Astronomical and Astrophysical Transactions (*AApTr*), 2019, Vol. 31, Issue 2, pp. 217–236,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

A study of coronal holes at the Crimean Astrophysical Observatory

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Received 1 October, 2018

The paper sheds light on the stages and tasks of the scientific activity of researchers at the Crimean Astrophysical Observatory (CrAO) on studying coronal holes (CHs) and their relation to the surrounding solar formations. The basis of the studies is represented by ground-based and space observations. Emphasis is put on the works of Crimean researchers, whereas exploring CHs is one of the important directions in the study of physical processes on the Sun at CrAO. It began in the late 1990s by putting into operation the Universal Spectrophotometer (USPh) at the Tower Solar Telescope TST-2 and it continues up to the present time. Structures comparable in size to the solar radius ($R_\odot$) – magnetic isolated complexes were first detected in the images of the Sun in the He I 1083 nm line at CrAO in 2012. The paper gives a historical overview of exploring CHs, as well as basic results on the study of CHs derived by researchers of CrAO.

Keywords: Sun, coronal holes, magnetic isolated complexes

1 Introduction

A coronal hole is commonly defined as an extended region located within the large-scale unipolar structure.

A coronal hole is a region that corresponds to the following criteria:

• when being observed in the He I 10830 Å (He I) line, the area is 2–4% brighter than the undisturbed part of the solar disk (Fig. 1a)

• the region is characterized by reduced intensity of the chromospheric network (Fig. 1a)

• these are observed as less bright sites as compared to the surrounding regions in extreme ultraviolet and soft X-ray solar images (Fig. 1b)

• this region is predominantly unipolar (Fig. 1c)

• a size of the region is equal to at least two supergranulation cells or $>6\times10^8$ km^2.

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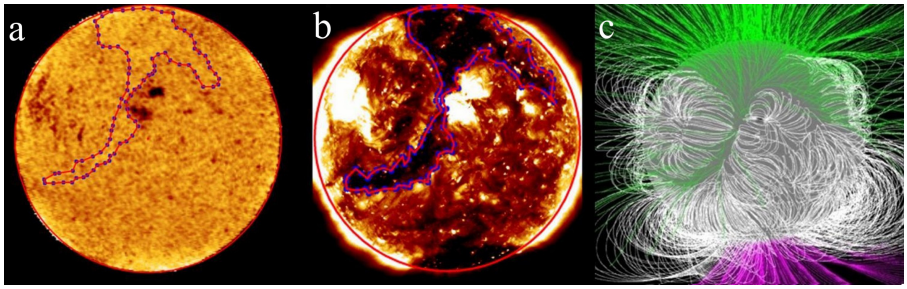


Figure 1 CHs in images of the Sun, 11.02.2017: (a) observations in the He I 10830 Å line (CrAO/TST-2), (b) Fe XII 193 Å (SDO/AIA), (c) magnetic field lines calculated from the PFSS model for the height 1.1 $R_{\odot}$.

The above criteria may seem excessively tight, for there are many CHs, which meet only some of them. The basic physical definition of the coronal hole states that it is a region of the open magnetic field. However, it can take effect in the solar atmosphere only at certain heights. At low heights, in the photosphere and chromosphere, the effect of the open magnetic field can be distorted. The criterion of unipolarity is of crucial importance. Yet, this criterion is often wrongly interpreted as attributable to all levels, including photospheric and chromospheric levels characterized by frequent occurrence of closed loop magnetic structures within the projection of CHs (Obridko, Solovyov, 2011).

Numerous measurements demonstrate that CHs are regions of low-density and low-temperature plasma (Zirker, 1977; Withbroe, 1988).

CHs are relatively long-lived large-scale structures in the solar atmosphere.

CHs, in general, may be observed anywhere on the solar disk; however, their spatial distribution, frequency of occurrence and evolution are governed by the solar cycle. Three types of CHs can be distinguished (Storini et al., 2006). First, there are polar CHs, which are located at the solar poles and have a lifetime comparable to that of the solar cycle. This category includes CH extensions, such as the "elephant trunk" CH observed in August, 1996 (Zhao et al., 1999). The second type is represented by isolated CHs, which are mostly limited to the low and middle latitudes and are not connected to the polar CHs. Their lifetime is comparable to several Carrington rotations (CRs). The third type consists of transient CHs, which are short-lived (hours or days) and their occurrence is often associated with powerful eruptions (flares) and/or filament disappearances. Polar CHs usually disappear during the maximum of a solar cycle and reappear, having already magnetic flux of opposite polarity, thus manifesting the polar field reversal. Isolated CHs behave quite differently. They tend to be more often detected at activity maximum and disappear near activity minimum (Abramenko et al., 2010). A more detailed study on CHs is presented in "Coronal Holes" (Cranmer, 2009).

The basic characteristic of CHs is the fact that these are sources of high-speed solar wind streams affecting the interplanetary space and heliosphere of the Earth. Therefore, exploration of CHs generates considerable interest for solar physics, geophysics, and plasma physics. A study of dynamic and statistical characteristics of

CHs is highly important for understanding physical processes governing variations in solar activity and relationships between the Sun and geosphere. Results of the studies can be used for predictions of evolution of solar formations as well as in space weather forecasting, which is of great importance for people, the technosphere and biosphere of the Earth.

2 Historical overview

Although the term "coronal hole" was not first used until the middle of the 20th century, people have reported the existence of visible features associated with the solar corona – seen during total eclipses – for centuries. A popular astronomy book from the first decade of the 20th century (Serviss, 1909) contained clear descriptions of coronal streamers, eruptive prominences, and polar plumes in coronal holes.

The exploration of coronal holes has the shortest track record in solar physics. CHs were first observed by Waldmeier (1956, 1957) in the late 50s when he identified darker regions in the solar corona from the images taken in the visible light with the coronagraph at the Swiss Federal Observatory in Zurich.

Ultraviolet and X-ray images of the solar disk were obtained with OSO space telescopes in the 1960s–70s proving the existence of CHs. During the same period, Hansen found that CHs were characterized by periodic appearances.

A systematic study of CHs began in 1973–1974, when detailed data were obtained from the Skylab mission. These observations confirmed many earlier ideas about coronal holes with data significantly better in quantity and quality (Huber et al., 1974; Kahler, 2000).

The number and quality of satellite-based observations of CHs are steadily increasing. Since the early 1990s, observational data have been acquired from YOHKOH, SOHO, TRACE, CORONAS-F, and SDO satellites.

Ground-based observations of CHS are generally available only in the He I 1083.03 nm line, which is formed in the upper chromosphere at heights ranging from 2.000-3.000 km and is excited by ultraviolet emission (Andretta & Jones, 1997). In this line, CHs tend to be brighter than the surrounding corona. It is an absorption line; it becomes weaker in CHs, thus leading to enhanced emission as compared to the neighboring parts of the corona.

Since 1974, CHs have been observed in the He I 10830 Å line with ground-based telescopes at the Kitt Peak National Solar Observatory (NSO, USA). CrAO began regular observations in this line in 1999.

CHs were observed not only in the helium line and in X-ray images, but also in radio emission at 17 GHz as is evident from Solar-Geophysical Data Reports (Coffey, 1999; Coffey, 2000)

3 Studying CHs at CrAO

In the 1980s, works on the preparation of technical capabilities and software to observe CHs were started at the Crimean Astrophysical Observatory under the supervision of



Figure 2 Natalia Nikolaevna Stepanian.

N.N. Stepanian (Fig. 2). Natalia Nikolaevna was an ideologue and scientific supervisor of practically all the works associated with studying CHs at CrAO. In cooperation with colleagues, she elaborated the system of taking observations in the He l line and data processing. Daily monitoring and presentation of observational data via Internet were organized, and extended databases were compiled. This allows CrAO to take part in the national and international observation programs "Solar Service", "SpaceWeather", etc.

Observations of CHs in CrAO are carried out with the diffraction spectrograph and Universal Spectrophotometer (USPh) at the Tower Solar Telescope TST-2 (Fig. 3) (Stepanian et al., 2000).

By means of USPh it is possible to take images of the Sun or individual sites of the disk in different spectral lines and record spectra of solar formations. The USPh scanner allows for shifting within two coordinates of the solar image at the spectrograph slit. The photomultiplier tube FEU-83 (Russ. abbr.) or CCD-camera are used as a receiver at the spectrograph exit. The rather high sensibility of these receivers allows one to use USPh for studying the Sun in the near-infrared region, particularly, in the He I line. Service programs enable us, within several minutes, to take into account limb darkening and analyze an image to identify CHs.

The observations in the He I line have been carried out regularly since 1999 and presented at the CrAO website solar.craocrimea.ru. (Fig. 4) shows an image of the Sun in the He I line derived at the telescope TST-2. Left panel – an unprocessed image, right panel – with account of limb darkening.

Exploring CHs is one of important directions in the study of physical processes on the Sun at CrAO. Over the period from the late 1980s, up to the present day, researchers of CrAO have published more than 30 papers on this issue. Under the scientific supervision of N.N. Stepanian, E.V. Malanushenko has defended a thesis for the PhD "A study of the solar atmosphere in the region of coronal holes". Data



Figure 3 Tower Solar Telescope TST-2.

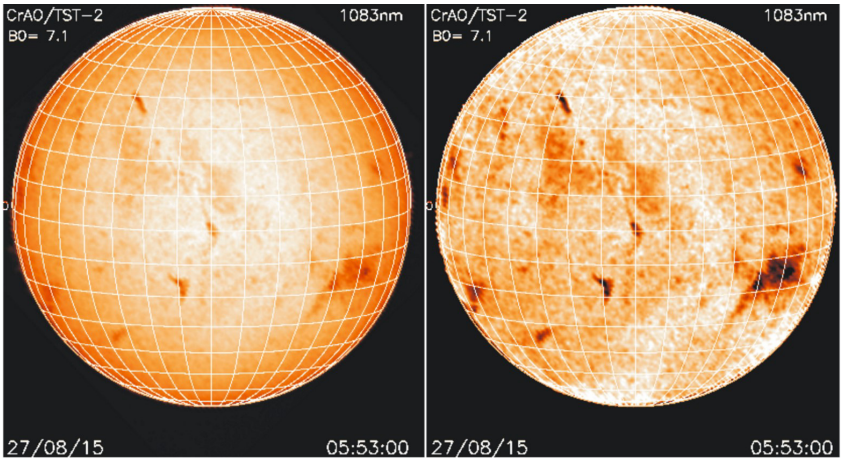


Figure 4 Images of the Sun in the He I 10830 Å line.

obtained with the telescope TST-2 were used practically in all the papers.

4 Some problems in the study of CHs

Coronal holes (CHs) are known to be the sources of high-speed streams of the solar wind. The fact that CHs are the most quiet regions on the Sun located in large-scale structures of background magnetic fields (BMF) of the same sign with a seeming

simplicity accounts for an increase in the speed of outflowing corpuscular fluxes from CHs, attenuation of the green coronal line, decreased brightness in X-rays, ultraviolet and microwave radio radiation, and slightly increased brightness in the He I line. These characteristics form the basis for numerous models of CHs which account for physical conditions and mechanism of CH illumination at the level of the corona, as well as an outflow of matter from them (Suess, 1979). The cause for the emergence of CHs is considered, for instance, in the model by Kovalenko (1981). The author supposes that the appearance on the Sun of a rather large structure of the background field of the same sign with super-radially divergent structure of magnetic field lines inevitably implies the emergence of CH in such a structure. Ambrosh (1994) comes to an analogous conclusion. From these models, it follows that many kinematic characteristics of CHs, at least, such structures of BMFs in which these CHs reside, as well as their variation with activity cycle should coincide or be close. If to consider CHs as an independent phenomenon, for example, a system of magnetic field tubes appearing at depths that differ from the place of emergence of BMF source, then both these phenomena may vary significantly. There are a number of facts that cannot be arranged in a simple scheme of models (Kovalenko, 1981; Ambrosh, 1994).

In the paper by Stepanian (1995) basic problems in exploring CHs are indicated. To clarify the origin of CHs and determine their difference from structures of background fields, N.N. Stepanian offered the following branches of studies:

1. *Dynamic characteristics of CHs and their variation with time.* The previously obtained notions about differences in dynamic characteristics of CHs and background fields prove about a different depth of sources of these formations and the variation in these depths with cycle. The study of evolutionary characteristics of polar CHs and their interaction with middle-latitude CHs allows one to derive additional notions about subphotospheric layers of CHs.

2. *Variation of physical conditions in CHs with height.* Currently, there are no determinations of physical conditions in CHs simultaneously in the wide range of heights from the photosphere to corona. Such notions might be obtained from simultaneous space (X-ray) and ground-based observations (in the visible, infrared and radio regions of a spectrum). The well-known fact about the variation in speed and density of the solar wind (up to 30%) should follow from the variation in physical conditions in the CH region.

3. *Motions in CHs and background magnetic fields.* The determination of basic modes of oscillations in the range of minutes – tens of minutes and separation of long-lived fluxes allows one to clarify the cooling mechanism of corona in CHs and the structure of the solar wind at different levels of the solar atmosphere, and to localize a source of the solar wind.

4. *Variation with cycle of structural elements in CHs and at their boundaries at different levels of the solar atmosphere.* These data allow one to make judgments about variation with cycle in the magnetic field of CH.

Data needed to solve these issues may be acquired from simultaneous space (X-rays and solar wind) and ground-based (visible, infrared and radio range) observations. Images in the He I line, in X-ray and radio wavelengths, maps of magnetic fields, spectra of CHs and quiet regions without CHs in the visible and infrared wavelengths are required for studying physical conditions and fluctuations in CHs. The theoretical base for processing observations may be represented by non-LTE calculations of line

contours, the construction and analysis of power spectra of speed fluctuations, calculations of Alfven wave distribution in the solar atmosphere, varieties of the cluster analysis for studying structural elements of CHs.

To solve these issues, the collaboration of several research groups is required.

These and some other directions formed the basis for studies of CHs at CrAO.

5 Some solutions of problems in the study of CH by scientists of the CrAO

The comparison of solar images in the He I and H_α lines (Malanushenko & Stepanian, 1994) allowed authors to conclude about the structure of the atmosphere in the region of CHs at corresponding heights.

The thin structure in the CH region in the middle chromosphere is suppressed in comparison with regions outside CH based on observations in the He I and H_α lines. From observations in the He I line, two regions in CH can be distinguished: boundary and inner, which significantly differ in the ratio of brightness and chromospheric network contrast. Images show that in the region of CH boundaries an enclosed range of dark points is observed. It delineates a region of CH with no filaments inside, but only point structures are observed.

Most theories consider CHs as an inevitable result of the existence of the unipolar region with an open magnetic field line configuration. However, Stepanian (1993) shows that there are a number of factors contradicting such a notion. Thus, CHs do not exist in all structures of background fields. The rotation rate of CHs is different from the rotation rate of background field structures, in which these CHs reside. If in the equatorial zone these rates are close to each other, then with the growing width, the rates of background field structures decrease faster than CH rates. Besides, variations in rotation differentiality with solar activity cycle are more noticeable in CHs than in background fields. This provides evidence that CHs are not just sites of background fields with the open magnetic field configuration. They seem to be associated with magnetic field fluxes, the source of which is located deeper than the source of background fields. In this case, we might expect a particular structure and physical conditions in CHs along all the height of the atmosphere.

Stepanian and Malanushenko (2001) showed that such a seemingly undisputed fact as the location of CHs in the structure of the magnetic field of a similar sign is not supported for bigger heights in the solar atmosphere. On the surfaces of sources (2.5 solar radii) only in 75% of cases above CHs, the magnetic field has the same sign as in the photosphere.

To solve a problem concerning the CH structure is significant for understanding the nature of CHs and conditions for arising high-speed streams of the solar wind. One of the basic characteristic features of the CH structure is a variation in its area with height. This notion allows one to infer about the character of divergence of magnetic field lines in CHs. The first observations of CHs with the Skylab spacecraft (Kahler et al., 1983) showed that, as a rule, each CH observed in the helium line, is coincident with CH of the same size observed in soft X-rays. Only a small number of CHs of small size observed in the helium line have no corresponding CH in X-rays. Further studies of CHs showed that the notion about the open magnetic configuration

in CHs is not often right. Thus, Malanushenko and Stepanian (1996) found that the variation in area with height is different for various CHs. CH areas can reach the maximum at different heights and a part of CHs is observed only at the lower level and absent at the upper one. These results were acquired based on limited data.

On the basis of extended observational data, Stepanian and Malashchuk (2002) distinguished two groups of CHs, which differ in the character of variations in area with height. This might be explained by the difference in the magnetic structure of the solar atmosphere in the region of CHs of these groups. CHs of the first group are regions with the open magnetic configuration. CHs of the second group comprise, at upper levels, loop structures and bright points, and their magnetic structure cannot be considered as completely open.

For the coronal holes of the first group the variation in area extends upward. For CHs of the second group the picture is more complicated; variations in area at different levels are often not related to each other. This provides evidence that the light in the He I 1083 nm line cannot be fully interpreted by the influence of coronal emission.

The analysis of observations shows that for CHs of the first group the changes in area are most often associated with the emergence of a new magnetic flux or with the disappearance of the existing inclusions of the magnetic field.

For CHs of the second group the synchronicity of variations in area is observed more seldom. Variations at the upper levels often occur at an unvarying area of CHs at the level of He I. Such variations are likely to be associated with variations in magnetic fields of nearby active regions at big heights, for instance, with coronal arch structures, their growth and variation in inclination.

The problem of relation between active regions (ARs) and coronal holes generates an increasing interest among researchers. Different aspects of this problem are considered: CHs as the last stage of ARs (Bumba et al., 2005), dissipation of CH due to development of AR and emerging of a flare near CH, evolution of AR arising in CH (Malanushenko & Stepanian, 2001; Bugaenko et al., 2004b). Stepanian and Malashchuk (2008) examined several cases of emerging and developing ARs in CHs. The general feature for all the considered cases of the birth of AR in CH is a stability of CH boundaries in the course of AR development. Boundaries of CHs do not vary till their dissipation at the moment of contact between AR and CH boundary. After AR degeneration, in many cases CH returns to its original form. Such a result was derived for chromospheric and coronal layers of the solar atmosphere. This provides evidence that the magnetic field structure near CH boundaries is very stable and it prevents the interaction between a new magnetic flux and magnetic fields outside CH. Following our data, no reliable conclusions can be made regarding the character of propagation of the new magnetic flux into the upper layers of the solar atmosphere. One may comment only on the complicated ways of the outflowing of the new magnetic flux into the upper layers of the solar atmosphere and its dissipation there.

Fainshtein et al. (2010) detected structures of magnetic field in CHs and explored its variation due to the emergence of active regions in CHs.

Based on a series of mean characteristics of magnetic fields in CH at different heights, which comprise or do not comprise AR, the distribution of these characteristics inside CH, as well as calculations of field lines in it, the following conclusions have been made. Field lines arising in CH without AR are open, or with very high

loops enclosed outside CH. The latter occurs in fully or partially enclosed CHs. The system of open loops is stable, varies a little with the birth of AR and is restored after its dissipation. ARs that emerge inside CHs are bipolar or multipolar magnetic structures. They are formed by enclosed field lines. Field lines, which begin in AR, enclose either inside AR or in the near neighborhood of AR in CH. Practically, there is no relation between AR inside CH and outer AR or other sites outside CH. Malashchuk et al. (2012a) revealed differences in the structure of magnetic fields above these two types of CHs at heights from the photosphere ($R_\odot$) to the surface of the source (2.5 $R_\odot$). Qualitative parameters, which characterize the relation between CH and height stratification of the magnetic field in the solar atmosphere, were determined for all CHs. Parameters A and B were introduced.

Parameter A is the field variation with height. The passage of the magnetic field zero line across CH at all heights was considered. A=0, if the zero line does not pass through CH. A=1, if the zero line passes through CH, even at one height.

Parameter B is a relation to the polar field. At the height of the photosphere, a sign of the magnetic field in the region of CH is compared to a sign of the polar field in the same hemisphere.B=0, if a sign of the magnetic field in CH and a sign of the polar field in the hemisphere are coincident. B=1, if signs of the magnetic field are not coincident. The emergence of AR in CH proved to be a frequent phenomenon. In one of two considered CHs, AR existed for even 1 day. The variation with height of the magnetic field configuration in the region of CH with AR (A=1) occurs one and a half times more often than the maintenance of the field sign above CH at all heights (A=0).

For CHs without ARs, the number of CHs with varying with height field structure (A=1) is significantly lower.

At the level of the photosphere, two of three CHs have the field sign that is opposite to the sign of the polar field of the hemisphere, in which CH locates (B=1).

Active regions in CHs are not ephemerous. They are not different in area from a number of ARs outside CHs.

Regular image taking of the Sun in the He I 1083 nm line provides an exceptional opportunity to have simultaneously data about brightness and position of several types of solar formations on the disk. One of the important characteristics of solar formations is their differential rotation and its variation with time. A number of works on the determination of solar rotation by different methods have been made so far. Earlier calculations were carried out according to tracers, then by measuring line-of-sight velocities. In recent years, the method for the spectral analysis of rotation periods is based on the Fourier transform of time series of different-type observations. Most of these works concern observations of solar magnetic fields (Vasil'eva et al., 2002; Kotov et al., 1999; Stepanian, 1983). Zyelyk et al. (2004) studied differential rotation of CHs, flocculi (FLs) and powerful active regions with sunspot groups based on observations in the He I 1083 nm line.

The analysis of power spectra showed that the variation with latitude in total spectrum power in the interval of periods from 20 to 35 days for CHs differs significantly from the variation with latitude for ARs and FLs. Total spectrum power for ARs and FLs at lower and middle latitudes practically coincides. Differences are noticeable just at higher latitudes. This result confirms the previously obtained results (Stepanian, 1983) about the different nature of ARs and CHs.

The investigation of variations with time in latitudinal distribution of rotation of powerful ARs and CHs was carried out by Stepanian et al. (2007). As a result of the Fourier transform of time series, over almost three solar cycles, the following results have been obtained. The rotation of ARs sufficiently differs from the rotation of CHs based on all parameters: a set of the most significant rotation periods, their latitudinal distribution and variation with time. The rotation of ARs and CHs is characterized by variation in rotation from cycle to cycle and the north-south asymmetry varying with time. Power spectra for the consecutive solar activity cycles are significantly different both for epochs of high activity and for minima.

The analysis of total spectrum power inside selected four intervals of periods from 21 to 33 days showed that the highest total power falls at period intervals 24–27 and 27–30 days. This holds true both for ARs and CHs. The correlation between total powers in the mentioned period intervals significantly varies with time.

The long-lived or consequently emerging ARs, which rotate with periods ranging from 24 to 30 days, are typical for the time of abrupt decreasing in the total equivalent width of ARs. This is not only a decline time of 11-year cycles, but also minima between recurrent maxima of activity within the same cycle. The predomination of long-lived CHs at decreasing total equivalent width is significant for CHs with rotation periods in the interval of 30–33 days.

All the aforementioned facts provide evidence that the rotation of solar formations is determined mainly by subphotospheric sources of particular formations, but not by the rotation of basic volumes of solar plasma, which comprise the undisturbed Sun.

Zhygalkin et al. (2008) investigated the relation between matter motion in CH and its evolution by the example of a long-lived CH. It was derived that the growth of CH is followed by the rising of matter at the photospheric level and its decay – by the lowering of matter. Fluctuation periods in photospheric layers of CH were suggested to be linearly associated with areas of CHs in the chromosphere. The evidence was obtained earlier from the study of relation between CHs with background magnetic fields and their differential rotation (Stepanian, 1993; Zelyk et al., 2004)

Webb et al. (1984) based on data of cycles 19–21 and Stepanian (1993) based on cycles 21–22 showed that after the polar field reversal CHs in structures of the background fields with a sign of the new polar field appear at high latitudes with a time lag from 5 to 20 solar rotations. In these papers, magnetic fields were determined from H_α maps. Later, Stepanian and Shtertser (2015) continued these studies using observational data over cycles 22–23 taken with TST-2. Areas of CHs located at solar latitudes of more than 60 degrees were compared to the evolution of large-scale magnetic fields on the Sun. The decrease in areas of CHs and growth of their low-latitude boundaries due to the change of a sign of the polar fields were found. The general feature for reversals in cycles between 19 and 23 is a presence of intervals from 5 to 20 Carrington rotations with no polar CHs. The relation between this interval and the time of the change of a sign of the polar fields varies from cycle to cycle. Differences in the length of intervals and time of their start are seen near the poles of the Sun over one and the same cycle. There is a new result about the approaching of low-latitude boundaries of CH to the pole before the reversal of polar fields.

6 Studying solar formations based on complex observations with ground-based telescopes and CORONAS-F satellite

Researchers from CrAO, in cooperation with colleagues from the Institute of Solar-Terrestrial Physics, Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation named after N. Pushkov of the Russian Academy of Sciences and the Lebedev Physical Institute of the Russian Academy of Sciences, performed a series of works devoted to the study of solar formations based on ground-based and space observations. An extended sample of 2001–2003 observational data was derived during SPIRIT experiment onboard the CORONAS-F spacecraft (Oraevsky & Sobelman, 2002), with the Siberian Solar Radio Telescope (Grechnev et al., 2003) and the multi-purpose spectrophotometer mounted on the Tower Solar Telescope at CrAO (Stepanian et al., 2000). Open magnetic tube calculations (OMT) were carried out based on magnetic field measurements acquired at the National Solar Observatory Kitt Peak. Data on the solar wind on the Earth's orbit were taken at OMNIweb *(http://nssdc.gsfc.nasa.gov/omniweb/)*. In the course of the study, boundaries of CHs were distinguished and their relation to active formation was determined. The magnetic field structure from the photosphere to corona was ascertained. A relation between the solar wind and structure formations on the Sun was studied.

The peculiarities of observations with instruments mounted on the orbital station CORONAS-F and telescope TST-2, data reduction techniques, and methods for the magnetic field calculation in the solar corona are described by Bugaenko et al. (2004a).

Within a unified approach, a method was elaborated to distinguish CHs and determine their areas based on observations of the Sun in the He I λ 10830 Å, Fe IX, X λ 171 Å, Fe XI λ 195 Å, Fe XV λ 284 Å lines. Examples of different variations in areas of CHs with height are given. From the analysis, it was shown that a coronal hole, the area of which increases with height, appears almost entirely in the region of the open magnetic tube, whereas almost the entire CH, the area of which decreases with height, appears in the region of enclosed field lines. At the photosphere level, the region of magnetic field inclusion (the magnetic field is opposite in sign to the main field of CH) was found to reach 20–25% of the area of CH. The coronal hole magnetic field becomes unipolar at heights of 25–30 thousand km (Bugaenko et al. 2004b).

Bugaenko et al. (2004c) distinguished and studied CH boundaries in terms of brightness distribution in the region of CH and magnetic field measurements and calculations. Such an inspection by the example of one CH shows that CH boundaries distinguished in two ways are often not coincident. Nevertheless, the method for constructing open and enclosed lines of force inside CH and its vicinity seems to be rather prospective for the further study of physical processes occurring in CHs and at its boundaries. The CH boundary determined based on footpoints of low arch structures covers not only the region with brightness typical for CH but the intermediate region of low contrast and low brightness that is adjacent to CH. This confirms the conclusion made by Malanushenko (1995) that there is no straightforward relation between brightness distribution of solar emission over the disk of the Sun in different spectral lines and distribution of open and closed magnetic field lines in the solar atmosphere. The comparison of evolutions of CHs and ARs arising in CHs or nearby them allow one to conclude about the stability of the outer boundary of CH

in this case and weak connection between magnetic fields of AR inside CH and outer – with regard to CH – magnetic fields.

Zhytnik et al. (2005) in their concluding paper from this series studied the relation between two classes of CHs which are recorded in different lines of solar emission with OMT obtained from field calculations in the corona in the potential approximation, as well as with quasi-stationary high-speed fluxes (HSF) of the solar wind on the Earth's orbit. The first class includes CHs the areas of which decrease with height ("enclosed" CHs), the second class comprises coronal holes the areas of which do not vary or increase with height ("open" CHs). Most "open" CHs are associated with OMT and HSF and most "enclosed" CHs are not associated with open magnetic tubes and high-speed streams of the solar wind.

As a result of this complex study, the quantitative, photometric and magnetic data about CHs at different levels of the solar atmosphere were obtained. The analysis of definition of CH boundaries, their variations with time and with regard to the development of active formations near CHs was carried out. The relation between the solar wind and structural formations on the Sun was studied.

7 Magnetoisolated complexes

The structures comparable in size to the solar radius were first detected by Malashchuk and Stepanian (2012) from solar images in the He I 1083 nm line. These structures can involve practically any of the known solar formations. The complex consists of a group of coronal holes, active regions and regions with intermediate characteristics between a coronal hole and an undisturbed (quiet) region (IRs). The characteristic feature of such complexes is a remarkable magnetic coupling between elements inside the complex and a weak relation with surrounding structures. Most magnetic field lines moving outwards from the complex appear to be either open or enclosed inside it. The boundary of such a structure can be clearly traced. A map of magnetic field measurements and field line calculations for initial points inside such a structure were superimposed onto an image in the helium line (Fig. 5). This shows that its boundary is coincident with the zero magnetic field line, and field lines intersect this boundary only in 20% of cases. These structures were referred to by the authors as "magnetoisolated complexes of solar formations" (MICSF) (Malashchuk et al., 2012b).

The idea of MICSF has been checked on higher levels in the corona (Malashchuk, Stepanian, 2013). Based on 2000-2002 solar observations in the Fe IX-X λ 17.1 nm line, we tried to ascertain whether MICSF are observed there and to determine their magnetic structure without using magnetic field calculations at various heights. Besides ARs, CHs and IRs, the magnetic structure of the complex is characterized by its boundaries, arch structures and filaments. MICSF detected earlier in the upper chromosphere have been identified in the corona (Fig. 6). The short arch structures are observed in the upper chromosphere, but their area is small compared to the area of AR from which they emanate. Numerous extended arch structures are observed in the coronal line. Their areas are comparable to the area of AR. For the both types of data, the boundary has the form of a high-brightness and low-contrast channel. Widths of channels depend on structures located close to boundaries inside and outside the

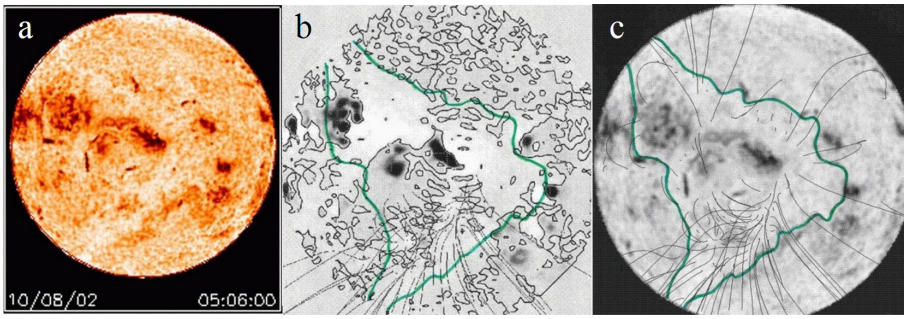


Figure 5 Solar image taken on August 10, 2002: a – in the He I λ 1083 nm line; b – magnetogram at the photospheric level with a plotted boundary of the complex (dark crooked line); c – force lines superimposed on the solar image in the He I λ 1083 nm line with a plotted boundary of the complex (dark crooked line).

complex. Most arch structures with one end that is located inside the complex do not cross the boundaries of the complexes (70% in the upper chromosphere and 80% of events in the corona). 80% of the coronal holes that appeared in complexes have an open structure of the magnetic field.

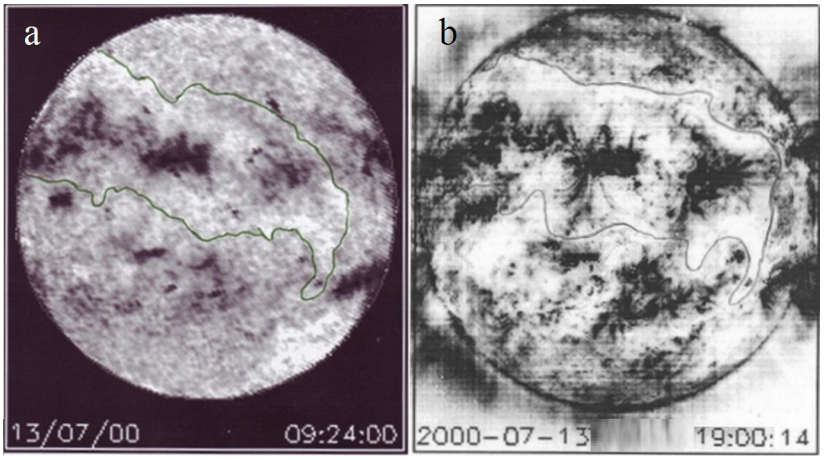


Figure 6 The complex image on June 13, 2000: a – the image in the He I 1083 nm line with a plotted boundary of the complex (dark crooked line); b – the negative image of the Sun in the 17.1 nm line.

MICSF first discovered in cycles 22–23 are confidently identified in cycle 24 (Malashchuk et al., 2016). The analysis of 2000 coronal arches (2012-2015) on images of the Sun in the Fe IX-X 17.1 nm line has shown that more than 80% of arch structures do not cross boundaries of the complexes. This confirms their magnetic isolation. Small complexes are sometimes observed inside large complexes, but magnetically isolated from an outer large complex. The existence time of complexes is often more

than two Carrington rotations. The heights of complexes are from 1.0 to 1.5 $R_{\odot}$. The essential fact is that this was concluded based on observations of coronal arches tracing magnetic field lines, but not according to calculations of arch structures. This ensures the independency of a result on the limitations which are inevitably assumed in field calculations.

In the paper by Fainshtein et al. (2013), the magnetic couplings between solar formations inside MICSF and regions outside the complexes were determined based on arch structures in the upper chromosphere and corona, as well as on magnetic field line calculations (Fig. 7).

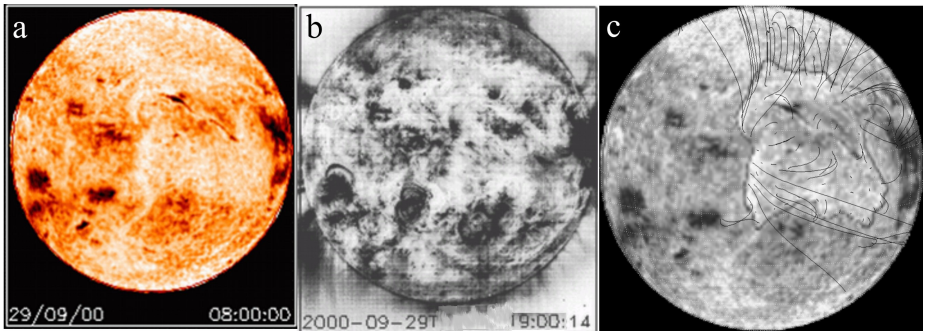


Figure 7 From left to right: the image of the Sun in the He I λ 1083 nm line on September 29, 2000; the negative image of the Sun in the 17.1 nm line. Force lines superimposed on the solar image in the He I λ 1083 nm line with a plotted boundary of the complex (dark crooked line).

Some 65% of force lines were found to enclose inside the complexes or not to enclose on the solar surface, and 35% of force lines intersect a boundary of the complex. Short force lines that intersect a boundary of the complex often merge low-strength points. Force lines enclosed in farther regions from the boundaries of the complex do not connect closely located regions. Short force lines are coincident in position with arch

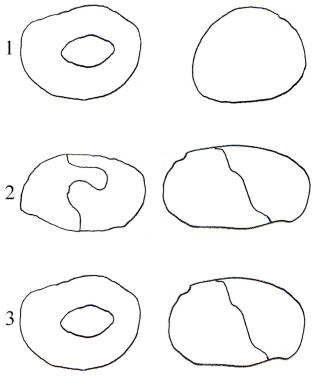


Figure 8 Three types of variations of the magnetic field with height above MICSF.

structures at the coronal level. The ends of long force lines coincide with the ends of arch structures, higher parts of which are not seen in the 17.1 nm line. Three types of variations of the magnetic field with height above the complexes are observed (Fig. 8): in one case, the predominant polarity in the complex is maintained with height up to the source surface; in other case, on the source surface, the complex is divided approximately in half by a neutral line of the magnetic field; in the third case, the situation typical for the second type of complexes is observed at height H=2.5 $R_{\odot}$.

The obtained results confirm the feasibility of existence of large-scale complexes of solar formations. The analogy of the complex with CH, in which AR originates, evolves and disappears, gives reasons to consider complexes as a part of solar activity evolution.

8 The 2015–2017 giant coronal hole

A series of papers between 2017–2018 (Tsap et al., 2017; Andreeva et al., 2018; Akhtemov et al., 2018a,b; Andreeva & Malashchuk, 2018a,b; Baranovsky et al., 2018) are dedicated to the study of evolution and influence of the long-lived giant CH (GCH) on the near-earth space. GCH emerged in June 2015 and during its evolution occupied a significant part of the northern hemisphere. It (Fig. 9) existed for more than 2 tens of rotations (CR 2165–CR 2188). The maximum area occupied by GCH was $\sim 8 \cdot 10^{11}$ km^2 in the corona and $\sim 6 \cdot 10^{11}$ km^2 in the photosphere. In its maximum GCH extended up to 30 degrees in the southern hemisphere.

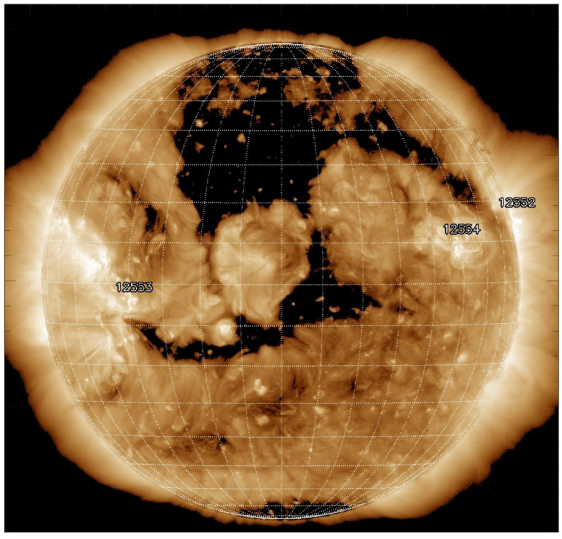


Figure 9 Full-disk images of the Sun obtained on Juny 13th, 2016 in the ultraviolet line of Fe XII (SDO/AIA).

Investigations have been carried out based on ground observations at the TST-2 telescope (CrAO RAS) and satellite data taken at SDO (SDO/AIA, SDO/HMI) and

ACE/SWEPAM, as well as on the modeling of the magnetic field in the potential approximation (PFSS). As a result of the analysis, we derived variations in such evolutionary characteristics of GCH as area, intensity, rotation rate, magnetic field strength and magnetic flux. The area of GCH at the photospheric level derived from model calculations was compared to the areas detected from observational data for the chromosphere and corona. Variations of vertical boundaries of GCH with height were studied.

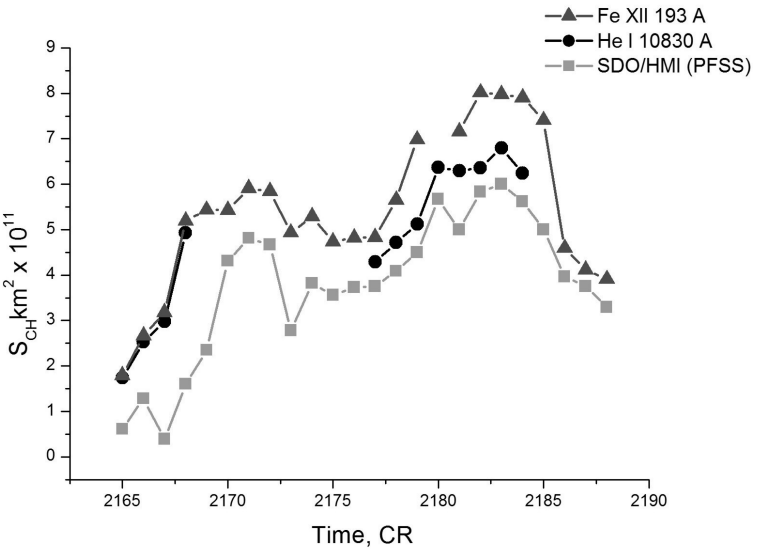


Figure 10 Variations in the area of GCH derived from observations in two spectral lines: Fe XII (open triangles) and He I (circles), as well as from calculations in the potential approximation based on data about MF taken by SDO/HMI (squares). The X-axis represents the time in the Carrington rotations.

Andreeva et al. (2018) show that variations in the area of GCH (Fig. 10) have occurred almost synchronously in boundaries determined from model calculations PFSS at the photospheric level and based on images of the Sun in the He I and Fe XII lines. The mean intensity of CH was dependent on the moment of its evolution. It varied from the intensity of the undisturbed region to the maximum intensity of CH. In the course of time, CH was becoming darker in the Fe XII 193 Å line. This process lasted for approximately the same time as a growth of the area. A decrease in intensity in the He I line is well correlated with an increase in intensity in the Fe XII line. Boundaries of GCH restricted by force lines from PFSS for the selected heights are well correlated with boundaries of GCH from intensity observations

Investigation of variations in vertical boundaries of GCH with height (Andreeva & Malashchuk, 2018a) has shown that boundaries of GCH derived from observations in the He l 10830 Å and Fe XII 193 Å lines are very close both in the direction East–West and in the direction North–South. Boundaries of GCH determined from magnetic field lines for the photosphere are consistent at the beginning and end of

the existence of GCH with the observed boundaries, but differ at the maximum of development of GCH. The maximum extension of CH occurs from the photosphere to the chromosphere approximately at height 1.0045 $R_\odot$, and then the radial extension takes place.

Akhtemov et al. (2018a) mentioned that this GCH significantly decreased the magnetic flux on a large area of the Sun on timescale of almost a year and a half. Even when CH was becoming decayed, the magnetic field strength and magnetic flux continued to decrease. The fact that no even relatively weak B, C, and M-class flares occur near CH proves the small magnetic field outflow from the deep layers of the Sun. Flares were observed just at the beginning of formation of CH and during its decay.

The analysis of variations in rotation rates of GCH in the course of its evolution, as well as rotation rates of ARs, which are contiguous and passing through this GCH (Andreeva & Malashchuk, 2018b), shows that ARs rotate with a higher speed than CH. The conclusion about different rotation rates of these formations confirms the suggestion about various depths of their formation.

Baranovsky et al. (2018) studied physical conditions in GCH based on observational data in chromospheric H_α and He I 10830 Å lines. The range of intensity variations in CH is 1.0046–1.0355 in the He I 10830 Å line and 0.9676–0.9753 in the H_α line from the emission intensity of the undisturbed Sun. To account for the observed peculiarities, intensities of CH were calculated for different models of the chromosphere. The temperature and density in CH were determined in the form of dependence of these quantities on the height in the chromosphere. Computations were carried out based on calculations of H_α and He I 10830 Å line profiles with the non-LTE program. At the chromospheric level, the temperature in CH is 500–1500 K lower compared to the undisturbed chromosphere; the density is 2-3 times lower.

Results acquired by Andreeva et al. (2018) and Akhtemov et al. (2018a) were used for the comparison with parameters of the solar wind and further investigation of the influence of GCH on the near-earth space weather.

Tsap et al. (2017) show that the relation between the extension of magnetic tubes with height and speed of the solar wind is not straightforward. This imposes the necessity of revising the previously obtained results, which follow from the modeling of the photospheric magnetic field in the potential approximation.

Further studies of this issue by Akhtemov et al. (2018b) show that the coefficient of mutual correlation between the speed of the wind and area of CH depending on the observation period can vary in wide limits reaching the maximum (~ 0.75) for CHs located in the region of the equator. The detected significant variations of the correlation coefficient are associated with the influence of activity complexes. The ancillary data that provide evidence of non-radial propagation of the fast solar wind were obtained. This can lead to errors when trying to predict its speed on the Earth's orbit.

Conclusions

For the 40-year period of exploring CHs at CrAO it has been possible to generate and modernize a system of observations at the TST-2 telescope, to compile an extensive

database of solar images in the He I line, organize daily monitoring and operational presentation of observational data via Internet. This allows CrAO to participate in the national and international observation programs "Solar Service", "Space Weather", etc.

Based on observations taken in the optical and infrared wavelength ranges at the TST-2 telescope and data derived during other experiments, a comprehensive study of CHs in the solar atmosphere has been made. The study of CH characteristics led to the detection of a series of characteristic features of CHs in the solar atmosphere. Differences in the structure of CHs at different heights were identified, dynamic characteristics and physical parameters of the atmosphere were considered, as well as situations of formation and decay of CHs. The derived results allow one to extend a morphological model of CHs and make a series of assumptions concerning the origin and evolution of CHs.

The fact that CHs are the sources of the high-speed solar wind, which affects the magnetosphere of the Earth, determines the practical relevance of studies of CHs. The study of dynamic and statistical characteristics is very important for understanding physical processes that specify the state of solar activity and connection between the Sun and geosphere.

Acknowledgements

V.M. Malaschuk, O.A. Andreeva were partially supported by the Regional RFBR-Crimea Grant N 17-42-92017.

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