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SOLAR ACTIVITY RESEARCH AT THE BAIKAL ASTROPHYSICAL OBSERVATORY OF ISTP SB RAS

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Abstract. The article presents the main results of solar studies carried out at the Baikal Astrophysical Observatory (BAO) of the Institute of Solar-Terrestrial Physics SB RAS (ISTP SB RAS) for 40 years. It outlines the history of BAO and lists its telescopes. Much attention is given to the Large Solar Vacuum Telescope (LSVT) designed to observe solar formations with high spatial and spectral resolution. Technical parameters of this instrument are specified along with some results of the studies carried out with it. Information about the full-disk chromospheric telescope and scientific problems solved with it is represented together with the basic scientific results. The telescope is used to study solar activity complexes and solar flares. References to the basic publications that have used BAO results are presented.

Keywords: astronomical instruments, solar observations, spectra, polarization, solar activity complexes, solar flares.

INTRODUCTION

The Baikal Astrophysical Observatory (BAO) of the Institute of Solar-Terrestrial Physics SB RAS (ISTP SB RAS) (until 1993, the Siberian Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (SibIZMIR)) is located in the village of Listvyanka on the southwest coast of Lake Baikal, 70 km from Irkutsk. Geographical coordinates of the observatory: 104°53′30″ E, 51°50′47″ N. BAO monitors solar activity, makes problem-oriented spectral, spectropolarimetric, and filter observations of nonstationary processes in the solar atmosphere to study mechanisms of their occurrence and development [Annual report on scientific and organizational activity..., 2017].

The main goal of BAO in the 1960s was to implement the then unique project — development of the Large Solar Vacuum Telescope (LSVT). The instrument designed to study the fine structure of solar formations should have met the highest requirements, surpassing world analogues in individual parameters. The project was headed by the Director of the Institute, corresponding member of the Academy of Sciences of the USSR, V. E. Stepanov.

The program for searching a point with optimal astroclimate executed at the Institute was primarily aimed at surveying the basin of Lake Baikal, where the air temperature inversion is regularly observed due to the considerable mass of cold water whereby the convection that reduces the image quality is effectively suppressed [Kovadlo, 2003].

In 1966, SibIZMIR launched field studies under the guidance of Sh.P. Darchiya to choose a location for the observatory. For three years, seven sites had been examined: Listvyanka, Bolshoye Goloustnoye, Torey, Mondy, as well as Bolshoy and Maly Ushkany Islands and a site on the ice of Lake Baikal (in winter), 15 km from the shore in front of the village of Listvyanka. In addition, the field studies were carried out two kilometers off Listvyanka at the top of a mountain 908 m high above sea level. These studies generally involved visual estimates of jitter of the solar limb and measurements of temperature fluctuations in the surface layer up to a height of 20 m [Darchiya, 1970, 1985; Ivanov, 1970; Aksamentova et al., 1971; Banin, 1971; Darchiya et al., 1971; Kovadlo et al., 1972, 1973]. According to the results of the survey, preference was given to Listvyanka.

In 1968, at the edge of the mountain behind the village of Listvyanka at an altitude of 70 m above lake level under the guidance of V.G. Banin, a temporary pavilion for the telescope ATSU-24 of the future observatory (Figure 1) was built. It began regular observations of the solar chromosphere.

The observations performed with this instrument as well as with the photospheric-chromospheric telescope AFR, delivered in 1971, confirmed that the selected site had excellent astroclimatic characteristics. It was decided to build LSVT there. The development of this instrument started in 1969; the LSVT building was constructed in 1972–1975 (Figure 2).

BAO from the very beginning was considered as a complex of several solar telescopes working under their own research programs and maintaining basic observations of LSVT. The network telescope AFR developed in the late 1950s within the framework of the International Geophysical Year [Zherebtsov, Yazev, 2008] no longer met current requirements. It was necessary to increase

Figure 1. The first BAO pavilion with the horizontal solar telescope ATSU-24

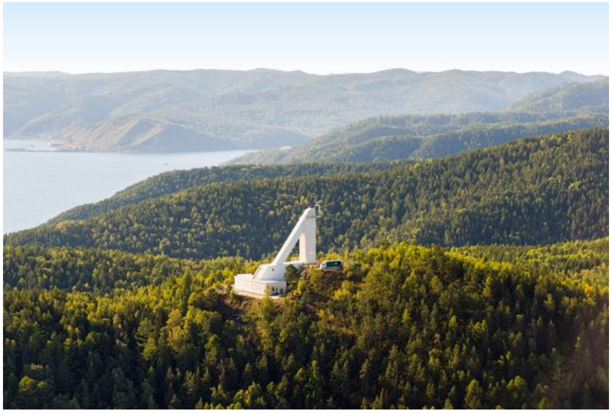

Figure 2. General view of LSVT

the spatial resolution of observations of the solar chromosphere up to 1 arcsec. In 1979, ISTP SB RAS designed an original optical scheme of a new chromospheric telescope with a theoretical resolution of 0.92 arcsec. In particular, the experience gained during observations with the ATSU-24 telescope was applied [Stepanov, Trifonov, 1974]. The full-disk chromospheric telescope built at the Institute began its observations in 1980.

Works in the village of Listvyanka were first carried out as field (expedition Vershina), but since the mid-1960s stationary objects were exploited: houses for observers, temporary pavilions of the telescopes ATSU-24, AFR-2 and -3. On April 25, 1978, the Scientific Council of SibIZMIR SB AS USSR decided to establish the Baikal Astrophysical Observatory in Listvyanka.

This paper dedicated to the 40th anniversary of BAO briefly outlines the history of the development of the observatory and reviews the key scientific results of the studies carried out using LSVT and full-disk chromospheric telescope. The paper does not discuss the results of the studies made with other BAO telescopes.

BAO TELESCOPES — LSVT AND FULL-DISK CHROMOSPHERIC TELESCOPE

Unique capabilities of LSVT enable high-quality observations of fine formations on the Sun. The theoretical spatial resolution of the telescope is 0.2 arcsec.

The optical scheme of the instrument comprises a polar siderostat 1 m in diameter, a two-lens achromatic objective 760 mm in diameter with a focal length of 40 m, and a spectrograph. The 40-m sloping telescope tube ~50 m^3 in volume is enclosed in a sealed metallic housing covered above and below by thick plane-parallel transparent plates made of optical glass K8. The special facility allows us to vacuum the telescope, reducing pressure inside its tube to a few millimeters of mercury.

LSVT is equipped with a high-dispersive spectrograph having the Ebert-Fastie optical scheme and a focal length of 15 m. This spectrograph can determine physical parameters of solar plasma: velocity of matter, chemical composition, magnetic field, as well as can estimate microturbulence temperature and velocity, and electron density. The main element of the spectrograph is a diffraction grating of size 200×300 mm having 600 groove/mm. The spectral resolution of the spectrograph is 0.0007 nm for the fifth order [Firstova et al., 1990].

The actual spatial resolution of the telescope–spectrograph complex is as high as 0.4 arcsec, which is critical to the study of the fine structure on the Sun. The spectrograph has two chamber mirrors, which allows simultaneous recording of different ranges of the solar spectrum. To obtain polarization spectra and calculate Stokes parameters, the spectral slit assembly is equipped with a rhombohedron and phase plates. Thus, four spectra (two spectral ranges, each in different polarizations) are formed in the chamber of the spectrograph. The spectra are recorded using a large-format CCD camera FLIGrab (2048×2048).

Figure 3 shows four prominence spectrograms obtained simultaneously in the Hα and Hβ lines in two polarizations. Simultaneously with the recording of the spectra, Hα filtergrams of the Sun are taken in the reflected light from the spectrograph mirror slit. The main devices of this optical unit in addition to reimaging lenses are a narrowband (5 nm) birefringent filter centered on the Hα line and a Princeton Instruments CCD camera (512×512 pixels).

The development of the full-disk chromospheric telescope was protected by the copyright certificate (V.G. Banin, Yu.A. Klevtsov, V.I. Skomorovsky, and V.D. Trifonov). The instrument was designed by V.D. Trifonov with the participation of V.Ya. Govorukhin,

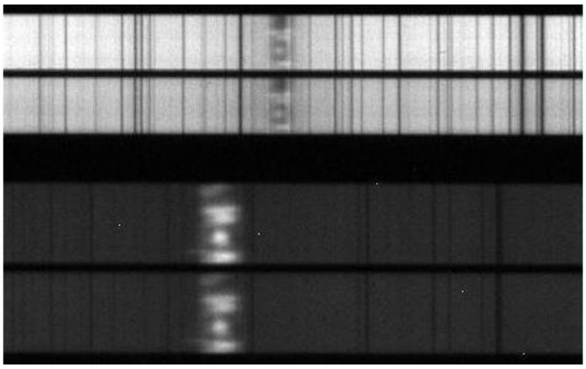

Figure 3. Spectrograms of two prominences obtained in the Hα (two bottom spectra) and Hβ (two upper spectra) lines simultaneously. Spectral length in Hα is 39 Å; in Hβ, 25 Å; height of spectral bands is 30 arcsec.

V.P. Kvacheva, and V.V. Trotsenko. Optical elements for the new telescope were made by Yu.A. Klevtsov under the guidance of V.I. Skomorovsky; electronics and control system were designed by the engineer A.A. Sidorenkov. Mechanical parts were manufactured at the workshops of the Institute. The final adjustment of the telescope was made by V.D. Trifonov and Yu.A. Klevtsov.

The telescope was installed at BAO in April 1980 in the stationary tower with a dome 5 m in diameter at an altitude of 12 m at 150 m from the shore of Lake Baikal (75 m above lake level, see Figure 4). The solar image diameter on an 80 mm film was 50–52 mm; the calculated resolution at the center of the field of view, 0.92 arcsec; at the edge, 1.3 arcsec. During the first months of observations in the summer of 1980, V.D. Trifonov managed to get excellent negatives of the full solar disk in the Hα line with a resolution close to 1 arcsec. Thus, the new telescope, entirely designed and manufactured at SibIZMIR AS USSR, in its main characteristics was highly competitive with the Lockheed telescope and surpassed the Zeiss Opton Germany telescope [Klevtsov Trifonov, 1980; Banin et al., 1982a]. The first observations confirmed that the chromospheric telescope had excellent characteristics [Banin et al., 1982b].

On request of a number of USSR observatories on the initiative of the Head of the Solar Physics Department of the Institute D. Sc. (Phys.&Math.) V.M. Grigoryev, a number of similar telescopes were constructed at pilot plants of the Academy of Sciences in Irkutsk and Novosibirsk for the Astronomical Institute of Uzbekistan (Tashkent), Astronomical Observatory of Ukraine (Lvov), Physics and Technology Institute of Turkmenistan (Ashkhabad), Sayan Astrophysical Observatory of SibIZMIR. Another two chromospheric telescopes were built for BAO: a large-scale image telescope for observations of separate active regions (14 m focal length) and a telescope for observations of the full solar disk in the K CaII line (5.3 m focal length).

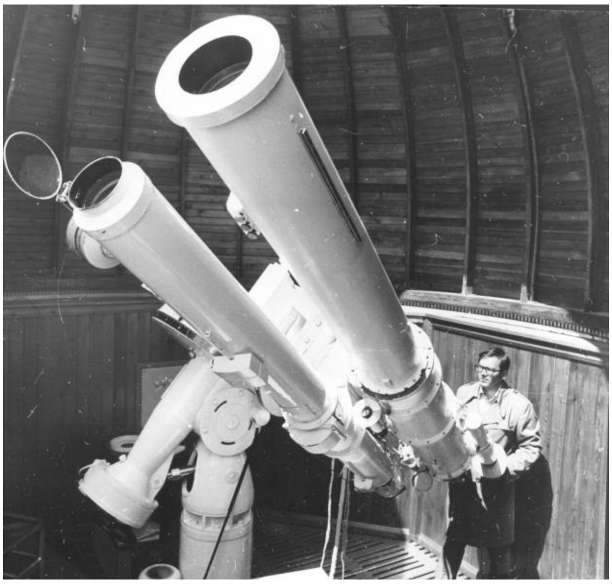

Figure 4. Observations with the photospheric-chromospheric telescope (A.V. Borovik, 1980)

In 2000, after the transition to the recording of solar images with the use of the Princeton Instruments CCD camera with a 2048×2048 matrix detector, necessary modifications were made in the design of the chromospheric telescope; and since 2008, a high-speed (2.5 fps) CCD camera Hamamatsu 9300-124 with a 2600×3800 detector has been used. It provides a series of frames with a high temporal resolution during observations of fast nonstationary processes in the solar chromosphere.

MAIN RESULTS OF STUDIES MADE WITH LSVT

The most interesting objects observed with LSVT are solar flares. One of the most important scientific problems associated with the occurrence of flares is the chromospheric heating mechanism. There is, however, no unified theory of flare formation.

According to current views, at the beginning of a flare energy in the corona is released and then chromospheric heating occurs. Energy can be transferred from the corona to the chromosphere in different ways — due to thermal conductivity, X-rays, and by charged particle beams. Preference is currently given to the last mechanism because there are observations showing good spatial coincidence between X-ray sources and emission elements during solar flares in the chromosphere. X-rays during a solar flare can be attributed to the deceleration of electrons when they are bombarding dense chromospheric layers. However, as derived from theoretical studies, the electron beam energy is not sufficient to support the process of chromospheric flare; there is therefore an assumption that proton beams can be involved in the chromospheric heating. The bombardment of the chromosphere by high-energy particles can cause impact linear polarization of spectral lines. The particle beams are assumed to radially invade the chromosphere, so the maximum polarization should be observed for the flares that are on the solar limb. Thus, the degree of polarization of spectral lines may depend on the position of the flare on the solar disk. The basic research conducted with LSVT is devoted to the study of the described processes.

The 2B/X4.8 flare emerging on the eastern solar limb on July 23, 2002 has been studied most thoroughly [Firstova et al., 2008, 2012, 2014]. This flare was also examined with RHESSI instruments [Krucker et al., 2003]. At LSVT, this powerful proton flare was observed from 00:29 to 01:29 UT. 250 Hα flare spectrograms have been processed. A flare spectrum is shown in Figure 5. In the spectrograms along the dispersion, 664 photometric cuts have been made.

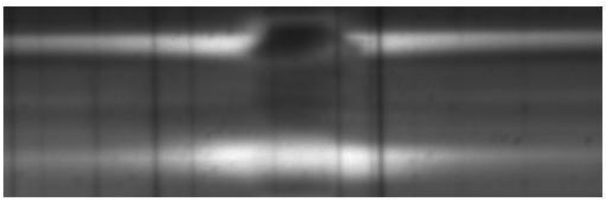

Figure 5. Hα spectrogram (one of two spectral bands) obtained when the LSVT spectrograph slit crossed two flare ribbons

In most of the cuts, no linear polarization was found. Only on the first 12 frames in small-scale (2–4 arcsec) flare areas, Stokes parameters were recorded in the range of from 2 to 6 % for only tens of seconds.

A difference was identified in the behavior of Hα intensity profiles and Stokes parameter profiles in two footpoints of one flare loop. Polarization is absent when the Hα profile is purely emission, without absorption at the line center. An important fact has been established: polarization found at the very beginning of the observed proton flare appeared only in nodes with self-absorption at the Hα center. The appearance of the central depression in the line profile indicates that accelerated electrons have an effect on the chromosphere during the flare. This is also proved by the short period during which the polarization was observed simultaneously with self-absorption of the line, and small sizes of the regions where the effect was detected.

To confirm the phenomenon of flare polarization of spectral lines, the data was also processed which had been acquired during 32 solar flares of X-ray importance C, M, and X (two flares) observed with LSVT. Evidence of the impact polarization was found only in 13 of them. Values of linear Stokes parameters were 2–7 %. The change of sign of the Stocks parameter with the depth of the chromosphere was first found from data in the Hα line [Firstova et al., 2014]. By cuts across the flare ribbon, the transition from negative to positive Stokes parameters was marked, altogether over a distance 1–2 arcsec. The change of the Stokes parameter sign is interpreted as a transition of polarization from the radial direction to the tangential one. In the case of proton beams, this occurs at 400 keV; and in the case of electron beams, at 200 eV.

Firstova [2015] continued studying the 2002 July 23 flare, using RHESSI observations of X-rays and γ radiation [Lin et al., 2003]. The author compared LSVT high-resolution spectropolarimetric data with RHESSI data. It was found that above the flare ribbon in which the Hα self-reversal and impact polarization occurred there was a γ-radiation source caused by the flux of high-energy (more than 1 MeV) and even relativistic electrons. Above the ribbon, where the line self-reversal was detected and no polarization was found, there was a typical source of hard X-ray with the 20–120 keV energy. Thus, the linear polarization observed during the flare is interpreted as an impact polarization caused by the bombardment of the chromosphere by high-energy electron beams.

An interesting object to study was the limb system of flare loops emerging after the M7.7 Masuda flare, which began on July 19, 2012 at 04:17 UT. The loops were observed with LSVT in the active region (AR) NOAA 11520 on the southwest solar limb [Firstova, Polyakov, 2017]. The time interval of these observations was 06:54–07:40 UT. This flare has also been examined in detail by Liu et al. [2013] from RHESSI and SDO/AIA data; unfortunately, there are no simultaneous observations of loops in the Hα line in that paper. The Hα spectra were recorded by the two-chamber spectrograph of LSVT, using a large-format matrix Fligrab. Figure 6 presents spectrograms obtained when the spectrograph slit was cutting the loop apex and footpoint in comparison with the cut of the nearby photosphere.

The purpose of the study was to determine physical conditions of plasma in cold loops. The height of the Hα flare loops was 42 000 km, loop cross-sections are comparable in their footpoints and apexes: 8500 and 11 400 km. The rate of loop arcade rise was assessed at ~3.5 km/s. The height difference between the Hα loops and the loops in the 94 Å line was about 2×10^4 km. Spectral Hα profiles were obtained in the loops (237 profiles), photosphere, and chromosphere. Equivalent widths of the Hα profiles in the loops varied from 1.18 to 1.56 Å. The spread of radial velocities in the loops was great, but it markedly decreased with increasing equivalent width. In most cases, the radial velocities were negative (from –0.96 to –16.36 km/s). The measured Doppler velocities of the Hα profiles (0.59–0.78 Å) allowed us to estimate the microturbulence temperature and velocity. With a temperature of $\sim1.5\cdot10^4$ K, the microturbulence velocity is 16.8–24.8 km/s. Knowing the equivalent width of Hα profiles, we can determine the electron density. According to calculations, the electron density in the Hα flare loops $n_e=10^{11}$ cm^{-3}.

Thus, the observations of solar flares with the LSVT polarizing optics have shown that during some flares there is impact linear polarization of the Hα line. This suggests the possibility of nonthermal energy transfer from the corona to the chromosphere. The observed impact polarization is attributed to the bombardment of the chromosphere by energetic particle beams. The polarization effect mainly occurs during the early impulsive phase.

MAIN RESULTS OF STUDIES CARRIED OUT WITH THE FULL-DISK CHROMOSPHERIC TELESCOPE

Regular observations with the full-disk chromospheric telescope began in 1980. The analysis of the data acquired by V.D. Trifonov, A.V. Borovik, and S.A. Yazev in 1980–1981 corroborated high astroclimatic characteristics of the selected site and a wide range of

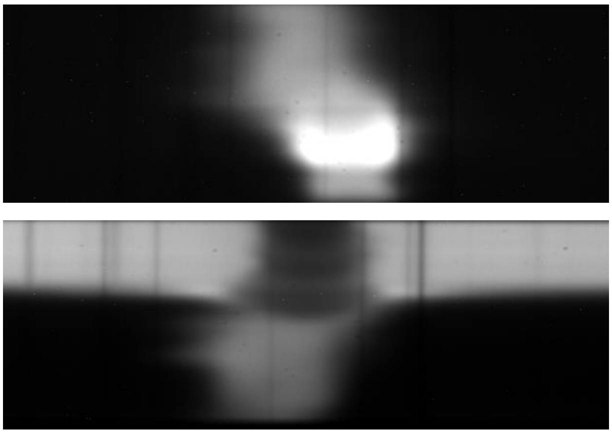

Figure 6. Spectrograms in the Hα line: spectrum at the loop apex (top); spectrum in the photosphere and loop footpoint (bottom)

possibilities of the new instrument [Banin et al., 1982b]. Among 11.5 thousand negatives there were 10.2 % of excellent images (the turbulent circle of jitter was less than 1 arcsec), 34.5 % of good images (the circle was within 1–2 arcsec).

The opportunity to observe the full solar disk, including the behind-the-limb structures, with high angular resolution allowed us to formulate the main scientific objectives:

- monitoring of solar activity in the chromosphere;
- study of solar activity complexes;
- study of solar flares;
- research on the phenomenology of chromospheric formations, in particular by fractal methods.

Monitoring of chromospheric activity

From 1980 to 1999, the full-disk chromospheric telescope was used for regular synoptic observations of the solar chromosphere. During irregular phenomena, the shooting speed increased, the Sun was photographed with the filter bandwidth shifted within ±1.0 Å with a step of 0.25 Å. Since 2000, the observations have been carried out under specific programs (not all year round).

Monitoring data is stored in ISTP SB RAS; observational results are cataloged; negatives (1980–1999) are partially digitized. The filtergrams obtained in 2000–2002 are available on the ISTP SB RAS website. Using the telescope, data on the state of the solar chromosphere has been obtained over nearly 30 years.

Study of solar activity complexes

The study of solar activity complexes (AC) was started in 1981 after obtaining high-quality data on the development of a large AC occurring in March–June 1981 and producing a series of strong homologous flares in May 1981, photographed by S.A. Yazev. These studies were initiated by V.G. Banin, who proposed a phenomenological model of activity complex [Banin, 1983] at the level of the photosphere and chromosphere, and continued by S.A. Yazev [1990a]. It has been shown that in the central AC part, in which there are active regions comprising one or several sunspot groups, strong (plage and sunspot) quasivertical magnetic fields prevail. The central AC part is encompassed by a belt of quasihorizontal magnetic fields disposed radially relative to the central part. Banin pointed to the similarity between structures of sunspot and ACs. Banin and Yazev developed a method for long-term activity areas based on the analysis of synoptic maps of the solar surface on which sunspots were plotted [Banin et al., 1988; Banin, Yazev, 1989]. The maps were constructed for each Carrington solar rotation in the heliocentric coordinates represented in a rectangular projection. On the maps, areas of heliographic degrees 20×20, where sunspot activity was observed for at least three solar rotations, were separated. These areas were called long-term activity areas [Banin, Yazev, 1989, 1991a, 1997] or AC centers [Yazev, 2015].

In 1986, AC monitoring was launched on the basis of sunspot observations, made with the BAO photospheric telescope, and chromospheric observations. The example of two activity complexes is shown in Figure 7. Since 1986, synoptic maps of sunspot activity used to identify AC centers have been made [Yazev, Rozhina, 1998] and ACs have been cataloged [Yazev, 2010a]. The described approach enabled the identification of a new and important manifestation of solar activity, as well as the study of its phenomenology, features of development, space and time characteristics. The traditional study of complexes of active regions allowed the analysis of the connection between active regions only at a given time, whereas the idea of AC considers primarily the evolution of active sources manifesting itself in the months-long development of AC centers. The transition from the consideration of complexes of active regions to the consideration of activity complexes allowed important regularities of the development of geoeffective structures on the Sun to be establish. Some regularities of AC development are discussed in the monograph “Phenomenon of Solar Activity Complexes” [Yazev, 2014].

From other sources of data, a statistical relationship between AC centers and strong solar flares has been found [Banin et al., 1991; Isayeva, Yazev, 2013; Isayeva et al., 2018]: about 80 % of strong proton events appeared to occur in AC centers and in their vicinities. It has been shown that in the place of decaying AC centers low-latitude coronal holes are formed [Banin, Jazev, 1991b; Yazev, 2010b]. The school of AC studies established by V.G. Banin in BAO continues to develop.

Study of solar flares

In the archive of observations made with the BAO chromospheric telescope there are a large number of images of flares of different power, including high-quality images , which have promoted a series of studies of the phenomenology of flares in the chromosphere.

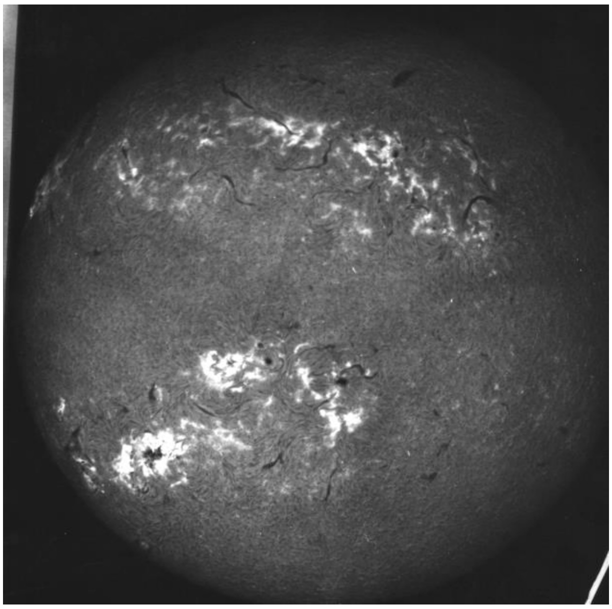

Figure 7. The solar chromosphere in January 1989: a large activity complex in the southern hemisphere and a decaying activity complex in the northern hemisphere

The studies began with the analysis of the development of a strong flare recorded by V.D. Trifonov with the aid of the serial telescope ATSU-24 on November 5, 1970 [Banin, Fedorova, 1971]. In [Banin, 1983; Banin et al., 1983; Golovko, 1983; Yazev, 1983], the authors described in unprecedented detail changes in the fine structure of the chromosphere before and during the 1981 May 16 strong flare, which were first observed with such a high angular resolution (Figure 8). The large field of view of the telescope (full disk) revealed activations of the fine structure and brightening occurring far from the flare and even in the other hemisphere [Sinkevich, Yazev, 2001].

The comparison of chromospheric disturbances with high-resolution magnetograms allowed V.G. Banin to determine the essential role of neutral lines in the development and propagation of flare activations at the chromospheric level. The author also noted the important role of convective structures in the formation of flare brightenings [Banin, 1984, 1986, 1998]. The developed approaches were also applied to a number of other flare events recorded by the BAO chromospheric telescope [Yazev et al., 1990a; Yazev, 1990b; Agalakov et al., 1995; Agalakov et al., 1997].

Due to the detailed analysis of the phenomenology of solar flares observed at BAO, the existing flare models have been improved [Sidorov, Adelkhanov, 1999; Sidorov et al., 2010]. This line of research was continued with the use of data from other instruments.

The high angular resolution of the BAO chromospheric telescope allowed us to pose and successfully solve the problem of studying the phenomenon of small solar flares (optical importance S) comprising more than 90 % of all solar flares observed in the chromospheric lines. The numerous BAO data was used to examine the morphology of low-power flares. Evidence has been obtained that small flares, as well as large ones, are followed by disturbance and activation of chromospheric structures — emergence of arch filaments and chromospheric activations centered around the flare [Borovik, 1988; Borovik, 1989]. Within 40–50 min before a flare, large-scale disturbances of filaments, filament channels, chromospheric network occur at distances up to 90–500 thousand km from the flare. Within 10–20 min before the flare, small-scale formations are activated mainly near flare nodes and at 10–60 thousand km from the flare. A cause of this may be changes in large-scale magnetic fields, accompanied by emergence of magnetic fields in an active region [Borovik, 1985; Sattarov et al., 1985; Borovik et al., 1986]. As a rule, the place of occurrence and development of small flares is the boundaries of the chromospheric network, where the magnetic field is strengthened.

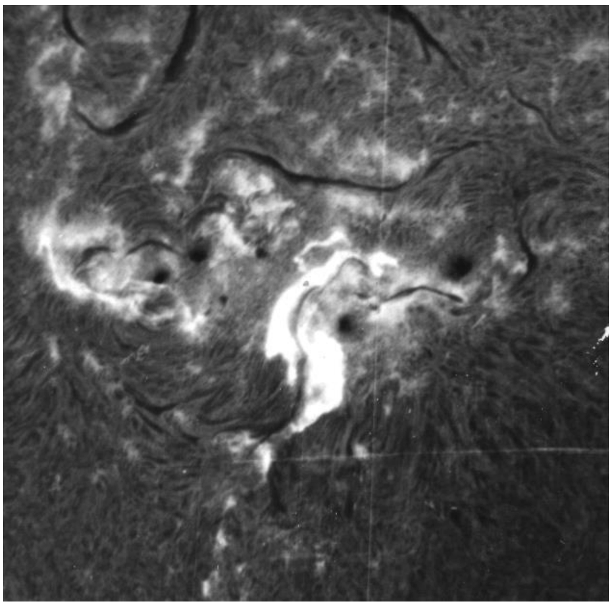

Figure 8. The 1981 May 16 flare. A fragment of an image from BAO

The study of low-power flares gained fresh momentum in works dealing with flares occurring far from sunspots in regions of the quiet chromosphere [Borovik, Myachin, 2002]. Previously unknown or extremely rare pre-flare activations were detected: type-S vortex structures, dark cells, ribbon channels. Space-time connections between active chromospheric structures (including widely spaced ones) were found which indicated that above neutral lines and on either side of them a complex extensive system of coronal loops was present or formed before a flare. Spotless flares, like flares in active regions, were proved to appear and develop at the boundaries of cells of chromospheric and magnetic networks (see Figure 8). The magnetic field topology plays a decisive role in the development of flares [Borovik, Myachin, 2010; Borovik et al., 2014]. Flare nodes usually appear in the close vicinity of magnetic hills with a strength of 80 G and higher. During their development in the magnetic hills, the field changes considerably.

On the basis of the analysis of chromospheric data, an empirical model has first been proposed [Borovik et al.,2016], explaining the basic stages of development of spotless solar flare (Figure 9).

The analysis of the observations has yielded a new interpretation of the role of low-power flares in the general structure of solar activity. Small flares are proved not to be random (background) solar events.

The results can be used to forecast chromospheric activity, large solar flares, and geoeffective solar phenomena. It has been found that small flares tend to gather into flare activity centers (FAC) in the main and secondary neutral lines of the longitudinal magnetic field component [Borovik, 1994a]. Such areas remain active for quite a long time (1–10 solar rotations), which is manifested in increased activity and density of small flares, activations of chromospheric filaments. The low-power flares can be regarded as indicators of changes in magnetic conditions of active region. They show places in the chromosphere that are most susceptible to magnetic disturbances.

It has also been found that low-power flares almost never occur in areas where large solar flares occur, which may be one of the conditions for accumulation of energy by the magnetic field of active region for a large flare. A few hours before a powerful flare, activity of small flares goes down or ceases altogether [Borovik, 1994b]. Evidence has been obtained that a series of small flares can cause some geomagnetic storms.

The features of small flares, found from BAO obser-

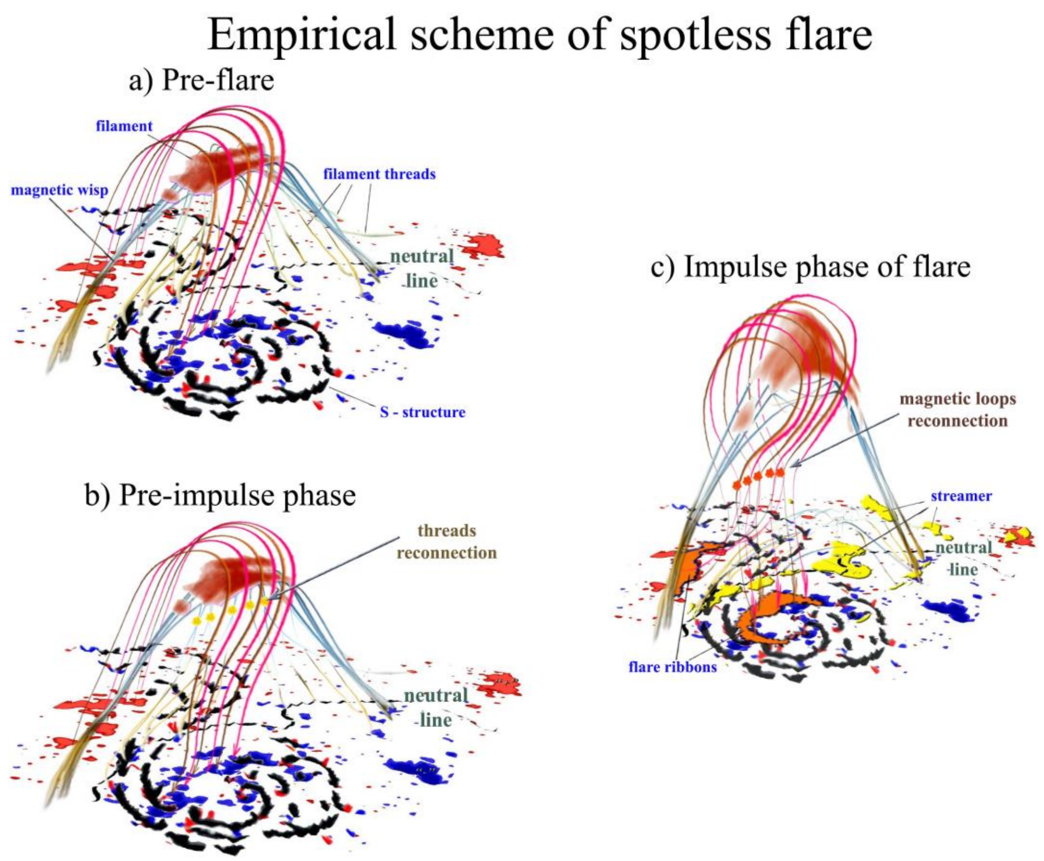

Figure 9. Scheme of development of a spotless flare [Borovik et al.,2016]

vations, were utilized as a basis for the statistical studies that used data from other observatories. According to a large volume of statistical data (more than 85 000 flares), small flares in terms of features of development do not differ from large solar flares. They, like powerful flares, have an explosive phase, accompanied by filament activations and disappearance, multiple intensity bursts. Among them there are flares covering sunspot umbra, two-ribbon and white flares. The most comprehensive and reliable data on time parameters of solar flares of different types, classes of area, and importance has been obtained for the first time. This allowed us to reconsider some ideas about solar flares [Borovik, Zhdanov, 2017, 2018].

Research on the phenomenology of chromospheric formations

The phenomenology of chromospheric formations was also studied with the aid of the BAO chromospheric telescope. A number of studies focused on parameters of the large quiet filament observed in 1984. Its structure, changes of its geometric parameters with distance away from large AC (height of the filament increased to 80 thousand km), its evolution over three solar rotations were studied [Yazev, Khmyrov, 1986, 1987; Khmyrov, Yazev, 1987]. Chromospheric structures in the form of regular closed ellipsoidal filaments were examined [Yazev, 1985]. The phenomenology of the so-called filament-streamer — a special prominence of active region that is characterized by high density, horizontal arrangement, and high-speed plasma flow along the filament body — was studied [Trifonov, 1985]. The dependence of characteristic dimensions of the chromospheric network on the magnetic field gradient near the neutral line and the morphology of structures in the neutral line were studied [Khmyrov, Yazev, 1990].

Using digital solar images obtained after the telescope had been upgraded (Figure 10), a number of studies of pre-flare changes in the orientation of chromospheric structures were carried out [Golovko et al., 2002; Golovko et al., 2003]. A two-dimensional tomography method was used to determine the density of distribution of chromospheric structures in directions in the vicinity of NOAA 9077 AR and reorientation of these structures within 15–55 min before the flare. The studies were continued with application of the multifractal analysis by calculating structural functions [Golovko et al., 2003; Salakhutdinova, Golovko, 2005]. The intermittent turbulence (multifractal structure) was shown to exist in the chromosphere and lower corona of active regions [Salakhutdinova, Golovko, 2005].

Synchronous observations in the Hα and 171 Å FeXI lines of the transition zone from the chromosphere to the corona discovered quasiperiodic (10–20 min) variations in scaling parameters (Figure 11) correlating with flares [Golovko et al., 2006; Golovko et al., 2009].

The multifractal segmentation of chromospheric images showed that areas of maximum values of the singularity

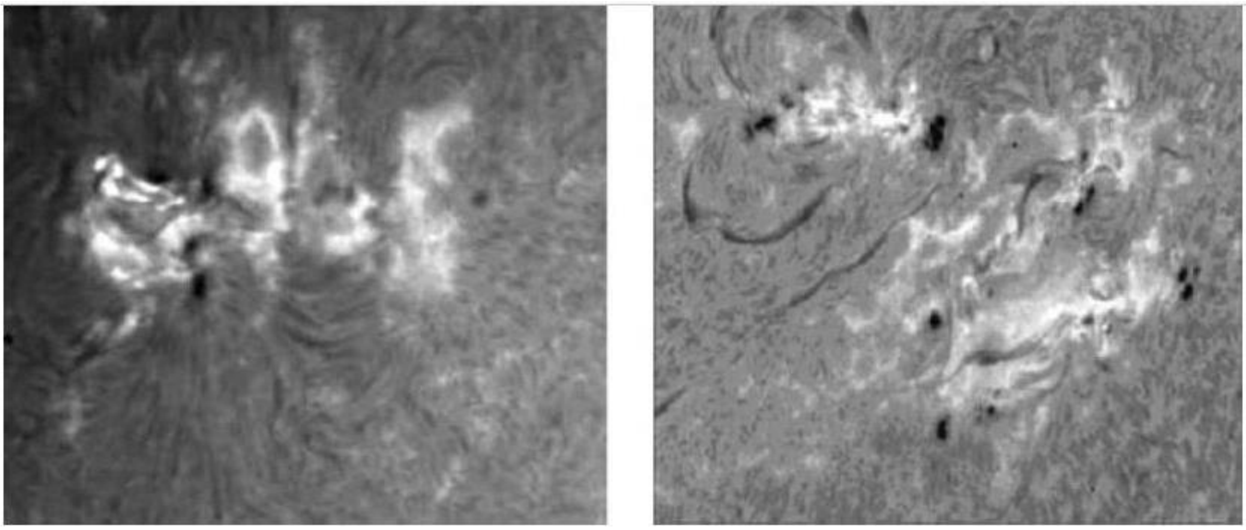

Figure 10. BAO images: active region NOAA 9077 (July 10, 2000; left); active complex (July 31, 2002; right)

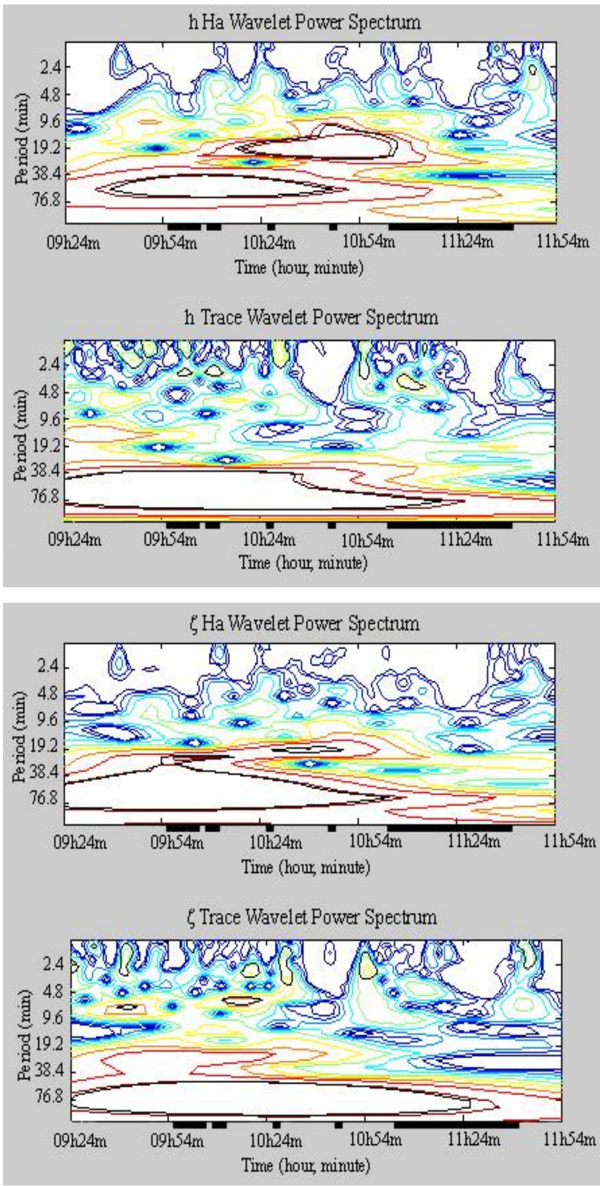

Figure 11. Wavelet spectra before a flare (two upper panels) and during the flare (two bottom panels)

index coincide with flare sources [Golovko, Salakhutdinova, 2009]. Later on, this method was first used to identify new magnetic fluxes from solar photospheric magnetograms [Golovko, Salakhutdinova, 2015]. The BAO data obtained with the full-disk chromospheric telescope is used for the comprehensive study of fast nonstationary processes in the chromosphere (Figure 12).

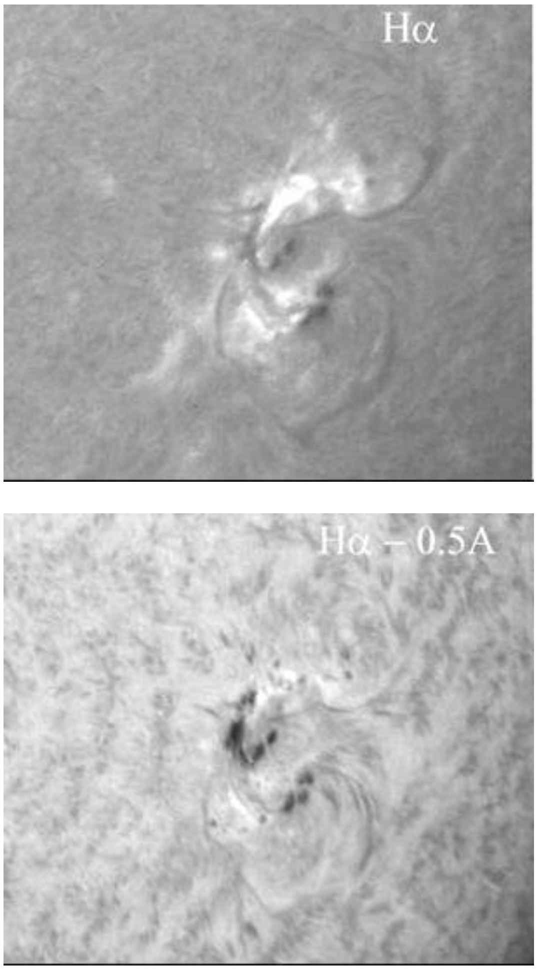

Figure 12. BAO images: 2017 September 07 flare in the center (top) and wing (bottom) of the Hα line (BAO)

The full-disk chromospheric telescope of ISTP SB RAS BAO proves to be a highly effective instrument that has been successfully operating for over a quarter of century. Results of observations with this telescope have been published in more than hundred papers and in several monographs, as well as presented in five PhD theses (Trifonov, Yazev, Borovik, Sidorov, Myachin) and three doctoral dissertations (Banin, Yazev, Firstova).

CONCLUSION

The Baikal Astrophysical Observatory, founded four decades ago, has shown its high efficiency. BAO is part of the global network of solar observatories. The observatory has repeatedly been involved in ground-based monitoring of solar activity within both national and foreign and international programs. In accordance with the priority directions in science and technology, BAO has carried out works under the Federal Special-Purpose Program "Creation and Development of a System for Monitoring of Geophysical Conditions on the Territory of the Russian Federation" and on themes under government contracts "Studies of Large-Scale Magnetic Fields", "Studies of the Internal Structure of the Sun, Characteristics of its Outer Layers and their Long-Period Changes", "Study of Solar Activity and its Manifestations in Near-Earth Space and Earth's Atmosphere". BAO has made important studies of the physical mechanism of chromospheric heating by determining physical plasma parameters during solar flares, has developed new approaches to the research into solar activity complexes, and has studied large and small solar flares.

The observatory was involved in research programs for projects of the Siberian Branch of the Russian Academy of Sciences "Physics of Active Processes in the Solar Atmosphere" and "Development of Methods and Techniques of Astrophysical Observations".

BAO hosts international conferences on solar-terrestrial physics and Baikal young scientists' international schools on fundamental physics.

Under the guidance of Corr. Member RAS V.M. Grigoryev, observatory staff participate in the program "Leading Scientific Schools" (NSh-733.2003.2).

As part of the integration project, in BAO students of Irkutsk and Buryat universities do introductory training and pre-graduation internship, as well as write graduate theses and course projects. Excursions are organized for school children and students.

The observatory is equipped with new equipment; research is carried on.

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