Properties of Emission of Coronal Holes on the Sun according to Observations in Radio Range

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This paper is a brief review devoted to the investigation of coronal holes (CHs) on the Sun. The special attention is paid to CHs research in the millimeter and centimeter wavelength ranges. Observations in the millimeter range and from satellites in ultraviolet and soft X-ray ranges, as well as observations of Solar eclipse on March 29, 2006 at centimeter waves with the radio telescope RATAN-600 have yielded new data for understanding of the physical nature of coronal holes on the Sun.

1 Statement of the problem

Coronal holes (CHs) are areas of low temperature and density at the surface of the Sun. These areas are unipolar, with an open configuration of the magnetic field. Polar coronal holes are always visible on the poles of the Sun during the periods of a minimum solar activity as the rotary directed dipole component of the magnetic field prevails at this phase. During the periods of an increased solar activity, CH can exist at any latitude of the Sun. A CH is formed by random convective motions of the open magnetic field lines in the photosphere and reconnection of lines of the open magnetic field with the closed coronal lines. Lines of the open magnetic field in CH expand super-radially. Carrying out a stream of the charged particles from CH and low rate of emergence of new magnetic flux [1] can explain low density of particles in CH on the Sun. For the first time, observations of a CH above the solar limb were performed by Waldmeier [2] in a green line (5303 Å) with coronograph of the Zurich observatory. CHs above the limb were observed as the least intensive and long-living formations. A progress in studying CHs started in 1973–1974 with spacecraft observations in the ultra-violet (EUV) and soft X-ray (3–60 Å) ranges. The CH areas are seen in EUV and soft X-ray ranges as very dark places on the Sun because of low density and temperature in CH. CHs are identified with the areas of increased brightness in the line HeI 10830 Å as they possess the lowest absorption in the line [3, 4]. Therefore, radiation in this line often serves as an indicator of a CH. CHs represent a huge interest not only as a phenomenon in the physics of the Sun, but also as the source of quasi-stationary high-speed streams of solar plasma – the solar wind which extends to

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the limits of the Solar System. The high-speed solar wind ($V = 700 - 800$ km/s) is the source of recurrent geomagnetic disturbances. By means of observations of solar eclipses in white light and from satellites in the ultra-violet (EUV) and X-ray ranges, a precise correlation between the high-speed solar wind and polar CHs, large low-latitude CHs was established [3, 5]. Magnitosphere protects the Earth from dangerous influence of the solar wind. It is obvious that the study of CHs is very important for human survival not only on the Earth, but also in space.

2 Observations of polar CHs at mm-wavelengths

Large coronal holes on the Sun emerge within approximately 7 years near a minimum of solar activity and are absent within 1–2 years near to a maximum [6]. Observations of polar CHs were first made in CRAO at the wavelengths of 8.2 and 13.5 mm with the radio telescope RT-22 (1974–1977) and in Australia (CSIRO) at 3.5 mm with the 4 m paraboloid (1977) [7]. Polar CHs are investigated at the solar latitude φ of up to 80°. Observations are impossible in the radio range if $\varphi > 80°$ as there is a steep temperature gradient near to the limb of the Sun. It was shown that the polar CHs are areas of the increased intensity of radio emission at mm-wavelengths. (If T is the excess of temperature over the temperature of the quiet Sun, $T = 1500$ K at $\lambda = 8.2$ mm, and $T = 2200$ K at $\lambda = 13.5$ mm.) Similar observations made in Japan on a radio telescope with the diameter $d = 45$ m have shown a considerably smaller temperature excess of $T =$ (240–560) K at $\lambda = 8.3$ mm. The temperature excess was not revealed in a polar area of the Sun at the wavelength of 3.1 mm [9]. More careful researches of polar CHs were performed in Finland (Metsähovi Radio Observatory) by means of a radio telescope of 14 m in diameter at 3.4, 3.5, and 8 mm with attraction of observations in the ultraviolet (EUV SOHO/EIT) and soft-X-ray (0.25–4) keV ranges and in white light. The polar areas at up to 70° of the solar latitude were studied with this radio telescope. Observations of polar CHs in Metsähovi Radio Observatory revealed that at the frequency of 87 GHz ($\lambda = 3.5$ mm) polar areas can demonstrate enhanced brightness as well as depressions. Sometimes a polar CH is visible as a radio depression with local brightening inside it [10, 11]. Comparisons of the obtained radio maps with the images of the Sun in the EUV and soft X-ray ranges allowed establishing the fact that the brightness increase in polar area at the mm-wavelengths correlates with polar plumes, diffuse EUV emission and bright points inside the CH. An increase of intensity of the radio emission in the mm-range coincides with the dark surfaces on images in the EUV and soft X-ray ranges (SOHO/EIT). However, from these observations it was impossible to determine, whether the increase of intensity of radiation from polar CH at the mm wavelengths is due to a thermal or non-thermal mechanism. Note that inside of the areas of an increased radio emission of polar CHs, there are medium and strong magnetic fields.

3 Emission of polar and low-latitude CHs in cm-range

CHs are areas of low radio emission at cm-wavelengths and are always identified with the most dark sites (except for floccules) on the surface of the Sun in EUV and soft X-ray emission. A depression of intensity of radio emission in CHs was revealed by 19 observations (1975–1987) on various radio telescopes in the range 1.38–21.4 cm. The average contrast of the CH radiation in relation to the level of the quiet Sun is 0.9. Radiation in the helium line HeI 10830 Å is weakly absorbed in CHs. Therefore, at cm-wavelengths CHs correlate with the bright areas on the Sun observed in this helium line. The intensity of magnetic fields in CHs is equal to 1–3 G. Observations of CH above the North Pole of the Sun on March 29, 2006 at cm-wavelengths (1.03, 1.38, 2.7, 6.2, 13, 30.7 cm) have been made on the northeast sector of the RATAN-600 by the method of "relay race" [12] during the maximum phase (0.998) of the solar eclipse. A center of the directional pattern (DP) was shifted at $h = +15$ arc min to investigate the radio emission above the North Pole of the Sun. The observation of the solar eclipse at RATAN-600 allowed us to determine physical characteristics of the CH above the North Pole of the Sun at the minimum of solar activity. The distribution of brightness temperature and electron density was reliably determined in the Northern polar CH on the Sun at the distances from 1 to 2 solar radii from the observations at $\lambda = 1.03$, 1.38, 2.7, 6.2, 6.3, 13, 30.7 cm and and their computer simulation [13]. As a first approximation, the electron density can be calculated at the wavelengths of 1.03 and 1.38 cm. It was established that the distribution of the electron density from the solar limb up to $2R_c$, where R_c is the radius of the optical disk of the Sun, is close to the distribution obtained in white light at the minimum of solar activity [13, 18]. As a consequence, a question arise, whether the physical characteristics of a large low-latitude CH and a polar CH are identical. Results of observations of the quiet Sun and low-latitude CHs on the background of the quiet Sun which were earlier obtained with RATAN-600 for a minimum of solar activity [8] have been utilized to answer this question. The coincidence of brightness temperatures of the quiet Sun with brightness temperatures found from the observations of the polar CH during the solar eclipse at $\lambda = 1.03$, 1.38, 2.7 cm testifies that a CH above the North Pole of the Sun is not visible at such short wavelengths. Low-latitude coronal holes on the background of the quiet Sun are not visible at short wavelengths either. Sharply dropping brightness temperature is revealed from the observational data for the solar eclipse at $\lambda = 6.2$, 13, and 30.7 cm over the range of distances (1.005–1.03) R_c, which testifies to a detection of a CH at these wavelengths. Investigation of low-latitude CHs also confirmed the detection of a CH if the wavelengths were greater than 4 cm. The simulated brightness temperatures of the low-latitude CHs were compared with the temperatures at the nearest points to the limb of the Sun which were obtained from the observations of the solar eclipse. It revealed their coincidence on close wavelengths. The coincidence of the above-mentioned properties of cm-radio emission of the low-latitude CHs and CHs above the North Pole of the Sun testifies to the same nature of large CHs regardless of the place of their location on the Sun.

4 Radio emission of CHs in meter and decameter ranges

CH researches were conducted on interferometers, multi-element radio telescopes and radio heliographs in the meter and decameter ranges ($\lambda = 73-970$ cm) during 1974–1989. In the meter range a lowered intensity of radio emission of CHs was detected [14]. These CHs are well correlated with the dark areas on the EUV-images of the Sun. The temperature of CHs was found to be $T = 0.8 \times 10^6$ K, and the average temperature outside of CHs was $T = 1.0 \times 10^6$ K, i.e. the lower intensity of the radio emission of CHs has been detected [14, 15, 16] according to the observations of CHs in the meter range at 3.75 m (80 MHz) and 1.88 m (160 MHz) in 1972. The study of CHs showed both the increased and lowered intensities of radio mission in the decameter range. This is connected with the uncertainty of identification of the observed areas on the Sun because of the influence of strong radio refraction [17].

5 Results

Summarizing, it is possible to briefly formulate the basic characteristics of coronal holes in various wavelength ranges.

CHs in the radio range correlate with the most dark sites on the surface of the Sun observed in the ultra-violet and X-ray (3–60 Å) ranges and with areas of the increased brightness in the line HeI 10830 Å. Polar coronal holes at mm-wavelengths can show both a brightness increase and a depression. In the cm-range of wavelengths CHs are observed as areas of a reduced intensity, starting from the wavelengths of about 4–6 cm. CHs on the surface of the Sun are not visible at short wavelengths of the cm-range. At cm-wavelengths the distribution of electron density in the CHs above the pole of the Sun at the distances from the solar limb up to $2R_c$ is close to that obtained in white light during the epoch of a minimum of solar activity. The temperature characteristics of big CHs in the cm-range do not depend on their location on the Sun. CHs are the areas of a lower intensity in the meter- and dm-ranges. CHs show both increased and lowered intensities of radio emission at decameter wavelengths. This is connected with the uncertainty of identification of the observed area on the Sun because of strong radio refraction.

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