new program was written for subsequent processing of observation results. The 2019 modernization . also improved the quality of the obtained solar images in the He I line, reduced the time for observations and processing.

Due to the fact that the new software for processing observations allows processing a large amount of data in a reasonably acceptable time frame, it became possible to process all observational material using a unified methodology and bring the visualization of all observations to a uniform appearance (see example in Fig. 1, right panel). This is convenient for analyzing, comparing, and viewing the obtained solar maps. Previously published DB was limited to only one image per day, although there could often be more observations. Also, only JPEG images of observations were available on the website, which is insufficient for computational analysis methods. We decided to supplement the database with FITS files as well. For these reasons, the formation of a new database was initiated [Andreeva et al., 2023b].

As a result of the observation data processing program operation, the data is stored in FITS format in two versions: intensity map with and without limb darkening. All information recorded during image scanning is included in the FITS file header: date and time of observation, width and height of the spectrograph slit, angle of the coelostat installation, pixel size in angular coordinates. These data enable users to easily perform coordinate transformations for desired analysis.

Additionally, for convenience of visual analysis, data is saved in JPEG format (Fig. 2) with supplementary information. The JPEG file represents a pair of maps with Solar disk images, normalized to 3.6 ″ x 3.6 ″ per pixel. The left image shows limb darkening, the right one is without darkening. The maps indicate image registration data - time and the corresponding value of the angle B_0(the angle between the solar equator and the line of sight). A grid with 10° intervals is overlaid on both images.

When working with observational data, it is necessary to account for instrumental effects that lead to measurement errors. Below we describe individual characteristics inherent to our observations.

Due to imperfect clock drive, in some months the obtained "raw" image may be stretched into an ellipse along one of the axes. During processing, the image proportions are adjusted to make the image close to circular shape.

Given that the solar disk image is not registered instantaneously but pixel by pixel, atmospheric tremor and telescope's own oscillations will always lead to some image deformation, to the extent that the limb of the resulting image in places deviates from a circle (for example, the northwestern part in Fig. 2).

Also, during the observation period (~45 min for a disk size of 701 x 701 px), the solar disk may be repeatedly obscured by passing clouds. As a result, the obtained image of the Sun will be partially covered by one or more dark bands. Such images are manually filtered from inclusion in the final catalog, however, they may be useful in analyzing certain local areas, therefore they are stored separately and can be sent upon request.

Positioning of the PMT input window on the spectral line is done manually. There is also a possibility of temporal drift of the spectrum image along the dispersion direction caused by the inherent oscillations of the spectrograph and imperfect centering of its mirrors. Therefore, generally speaking, the wavelength at which scanning is performed will not exactly coincide from image to image, which should be taken into account when comparing numerical intensity values between different maps.

Below we present the updated database, its structure and access to it, discuss the issues of primary image analysis, and compare them with images of the solar disk obtained in other spectral lines and synthesized by various methods.

4. UNIFIED DATABASE

The updated database is located on our department's website in the "Observations" section and can be accessed via the link (https://sun.crao.ru/observations/hel-1083nm) (Fig. 3).

At the top of the page is the latest uploaded image in the He I line. Below − is a table of observations by years and months with links to the corresponding directories. Figure 4 shows an example of the contents of one of the directories.

In the root directory for each month, there are jpg files and 2 folders: fits and fits_cor, which contain intensity maps in FITS format with and without limb darkening, respectively. The names of the FITS files match the names of the corresponding JPEG images.

Previously, only one image of the Sun in the He I line was displayed on our space weather page per observation day, despite the fact that several images could have been obtained during the day. The updated database now includes these missing images. An example of several consecutive images for one day is shown in Figure 5.

As mentioned above, the archive also contains maps where part of the disk is covered by passing clouds. Such images are not published on the website and can be sent upon request (or will later be placed in a separate catalog).

Data can be downloaded via an anonymous FTP server. The directory is available at: (ftps://sun.crao.ru/helium/) through Windows Explorer or other available means. In addition, you can get the files of interest for any period in a single archive by contacting A. Plotnikov at: *plotnikov.andrey.alex@yandex.ru*

5. IDENTIFICATION OF SOLAR FORMATIONS ON THE SOLAR DISK

It is interesting to analyze how solar structures from our BST-2/CrAO database maps of the solar disk correlate with solar images in other spectral lines and those synthesized by different algorithms. For comparison, we examined solar images in H-alpha spectral lines obtained at Kanzelhöhe Observatory (*eng* . KSO, Kanzelhoehe Solar Observatory), iron Fe XII 195 (EIT/SOHO, Extreme ultraviolet Imaging Telescope on board Solar & Heliospheric Observatory) and 193 Å (AIA/SDO, Atmospheric Imaging Assembly on board Solar Dynamics Observatory). We used publicly available data for the same dates, close in time. This was not always possible, so we took what was available on that day. Considering that we performed a primary analysis to detect solar formations that do not change so quickly during the day, we considered it acceptable to make such an assumption. In He I line images, coronal holes (CH) appear as brighter areas than the surrounding surface, while active regions and filaments are colored dark. In H-alpha images, filaments are dark, and active regions (AR) are bright areas of the surface. In Fe XII 195 and 193 Å lines, CHs are colored deep dark, ARs are bright, and filaments are dark formations. For comparison, we also used daily interactive maps of solar activity (SA) based on data from the Kislovodsk Mountain Astronomical Station (KMAS), presented on the ObserveTheSun.com website, and solar images with CHs identified by two traditional popular algorithms, SPoCA and CHIMERA.

Examples of comparing the identification of solar formations in He I line images obtained with the BST-2/CrAO telescope on July 4, 2003, August 6, 2012, and October 11, 2023, with images from other sources are shown in Fig. 6–8.

All three images in Fig. 6 clearly show all ARs, the northern polar CH, and a huge southern CH extending from the pole, crossing the equator, to low latitudes of the Northern hemisphere. Additionally, dark filament threads in the western part of the Northern hemisphere are clearly visible in the He I line image.

In our previous studies of coronal holes (CH) using solar images in the Fe XII 193 Å line (AIA/SDO), there were difficulties in identifying them, as both CHs and filaments appear as dark formations in this line. At the same time, images in the He I line allow for their unambiguous distinction. This is well demonstrated by Fig. 7. The large filament in the center of the Southern hemisphere, which is difficult to distinguish in the Fe XII 193 Å line (AIA/SDO) images and identified by the CHIMERA and SPoCA algorithms, is confidently visible in the He I line image. This fact is also confirmed by H-alpha/KSO solar maps and the website https://observethesun.com.

On the other hand, a weak CH located close to the center at low latitudes of the Northern hemisphere in the He I line image becomes possible to distinguish only after viewing images from other sources (bottom row of Fig. 7).

It is also known that currently there is no single optimal algorithm for CH detection. Fig. 8 shows interactive maps of solar activity based on KGAS data and solar images with CHs identified by the CHIMERA and SPoCA algorithms - bottom row. Most of the CHs identified by these algorithms are also visible in the He I line images.

The analysis showed that there is fairly good agreement in the identification of solar structures on the solar disk. Using solar images in different spectral lines and identifying solar structures by various synthesized methods is a good method for reliable identification of solar formations on the solar disk.

6. CONCLUSION

As a result of forming a unified database of observations in the He I 10830 Å line, obtained on the universal spectrophotometer of the BST-2 telescope at CrAO from 1999 to the present , we have received a unified visualization of observational material that is convenient for viewing, analysis, and comparison. The database has been supplemented with previously missing full-disk solar maps, and not only JPEG but also FITS files have become available to users. The primary analysis comparing solar images from the updated database with images obtained by other methods has shown that this is a good method for reliable identification of solar formations on the solar disk.

Unified DB can be useful for conducting scientific research in the field of studying the nature and evolution of coronal holes, their connection with other structures on the Sun. This contributes to solving such important problems of solar physics as the study of the structure, rotation and evolution of the large-scale magnetic field, and the formation of solar wind flows.

We hope that these data will be in demand not only by our staff, but also by specialists from a wider circle.

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We express our deep gratitude to G.A. Sunitsa and D.G. Semenov − highly qualified engineers, for improving and maintaining all systems of the BST-2 telescope in working condition during the period under review, as well as to A.S. Kutsenko – for the work done to modernize the technical and software capabilities of solar observations in the He I 10830 Å line, which made it possible to improve quality and reduce observation time.

The authors are grateful to the teams of SDO/AIA, SOHO/EIT, CGAS, KSO for the opportunity to have access to observational data for identification and comparison of solar structures on the solar disk with the results of our observations in the He I line.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest with other researchers in this field.

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Figure captions

Fig. 1. Images of the Sun obtained in the He I 10830 Å line with the universal spectrophotometer of the BST-2/CrAO telescope in different periods. On the left - before unification, on the right - maps of the solar disk for the same dates, but processed according to a unified methodology.

Fig. 2. Images of the Sun obtained in the He I 10830 Å line with the universal spectrophotometer of the BST-2 telescope. On the left - unprocessed image, on the right - processed, taking into account limb darkening and eliminating backlash. Coronal holes in this line appear as brighter formations compared to the surrounding surface, while filaments and active regions appear very dark.

Fig. 3. Unified database of observations of the solar disk in the He I 10830 Å line, presented on the CrAO page.

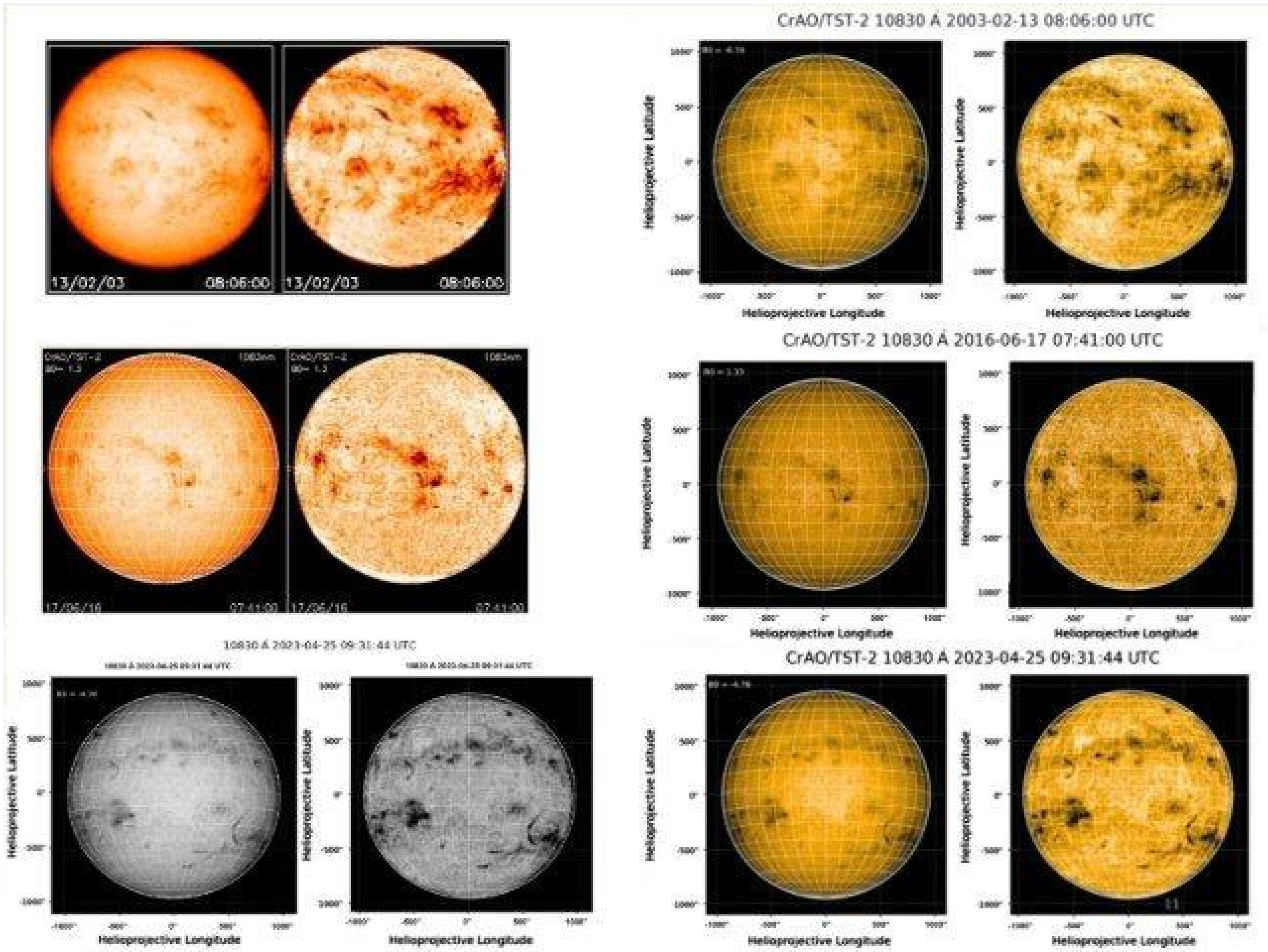
Fig. 4. Directory structure of the updated database. April 2021.

Fig. 5 . Solar disk maps obtained in the He I 10830 Å line on the same day –October 11, 2023 at 09:17, 10:03, and 11:05. On the left - images with limb darkening, on the right - processed taking into account darkening.

Fig. 6. Images of the Sun obtained on 4.07.2003 in spectral lines He I 10830 Å– on the left and Fe XII 195 Å – on the right, in the center – interactive maps of SA according to CHAS data from the ObserveTheSun.com website.

Fig. 7. Images of the Sun obtained on 6.08.2012 in spectral lines He I 10830 Å H-alpha and Fe XII 193 Å– upper row from left to right. Bottom row: in the center – interactive maps of SA according to CHAS data from the ObserveTheSun.com website. On the left and right are images of the Sun with CH identified by CHIMERA and SPoCA algorithms respectively.

Fig. 8. Images of the Sun obtained on 11.10.2023 in spectral lines He I 10830 Å, H-alpha, Fe XII 193 Å – upper row from left to right. Bottom row: in the center interactive maps of SA according to CHAS data from the ObserveTheSun.com website. On the left and right − images of the Sun with CH identified by CHIMERA and SPoCA algorithms respectively.



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08:06:00
13/02/03
08:06:00
CrAO/TST-2 10830 Å 2003-02-13 08:06:00 UTC
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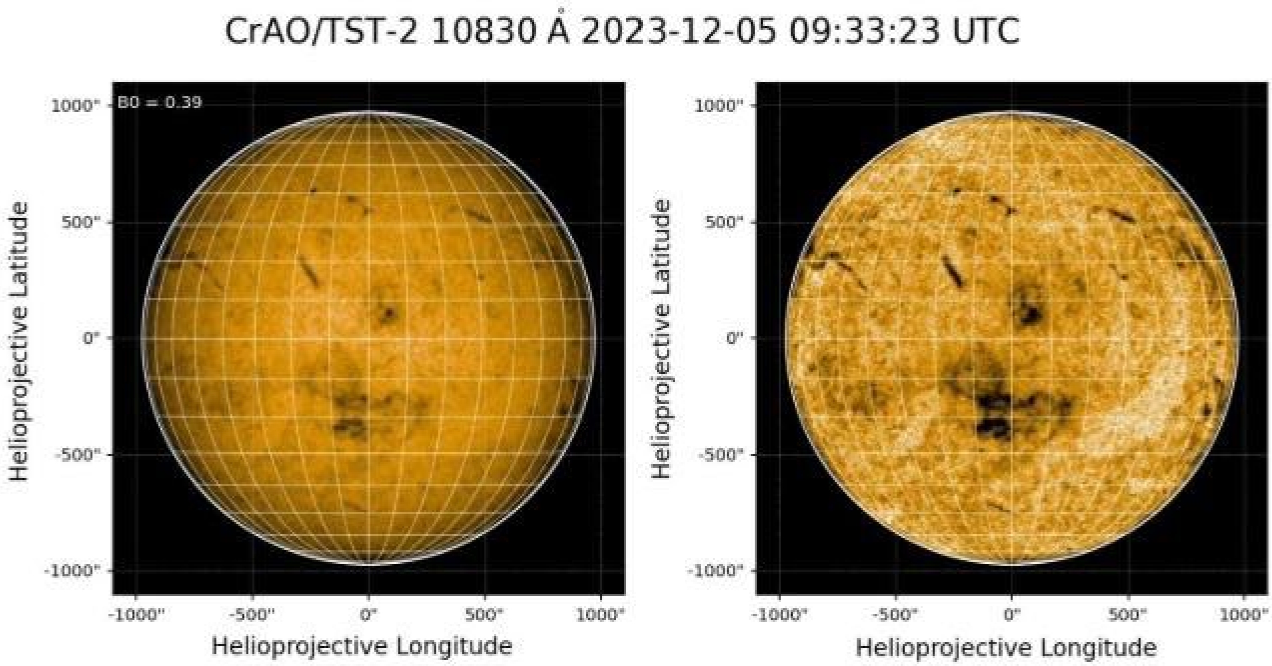
CrAO/TST-2 10830 Å 2016-06-17 07:41:00 UTC
10830 Å 2023-04-25 09:31:44 UTC
CrAO/TST-2 10830 Å 2023-04-25 09:31:44 UTC

Fig. 1.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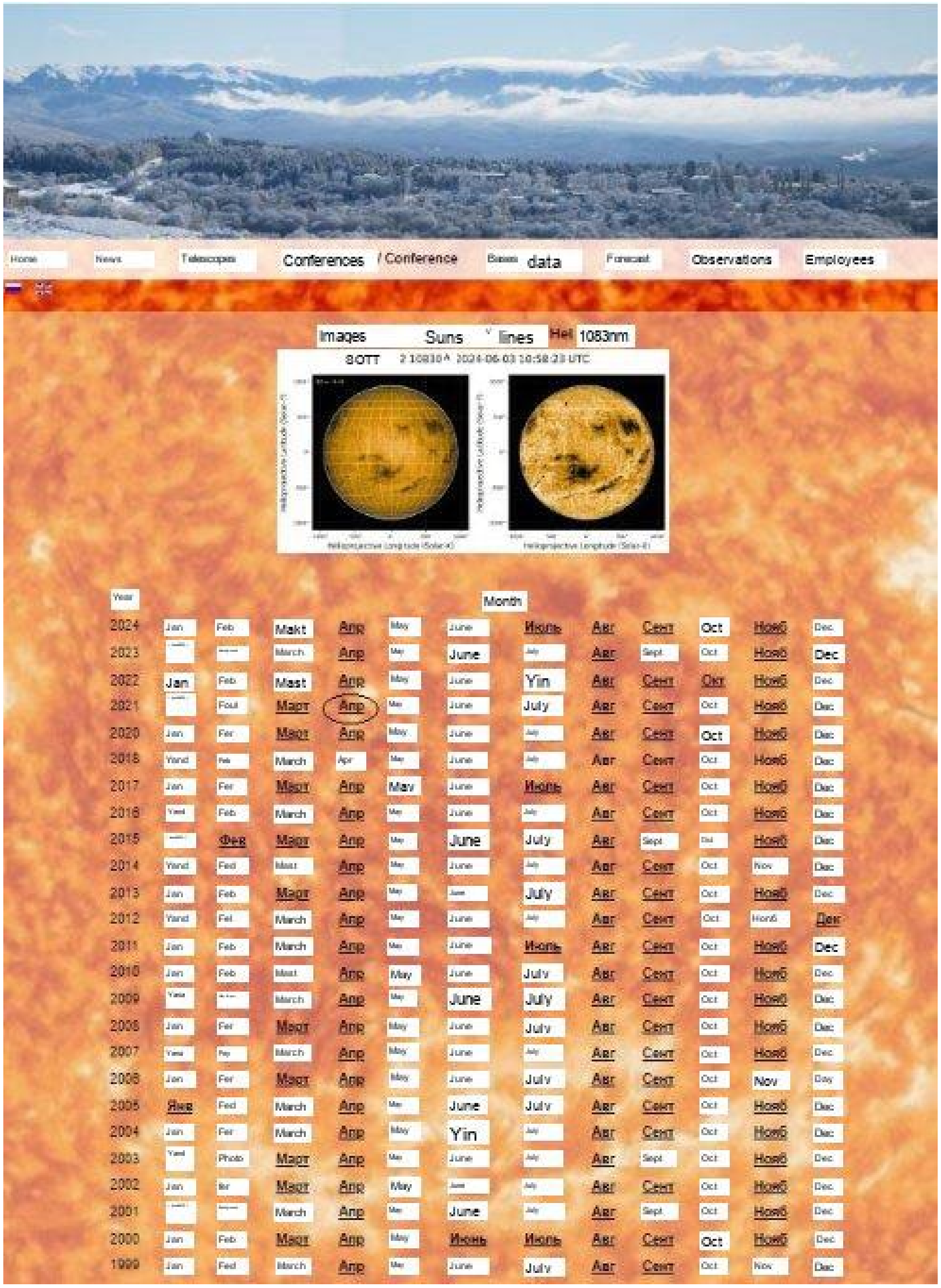
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Fig. 3.

Index of /~data/helium/21_04

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20210402_0942.jpg	2023-12-29 16:25	177K	
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20210424_0806.jpg	2023-12-29 16:25	205K	
20210424_0852.jpg	2023-12-29 16:25	204K	
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20210430_0547.jpg	2023-12-29 16:25	205K	
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Fig. 4.

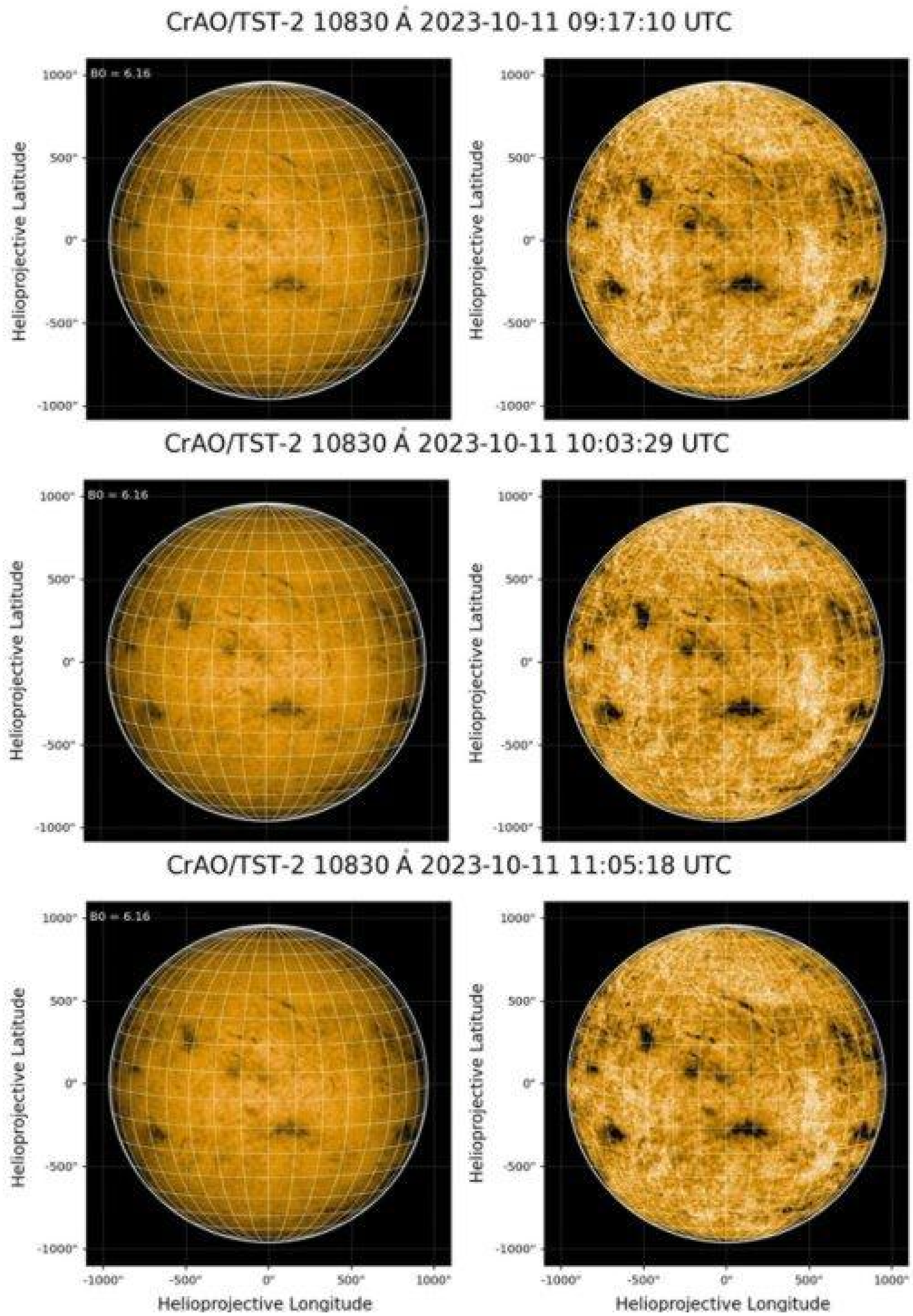
CrAO/TST-2 10830 Å 2023-10-11 09:17:10 UTC
CrAO/TST-2 10830 Å 2023-10-11 10:03:29 UTC
CrAO/TST-2 10830 Å 2023-10-11 11:05:18 UTC
B0 = 6.16
Helioprojective Latitude
Helioprojective Longitude
1000"
500"
0"
-500"
-1000"

Fig. 5.


4.07.2003
CrAO/TST-2 He I 10830 Å
ObserveTheSun.com
SOHO/EIT Fe XII 195 Å
SolarMonitor.org

Fig. 6.

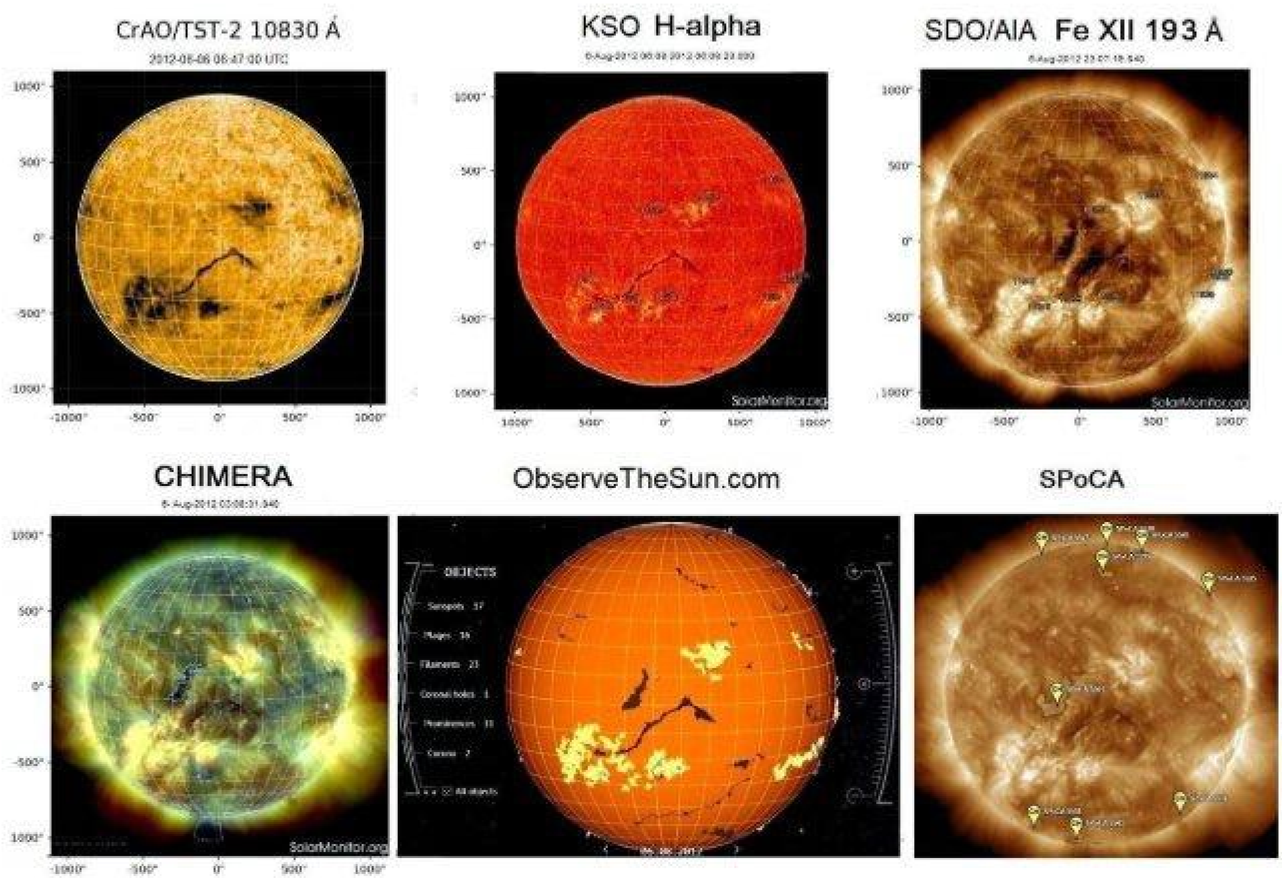
CrAO/TST-2 10830 Å
KSO H-alpha
SDO/AIA Fe XII 193 Å
CHIMERA
ObserveTheSun.com
SPoCA
SolarMonitor.org

Fig. 7.

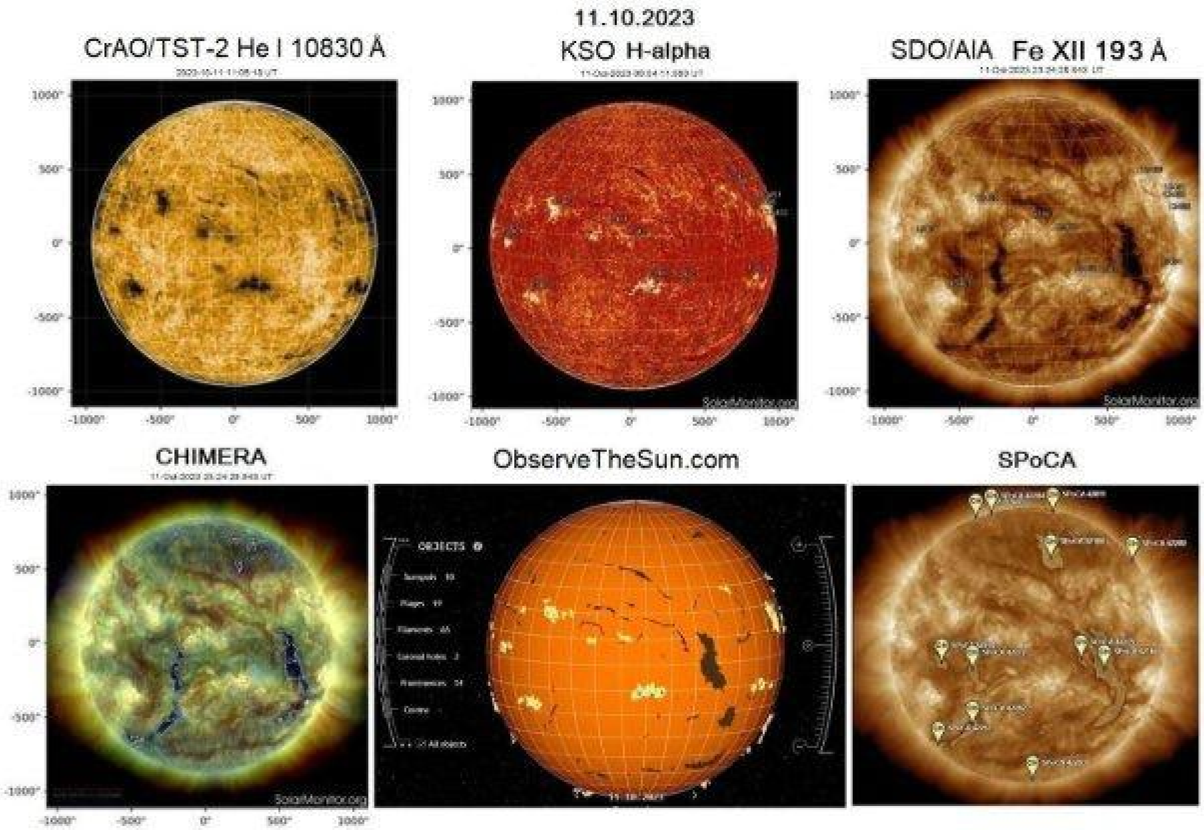
11.10.2023
CrAO/TST-2 He I 10830 Å
KSO H-alpha
SDO/AIA Fe XII 193 Å
CHIMERA
ObserveTheSun.com
SPoCA
SolarMonitor.org
OBJECTS

Fig. 8.