ISSN 0016-7932, Geomagnetism and Aeronomy, 2016, Vol. 56, No. 8, pp. 1010–1014. © Pleiades Publishing, Ltd., 2016.

Physical Characteristics of the Radio Emission of Solar Coronal Holes

O. A. Golubchina

St. Petersburg Branch of Special Astrophysical Observatory, Russian Academy of Sciences, St. Petersburg, Russia

e-mail: golubchina_olga@mail.ru

Received February 16, 2016; in final form, March 11, 2016

Abstract—This paper presents a brief overview of works dedicated to the studies of solar coronal holes (CH). Special attention is paid to CH studies at millimeter and centimeter wavelengths. The observational data in the millimeter range, combined with satellite observations in the ultraviolet and soft X-ray range, as well as solar eclipse observations of March 29, 2006, at centimeter wavelengths with RATAN-600, provide new results for understanding the physical nature of coronal holes on the Sun.

DOI: 10.1134/S0016793216080077

1. INTRODUCTION

Coronal holes (CHs) are areas of decreased temperature and density on the surface of the Sun. They represent unipolar regions with open configuration of the magnetic field. The polar coronal holes are always visible on the Sun's poles during the periods of minimum solar activity, because the rotation-oriented dipole component of the magnetic field is dominant at these times. During te periods of maximum solar activity, CHs can exist at any solar latitudes. One of the latest concepts of CH formation is presented in (Fisk and Schwadron, 2001; Abramenko et al., 2006). The lines of the open magnetic field form a CH either by random convective motions in the photosphere or by reconnection of the open magnetic field lines with closed lines. In coronal holes, the open magnetic field lines expand superradially, as implied by the three-dimensional structure of the polar CH density (Granmer, 2009). From the white-light coronagraph observations on *Skylab* satellite, it was found that, at the 3 Rs level (Rs is the radius of the optical disk of Sun), the CH cross-section was seven times larger than if the open magnetic field were purely radial (Munro and Jackson, 1977). In (Abramenko et al., 2006), it is shown that the emergence rate of a new magnetic flux in the form of "ephemeral" dipoles in CH is two times lower than in the adjacent regions of the quiet Sun. The charged particle outflow from the CH and low emergence rate of new magnetic dipoles can explain the low density of particles in solar CH.

The first CH observations off the limb were performed by Waldmeier (Waldmeier, 1956) in the 5303 Å green line on a coronagraph of the Zurich observatory. The CHs were observed off the limb as the least intensive and long-lived formations. Significant progress in CH studies started in 1973–1974, with spacecraft observations in the ultraviolet (EUV) and soft X-ray (3–60 Å) ranges. The CH regions in the EUV and soft X-ray ranges are observed as the darkest areas on the Sun due to low density and temperature in CH. In the HeI 10830 Å line, the areas identified with CHs are characterized by an increased brightness, as the HeI 10830 Å line in CHs has the lowest absorption in general, which is also due to low density and temperature (Granmer, 2009; Zirin, 1966). For this reason, the radiation in the HeI 10830 Å line often serves as an indicator of CH (Borovik et al., 1990; Pohjolainen et al., 2000; Harvey and Recely, 2002; Zhigalkin et al., 2008). CHs are objects of high interest, not only as a solar physics phenomenon but also as a source of quasistationary high-velocity solar plasma flows—the solar wind, which propagates beyond the boundaries of the Solar System. The slow solar wind exists continuously; its velocity is $V \sim$ 300–400 km/s. The sources of slow solar wind are small CHs, helmet streamers, borders between CHs and streamers, and active regions on the Sun. The high-velocity solar wind ($V \sim$ 700–800 km/s) is a source of recurrent geomagnetic perturbations. Based on observations of solar eclipses in white light, as well as observations from satellites in the UV and X-ray ranges, a distinct correlation was found for the high-velocity solar wind, polar CHs, and large low-latitude CHs, as well as pseudostreamers and plumes. These CHs exist for months, and the recurrent streams of solar wind reach the Earth with a periodicity of the Sun's rotation (~27 days) (Wang et al., 2007; Granmer, 2009). The planet is protected from the hazardous effects of the solar wind by the magnetosphere. It is obvious that the study of coronal holes is vitally important for human existence not only on the Earth, but also in space.

2. OBSERVATIONS OF POLAR CORONAL HOLES AT MILLIMETER WAVELENGTHS

Large coronal holes on the Sun exist for approximately 7 years around the minimum of solar activity and disappear for 1–2 years near the maximum of solar activity (Harvey and Recely, 2002). During the period of minimum solar activity, the magnetic field of the Sun is poloidal, so CHs are present in the polar regions of the Sun. The first observations of polar CHs were performed at the Crimean Astrophysical Observatory (CRAO) at the 8.2 and 13.5 mm wavelengths with the RT-22 radio telescope (1974–1977) and in Australia at the 3.5 mm wavelength (CSIRO) with a 4 m diameter paraboloid (1977) (Babin et al., 1976; Efanov et al., 1979). At the CRAO, polar CHs were studied at solar latitudes of up to $\phi = 80°$. At heliographic latitudes of $\phi > 80°$, observations in the radio range are impossible due to the large temperature gradient near the Sun's limb. Based on those observations, it was shown that polar CHs were areas of intensified radio emission at millimeter wavelengths (ΔT is the excess temperature over the quiet Sun's temperature; $\lambda = 8.2$ mm, $\Delta T = 1500$ K; $\lambda = 13.5$ mm, $\Delta T = 2200$ K). Similar observations conducted in Japan with a radio telescope with a 45 m diameter, showed significantly lesser brightenings: at $\lambda = 8.3$ mm, $\Delta T = (240–560)$ K. At the 3.1 mm wavelength, brightening in the polar region of the Sun was not detected (Kosugi et al., 1986). Later, numerous, more thorough studies of polar CHs were performed in Finland (Metsahovi Radio Observatory) with a 14 m diameter radio telescope at 8, 3.4, and 3.5 mm wavelengths combined with observations in the ultraviolet (EUV SOHO/EIT) and soft X-rays (0.25–4 keV) (Pohjolainen et al., 1998; Pohjolainen, 2000; Pohjolainen et al., 2000; Riehokainen et al., 2001). The spatial resolution of the telescope is approximately 1 arcminute; the spatial resolution of EUV SOHO/EIT instruments is several arcseconds. The polar regions were investigated with a radio telescope up to a heliographic latitude of $\phi \sim 70°$. The polar CH observations at the Metsahovi Radio Observatory showed for the first time that at the 87 GHz frequency ($\lambda = 3.5$ mm) polar regions can appear both in brightening and in depression. Sometimes, polar CHs are visible as radio depressions with local brightenings inside (Pohjolainen et al., 1999; Pohjolainen, 2000). Thus, it cannot be said that polar CHs are areas of increased radio emission at $\nu = 87$ GHz. The calculated and observed radio depression values in CH at $\nu = 87$ GHz were $\Delta T = (30–40)$ K and $\Delta T = (22–130)$ K, respectively. The radio brightenings in the polar coronal region correlate with various structures: bright dots in CHs and in diffuse bright structures; diffuse bright structures along the CH borders; plumes and streamers. In the X-ray range, bright dots are associated with magnetic bipolar regions. The sizes of the bright dots are 10–50 arcsec in the EUV and soft X-ray radiation (Pohjolainen, 2000). The calculated temperature values of the bright dots $T = (10–390)$ K correspond quite well to the observed temperatures $T = (30–150)$ K. Continued collaborative studies at $\nu = 87$ and 37 GHz ($\lambda = 3.4$; 8 mm) in the EUV (SOHO/EIT) and optical range at the Kislovodsk Mountain Astronomical Station confirmed the previous observational results at $\nu = 87$ GHz: the increase of radio emission intensity in the millimeter range matches the dark surfaces in the images in the EUV and soft X-ray ranges (SOHO/EIT) (Riehokainen et al., 2001). Precise coordinate measurements of positions of grouped polar faculae and bright diffuse structures in the optical range made it possible to discover that these polar faculae and bright diffuse structures were often visible in the polar regions of increased radio emission and were located around the bright structures visible in the ultraviolet at SOHO/EIT. The authors believe that these bright structures are apparently plume bases. The polar faculae and bright diffuse structures are seen along the borders of increased radio emission areas, inside relatively dark regions, but they avoid both dark and bright regions. However, it is impossible to tell from those observations whether the thermal or nonthermal mechanism of radiation sustains the increase of polar CH radiation intensity in millimeter wavelengths. It is interesting that moderate and strong magnetic fields are present inside the areas of increased radio emission of polar CH.

3. CENTIMETER RADIO EMISSION OF POLAR AND LOW-LATITUDE CORONAL HOLES

The most active studies of coronal holes at centimeter wavelengths started in the 1980s at almost all large radio telescopes around the world. At centimeter wavelengths, CHs appear as areas of decreased radio emission and are always identified with the darkest regions (except for flocculi) on the solar surface in the ultraviolet and soft X-ray ranges. A decrease of radio emission intensity in CHs was discovered based on observational data (1975–1987) from 15 different telescopes in the 1.38–21.4 cm range. The average value of CH radiation contrast, relative to the quiet Sun level, equaled 0.9. In the helium line HeI 10830 Å, as was said above, the radiation absorption in CH is low. For this reason, at centimeter wavelengths CHs correlate with the bright regions on the Sun in the helium line. The studies performed at $\lambda = (11.7–31.6)$ cm with RATAN-600, upon the emergence of a CH on the limb, show a decrease of the quiet Sun's radio radius by 5–10% (Borovik et al., 1990). The X-ray images show the quiet solar corona as a set of extended loops 50–100 thousand km high. The absence of such loops in the CH explains the decrease of the quiet Sun's radio radius in the long centimeter waves at the emergence of the CH on the limb. On average, the magnetic field intensities in the CH are equal to 1–3 Gs.

The observation of a CH above the north pole of the Sun on March 29, 2006 at centimeter wavelengths (1.03, 1.38, 2.7, 6.2, 13, 30.7 cm) was conducted at the northeast section of RATAN-600 by 'relay' method (Golubchina and Golubchin, 1981) during the maximum phase (0.998) of the solar eclipse. The solar eclipse observation at RATAN-600 allowed to determine physical characteristics of the CH above the north pole of the Sun in the period of minimum solar activity. Based on the observational data and its model representation, the distribution was determined for the brightness temperature and electron concentration in the north pole coronal region of the Sun at $\lambda = 1.03$, 1.38, 2.7, 6.2, 6.3, 13, 30.7 cm, at the distances from 1 to 2 solar radii (Golubchina et al., 2011; Golubchina and Korzhavin, 2013a; Golubchina and Korzhavin, 2013b; Golubchina and Korzhavin, 2014). The obtained electron concentrations above the polar region off the solar limb were compared with the white-light measurement results. It was found that the electron concentration distribution at the distance of up to 2 Rs from the solar limb, according to the measurement data at 1.03 cm and 1.38 cm wavelengths, was close to the distributions obtained in white light in the period of minimum solar activity (Golubchina and Korzhavin, 2014; Zheleznyakov, 1964). As a consequence, a question arose as to whether the physical characteristics of large low-latitude CHs and polar CHs were identical. In order to answer that question, the results from observations of the quiet Sun and of low-latitude CHs against the quiet Sun background were used; they were obtained earlier with RATAN-600 in the period of minimum solar activity (Borovik et al., 1990). During the observation of the maximum phase of solar eclipse on March 29, 2006, with RATAN-600 in the period of minimum solar activity, the center of the antenna pattern was shifted in altitude by +15 arcmin, in order to scan the near-polar region of the Sun. Additionally, to confirm that a polar CH was registered above the north pole of the Sun, the brightness temperature distributions were compared between the solar eclipse and the quiet Sun observations, acquired with the Large Pulkovo Radio Telescope (LPR) and RATAN-600 (Borovik et al., 1990; Golubchina and Korzhavin, 2014). During regular observations with the LPR and RATAN-600 radio telescopes, the antenna pattern center was locked on the center of the optical disc of the Sun. In order to avoid the possible influence of brightening on the quiet Sun limb at wavelengths $\lambda > 6$ cm, the distributions of the quiet-Sun brightness temperatures in the period of minimum solar activity were used. The positional angle during those observations was P = 26°. The brightness temperatures of the quiet Sun, quoted in (Borovik et al., 1990), turned out to be higher than the brightness temperatures obtained from the solar eclipse observations at 6.2, 13, and 30.7 cm wavelengths in the interval of 1.01–1.2 Rs (Golubchina and Korzhavin, 2013b), which confirmed the registration of a CH above the north pole of the Sun during the eclipse. The coincidence between the brightness temperatures of the quiet Sun and brightness temperatures from the eclipse observations of CH at 1.03, 1.38, and 2.7 cm short waves is evidence that the CH above the north pole of the Sun is not visible at short wavelengths. The low-latitude CHs against the quiet Sun background are also not visible at short wavelengths of radio emission. During observation of the solar eclipse, a rapid decrease in brightness temperatures was detected at 6.2, 13, and 30.7 cm wavelengths at the distance intervals of 1.005–1.03 Rs, which is evidence of a CH registered at these wavelengths. The investigation of low-latitude CHs also confirmed the registration of a CH, starting from the waves longer than 4 cm. Comparison of the average empirically consistent model values of temperatures for low-latitude CHs with the brightness temperatures near the solar limb acquired from solar eclipse observations showed their coincidence at close wavelengths (Golubchina and Korzhavin, 2013b).

The coincidence between the aforementioned properties of centimeter radio emission of low-latitude CHs and those of the CH above the north solar pole is evidence that large CHs are identical in nature regardless of their location on the Sun. The identity of characteristics of equatorial and polar CHs was mentioned in (Munro and Jackson, 1977), based on the observations of coronal holes in the EUV range (the Harvard OSO-4 instrument).

4. RADIO EMISSION OF CORONAL HOLES AT METER AND DECAMETER WAVELENGTHS

The first CH observations in the meter range were conducted with a radioheliograph in Culgoora at 3.75 m (80 MHz) and 1.88 m (160 MHz) wavelengths in 1972. The "dark" areas, which were discovered in the solar radio emission, correlated well with the dark regions in the ultraviolet images of the Sun. The authors came to the conclusion that those dark areas were solar CHs. The temperature of CH was $T \sim 0.8 \times 10^6$ K, and the average temperature beyond CH was $T \sim 1.0 \times 10^6$ K. Thus, a reduced radio emission intensity was registered in CH at meter wavelengths (Dulk and Sheridan, 1974). In 1974–1989, the CH studies in meter and decameter ranges ($\lambda = 73$–970 cm) were performed with interferometers, multielement radio telescopes, and radioheliographs in Culgoora, Nancay, and Clark Lake. The results of the observations distinctly showed that CHs were areas of decreased intensity in the range of meter wavelengths (Dulk and Sheridan, 1974; Dulk et al., 1977; Wang et al., 1987; Shibasaki et al., 2011). In the decameter range of wavelengths, CHs manifest both increased and decreased radio emission intensity. This uncertainty is associated with the uncertainty of identification of the observed area on the Sun due to the influence of strong radio refraction (Lantos et al., 1987).

5. DISCUSSION

The latest studies in the millimeter range, which are based on observations from a 14-meter telescope at the Metsahovi Radio Observatory, combined with observations from satellites in the EUV and X-ray ranges and from white-light coronagraphs, showed the nonuniformity of CH structure in the millimeter range. The areas of increased radio emission generally coincide with the dark areas in the EUV (SOHO/EIT). However, the increase of radio emission intensity of polar CHs can be associated with the appearance of polar faculae, plumes, bright dots, and strong magnetic fluxes in the antenna pattern. Sometimes, the brightenings in CH are inexplicable. The MDI observations of the Sun and the EUV images (SOHO/EIT) made it possible to see the finer processes in CH, providing a deeper understanding of CH physics (Abramenko et al., 2006). In particular, it was discovered that the emergence rate of new small dipoles in CH was two times lower than in the surrounding areas of the quiet Sun. The latter confirms that fact that the open magnetic flux is concentrated where the emergence rate of new magnetic flux is minimum, and the solar CHs are exactly such areas. The observation of the solar eclipse on March 29, 2006, with RATAN-600 in a wide range of centimeter wavelengths for the first time allowed to determine in the radio range the brightness temperature distribution in CH above the north pole of the Sun at the distance of up to two solar radii from the limb. Additionally, it was concluded that the temperature characteristics of large CHs did not depend on the location of CH on the Sun. The identity of properties of polar and low-latitude CH in the EUV range (OSO-4) was mentioned in (Munro and Jackson, 1977). The results of white-light observations of polar CH during the eclipse of March 29, 2006, in Libya demonstrated the complex structure of the CH above north solar pole (Wang et al., 2007). Comparison of such high-quality observations with observations in other ranges brings us closer to a full understanding of the nature of solar CHs.

6. CONCLUSIONS

Summarizing all the information above, we can briefly formulate the main characteristics of CHs in different wavelength ranges.

(1) CHS in the radio range, as well as in the ultraviolet and X-ray range, are generally areas of unipolar magnetic field with an open configuration.

(2) In the radio range, CHs correlate with the darkest regions on the solar surface in the ultraviolet and X-ray ranges (3–60 Å) and with the areas of increased brightness in the HeI 10830 Å line.

(3) At centimeter wavelengths, solar CHs are observed as areas of decreased intensity, starting from the wavelengths $\lambda > 4$–6 cm. At short centimeter wavelengths, CHs are not visible on the solar surface. The radio emission of the polar regions of the Sun is the least intensive in the centimeter range during the period of minimum solar activity.

(4) In the centimeter wavelength range, the electron concentration distribution in the CH above the pole at the distances of less than 2 Rs from the Sun's limb is close to the electron concentration obtained from the white-light observations in the epoch of minimum solar activity.

(5) In the centimeter range, the temperature characteristics of at least large CHs are not dependent on the CH location on the Sun.

(6) In the radio range of meter and decameter waves, CHs are areas of decreased intensity.

(7) In the decameter range of wavelengths, CHs manifest both increased and decreased radio emission intensity. This uncertainty is associated with the uncertainty of identification of the observed area on the Sun due to the influence of strong radio refraction.

REFERENCES

Abramenko, V.I., Fisk, L.A., and Yurchyshyn, V.B., The rate of emergence of magnetic dipoles in coronal holes and adjacent quiet-sun regions, *Astrophys. J. Lett.*, 2006, vol. 641, no. 1, pp. L65–L68.

Babin, A.N., Gopasiuk, S.I., Efanov, V.A., et al., Intensification of magnetic fields, millimeter-range radio brightness, and H-alpha activity in polar regions on the sun, *Izv. Krym. Astrofiz. Obs.*, 1976, vol. 55, pp. 3–13.

Borovik, V.N., Kurbanov, M.S., Livshits, M.A., and Ryabov, B.I., Coronal holes against the quiet-Sun background: An analysis of RATAN-600 observations in the 2–32-cm wavelength range, *Sov. Astron.*, 1990, vol. 34, pp. 522–534.

Dulk, G.A. and Sheridan, K.V., The structure of the middle corona from observations at 80 and 60 MHz, *Sol. Phys.*, 1974, vol. 36, pp. 191–202.

Dulk, G.A., Sheridan, K.V., Smerd, S.F., and Withbroe, G.L., Radio and EUV observations of a coronal hole, *Sol. Phys.*, 1977, vol. 52, pp. 349–367.

Efanov, V.A., Moiseeva, I.G., Nesterova, N.S., and Stewart, R.T., Radio emission of the solar polar regions at millimeter wavelengths, *Symp. – Int. Astron. Union*, 1980, vol. 86, pp. 141–145.

Fisk, L.A. and Schwadron, N.A., The behavior of the open magnetic field of the Sun, *Astrophys. J.*, 2001, vol. 560, no. 1, pp. 425–438.

Golubchina, O.A. and Golubchin, G.S., The relay metod, *Astrofiz. Issled. (Izv. Spets. Astrofiz. Obs.)*, 1981, no. 14, p. 125.

Golubchina, O.A., Korzhavin, A.N., and Tokhchukova, S., Brightness temperature distribution in solar corona based on RATAN-600 observations of the maximum phase of March 29, 2006 solar eclipse, *Astrophys. Bull.*, 2011, vol. 66, no. 4, pp. 488–495.

Golubchina, O.A. and Korzhavin, A.N., Distribution of centimeter-wave brightness temperature of solar polar region, *Astrophys. Bull.*, 2013a, vol. 68, no. 2, pp. 219–225.

Golubchina, O.A. and Korzhavin, A.N., Comparative analysis of the distributions of brightness temperatures in the solar polar region based on observational data obtained with RATAN-600 in the microwave range during the solar eclipse of March 29, 2006, *Geomagn. Aeron. (Engl. Transl.)*, 2013b, vol. 53, no. 8, pp. 1025–1029.

Golubchina, O.A. and Korzhavin, A.N., Brightness temperatures and electron density in the solar polar coronal region on the basis of MW observations, *Geomagn. Aeron. (Engl. Transl.)*, 2014, vol. 54, no. 8, pp. 1039–1044.

Granmer, S.R., Coronal holes, *Living Rev. Sol. Phys.*, 2009, vol. 6, id 3.

Harvey, K.L. and Recely, F., Polar coronal holes during cycles 22 and 23, *Sol. Phys.*, 2002, vol. 211, no. 1, pp. 31–52.

Kosugi T., Ishiguro, M., and Shibasaki, K., Polar-cap and coronal hole-associated brightenings of the Sun at millimeter wavelengths, 1986, *Publ. Astron. Soc. Jpn.*, vol. 38, pp. 1–11.

Lantos, P., Alissandrakis, C.E., Gergely, T., and Kundu, M.R., Quite sun and slowly variable component at meter and decameter wavelengths, 1987, *Sol. Phys.*, vol. 112, no. 2, pp. 325–340.

Munro, R.H. and Jackson, B.V., Physical properties of a polar coronal hole from 2 to 5 solar radii, *Astrophys. J.*, 1977, vol. 213, pp. 874–886.

Pohjolainen, S., Portier-Fozzani, F., and Ragaigne, D., Radio bright structures near the solar poles at millimeter wavelengths, in *Solar Physics with Radio Observations, Proceedings of the Nobeyama Symposium 1988*, Bastian, T., Gopalswamy, N., and Shibasaki, K., Eds., NRO Rep. 479, 1988, pp. 31–36.

Pohjolainen, S., Portier-Fozzani, F., and Ragaigne, D., Comparison of 87 GHz solar polar structures with EUV and soft X-ray emission, *Astron. Astrophys. Suppl. Ser.*, 2000, vol. 143, pp. 227–263.

Pohjolainen, S., On the origin of polar radio brightenings at short millimeter wavelengths, *Astron. Astrophys.*, 2000, vol. 361, no. 1, pp. 349–358.

Riehokainen, A., Urpo, S., Valtaoja, E., et al., Millimeter-radio, SOHO/EIT 171 Å features and the polar faculae in the polar zones of the Sun, *Astron. Astrophys.*, 2001, vol. 366, pp. 676–685.

Shibasaki, K., Alissandrakis, C.E., and Pohjolainen, S., Radio emission of the quiet Sun and active regions, *Sol. Phys.*, 2011, vol. 273, pp. 309–337.

Waldmeier, M., Synoptische Karten der Sonnenkorona, *Z. Astrophys.*, 1956, vol. 38, pp. 219–236.

Wang, Y.-M., Biersteker, J.B., Sheeley, N.R., et al., The solar eclipse of 2006 and the origin of raylike feature in the White-light corona, *Astrophys. J.*, 2007, vol. 660, pp. 882–892.

Wang, Z., Schmahl, E.J., and Kundu, M.R., Meter wave observations of a coronal hole, *Sol. Phys.*, 1987, vol. 111, no. 2, pp. 419–428.

Zheleznyakov, V.V., *Radioizluchenie Solntsa i planet* (Radioemission of the Sun and Planets), Moscow: Nauka, 1964.

Zhigalkin, R.K., Malashchuk, V.M., and Stepanian, N.N., Relationship between the motion of matter in coronal holes and their evolution, *Bull. Crim. Astrophys. Obs.*, vol. 104, no. 1, pp. 96–101.

Zirin, H., *The Solar Atmosphere*, Waltham, Massachusetts: Blaisdell, 1966.

Translated by M. Chubarova