BRIGHTNESS TEMPERATURES AND ELECTRON CONCENTRATIONS OF THE OPEN NORTHERN POLAR REGION OF THE SUN FROM OBSERVATIONS IN THE SANTIMETER WAVE DIAPAZON AT THE MAXIMUM PHASE OF THE SOLAR Eclipse on 29.03.2006.

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Received February 23, 2025

Revised April 07, 2025

Accepted June 17, 2025

Abstract. This paper presents a study of the radio emission source of the open northwestern limb of the Sun (uncovered by the Moon) during observations of the maximum phase of the (F = 0.998) of the solar eclipse on 29.03.2006 at the radio telescope RATAN-600 in the centimeter wavelength range (1.03-30.7) cm. The modeling of radio emission of the Sun and the Moon was used in the processing of the observations under the assumption of circular symmetry of the distribution of brightness temperatures of radio emission in the atmosphere of the Sun and the Moon. The obtained distributions of brightness temperature, electron concentration of the open northwestern limb of the Sun with distance from the center of the Sun's optical disk are discussed. The presented brightness temperature distributions indicate a possible lower boundary of solar wind formation from the open north polar region of the Sun.

DOI: 10.31857/S00167940250709e2

1. INTRODUCTION

Observations of the maximum phase (F = 0.998) of the solar eclipse of 29.03.2006 were made on the northeastern sector of RATAN-600 in one azimuth, on the irradiator No. 1 in the "relay" mode (Fig. 1), in the centimeter wavelength range (1.03, 1.38, 2.7, 6.2, 13, 30.7) cm. The angular dimensions of the horizontal (rh) and vertical (rv) antenna radiation patterns are given in Table 1 [Golubchina and Golubchin, 1981]. The center of the antenna radiation pattern (ARD) was shifted in height relative to the center of the Sun's optical disk by +15 angular min. to the north pole of the Sun. At the time of the maximum phase of the solar eclipse, the open part of the Sun was 0.2% of the area of the Sun's optical disk.

The study of the observational results revealed a complicated situation in identifying the open northwestern limb of the Sun (the Sun's coronal sickle) and the polar coronal hole. The calculated position of the Moon and the Sun at the time of the maximum phase of the eclipse on 29.03.2006 shows the extent of the open northwestern limb of the Sun up to the North Pole of the Sun (Fig. 2), where, according to observations [Nelson, L., Reginald et al., 2009], the northern polar coronal hole was located. Therefore, as a result of the refinement of the identification of the coordinates of the radio emission sources obtained from observations at the RATAN-600 radio telescope, the study of the brightness temperatures and electron concentrations of the open northern polar region of the Sun during the maximum phase of the eclipse was the most interesting (Fig. 2).

In Fig. 2 the black part of the circle is the open part of the Sun (the open north-western limb of the Sun) at the moment of the maximum phase of the solar eclipse on 29.03.2006. (EW) and (NS) - east-west and north-south directions of the solar disk; (QQ') - projection of the celestial equator, OP - direction to the North Pole of the World, OD - direction of the RATAN-600 radio telescope. The segments of vertical straight lines show the position of the knife DNA relative to the optical center of the Sun at different moments of time when observing on the northeastern sector of RATAN-600.

At the moment of the maximum phase (F = 0.998) of the solar eclipse on 29.03.2006 (RATAN-600), a part of the northwestern limb of the Sun remained open. The maximum radio emission of the source on the records is identified with the position of this open northwestern limb of the Sun (Figs. 2, 3, 4, 5).

2. DISTRIBUTION OF BRIGHTNESS TEMPERATURES OF RADIO EMISSION OF THE OPEN WESTERN LIMB OF THE SUN IN THE CENTIMETER WAVELENGTH RANGE

The center of the antenna pattern (DNA) was shifted in height relative to the center of the Sun's optical disk by +15 angular minutes to the North Pole of the Sun. This allowed us to determine the brightness temperatures of the radio emission of the northwestern limb of the Sun. When processing the data of solar eclipse observations of 29.03.2006, we created semi-empirical models of the Sun (Moon) in the centimeter wavelength range (1.03, 1.38, 2.7, 6.2, 13, 30.7) cm at distances from ~1 Rs to 2 Rs from the center of the Sun's optical disk (Rs is the radius of the Sun's optical disk). The brightness temperatures (Tb) of the model rings of the Sun (Moon) were set either according to the literature data, or by fitting them by trial and error, or using the computational method for given observational wavelengths [Zheleznyakov, 1964; Sobolev, 1967; Golubchina et al., 2011; Golubchina & Korzhavin, 2013]. Antenna temperatures (Ta) were calculated using the antenna smoothing equations for the vertical and horizontal DHAs, taking into account antenna overexposure during the "relay" observation method [Golubchina et al., 2011; Golubchina and Korzhavin, 2013]. The antenna smoothing equation relates the measured antenna temperature Ta (φ0) of the observed source to its brightness temperature Tb (φ):

$$Ta(\varphi 0) = \int Tb(\varphi) A(\varphi - \varphi 0)\, d\varphi. \quad (1)$$

Here A (φ - φ 0) is the normalized vertical antenna pattern, (φ - φ 0) is the angle of deviation from the center of the vertical DNA, Tb (φ) is the brightness temperature distribution over the source, Ta (φ 0) is the antenna temperature of the observed source.

The degree of coincidence of the modeled distribution of the antenna temperature over the Sun with the record of observations of the Sun's radio emission during the maximum phase of the solar eclipse is an estimate of the model quality [Golubchina and Korzhavin, 2013].

Distributions of brightness temperatures of the Sun according to the data of observations of the solar eclipse of 29.03.2006 are shown in Fig. 6. The article [Golubchina and Korzhavin, 2013] gives a detailed table of the values of brightness temperatures at the wavelengths of our observations with increasing distances from the Sun's limb. The sharp drop in the brightness temperatures of the radio emission of the Sun's open limb at $\lambda = 13$ and 30.7 cm (Fig. 6) is related to the presence and influence of the north polar coronal hole, the results of observations of which in the optical wavelength range were given in [Nelson, Reginald et al, 2009] A comparison of the maximum brightness temperatures of radio emission from the northwestern limb of the Sun according to the results of observations at centimeter wavelengths at the RATAN-600 radio telescope during the maximum phase of the solar eclipse on 29.03.2006 with the results of the average values of coronal emission from the quiet Sun obtained earlier at close wavelengths at the BPR and RATAN-600 radio telescopes in the normal observing mode [Borovik et al., 1990] showed that these temperatures are very close. They are given in Table 2. This confirms the fact that we identify and study the coronal radio emission of the Sun's northwestern limb.

3. DISTRIBUTION OF ELECTRONIC CONCENTRATION (n_e) OF THE OPEN NORTHWESTERN REGION OF THE SUN ACCORDING TO OBSERVATIONS RADIO EMISSION OF THE SUN DURING THE MAXIMUM PHASE OF THE SOLAR ECLIPSE ON 29.03.2006.

In radio astronomy, the approximate Baumbach-Allen formula [Zheleznyakov, 1964; Sobolev, 1967] is often used to determine the electron concentration of the solar corona:

$$n_e\,(r/Rs) = 10^8\,[1.55\,(r/\,Rs)^{-6} + 2.99\,(r/\,Rs)^{-16}\,], \qquad (2)$$

Rs - radius of the Sun's optical disk, r/Rs - distance from the center of the Sun's optical disk in radii of the Sun's optical disk.

In this work, the results of the brightness temperature distribution obtained from the cited observations of the solar eclipse of 29.03.2006 at RATAN-600 were used to determine the electron concentration. The procedure for determining the electron concentration is described in detail in [Golubchina and Korzhavin, 2014].

Let us briefly summarize the scheme for calculating the electron concentration. The radiation pattern of the RATAN-600 radio telescope is knife-edge (Table 1).

Rs is the radius of the Sun's optical disk, r/Rs is the distance from the center of the Sun's optical disk in radii of the Sun's optical disk. We assume the length of the optical path along the beam of view (Δ L) to be equal to the size of the vertical DNA at the level of 0.01. Then for waves (1.03-6.2) cm:

$\Delta L = 2\times10^9$cm; for waves (13.0-30.7) cm -$\Delta L = 7\times10^{10}$cm.

Brightness temperature:

$$T_b(R) = T_e\tau = T_e\mu(R)\Delta L. \qquad (3)$$

In the first approximation, we assume the mean value of the electronic temperature of the solar corona $T_e= 1.4 \times 10^6$, since the coordinates of the maximum of the radio emission from the Sun's open limb for all waves of our measurements are r/Rs >1,$\lambda -$ is the observation wavelength, andμ is the absorption coefficient. The formula for the absorption coefficient is given in the work of V.V. Sobolev. [1967]. Substituting the necessary data into this formula, we obtain equations (4, 5) for calculating the absorption coefficient (μ) and electron concentration (n_e) at a given distance r/Rs:

$$\mu\,(r/Rs) = 10^{-21}\, 0.19\, n_e(r/Rs)^{2}\, T_e^{-3/2}\, \lambda^2, \qquad (4)$$

$$n_e(r/Rs) = [T_b(r/Rs) / 10^{-21}\, 0.19\, \lambda^2\, T_e^{-1/2}\, \Delta L]^{1/2}. \qquad (5)$$

Setting the brightness temperatures found from the solar eclipse observations of 29.03.2006 for different distances from the center of the Sun at a fixed wavelength, we calculate the distribution of electron concentration of the open northwestern limb of the Sun over the distance from ~Rs to 2 Rs (Fig. 7).

Despite the fact that we solved the problem of determining the electron concentration in the first approximation, the results obtained agree with the generalized data obtained in white light for the polar and equatorial regions during the solar activity minimum (Fig. 8).

4. ABOUT THE LOWER BOUNDARY OF THE SOLAR WIND FORMATION REGION OF THE OPEN NORTHWESTERN REGION OF THE SUN DURING THE OBSERVATION OF THE MAXIMUM PHASE OF THE SOLAR ECLIPSE ON 29.03.2006. IN THE CENTIMETER WAVELENGTH RANGE

The solar wind is electromagnetic waves, streams of high-energy charged particles propagating from the Sun beyond the boundaries of the solar system. The solar wind mainly consists of ionized particles (electrons, protons, helium nuclei (α -particles)). It is currently believed that the main sources of the solar wind, are coronal holes (CHs) on the quiescent Sun, polar coronal holes, and coronal mass ejections. The accuracy of our Ta = 1 K measurements. The minimum brightness temperature (Tb $\approx$ 0 K) of the Sun's radio emission at all radio wavelengths of our observations in the north polar region of the Sun was recorded at a distance of ~ 1.2 Rs (7.6×10^5km) from the center of the Sun's optical disk (Fig. 6). It is possible that during the maximum phase of a solar eclipse, the solar wind from the open northwestern limb of the Sun is due to radio emission from the northwestern limb of the Sun only near the solar disk at distances <1.2 Rs. This result may be useful in the study of the Sun at close distances by spacecraft.

5. CONCLUSIONS

1. During the maximum phase of the eclipse (29.03.2006), the Moon's coverage of the Sun eliminated the background radiation of the Sun's disk, preventing the study of its weak coronal emission at distances from 1.005 Rs to 2 Rs. A specially created method of observation and processing of the data obtained on RATAN-600 made it possible to find the distributions of brightness temperatures and electron concentrations of the open northwestern limb of the Sun in the microwave range (1.03, 1.38, 2.7, 6.2, 13, 31) cm at distances~ from Rs to 2 Rs by just one observation of the Sun.

2. The distribution of electron concentration at a distance from 1.005 Rs to 2 Rs was obtained at the wave 1.03 cm, which agrees with the literature data of white-light observations of total solar eclipses during the period of minimum solar activity [Zheleznyakov, 1964].

3. It is possible that the solar wind contribution from the open northwestern limb of the Sun in the microwave range may be due to radio emission from the northwestern limb of the Sun, but only near the solar disk at distances < 1.2 Rs.

CONFLICT OF INTERESTS

The author declares that he has no conflict of interest.

REFERENCES

1. *Golubchina O., Golubchin G.* The relay method // Astrophysical Research, 1981, (IAIA CAO), V. 14, P. 125-131.
2. *Golubchina O., Bogod B., Korzhavin A., et al.* Radio emission of a high-latitude prominence in a wide range of centimeter wavelengths // Astrophys. Bulletin, 2008, V. 63, No. 1. P. 36-44.
3. *Golubchina O., Korzhavin A.* Distribution of the brightness temperature of the radio emission of the polar region of the Sun in the centimeter wavelength range // Astrophys. Bulletin, 2013, V. 68, No. 2. P. 232-238.
4. *Zheleznyakov V.V.* Radio emission of the Sun and planets. Moscow: Nauka, 558 p. 1964.
5. *Sobolev V.V.* Course of theoretical Astrophysics. Moscow: Nauka, 528 p. 1967.
6. *Borovik V.N., et al.* Coronal holes against the quiet-sun background: An analysis of RATAN-600 observations in the 2-32 cm wavelength range // Sov. Astron, Vol. 34, pp. 522-530, 1990.
7. *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.

8. *Golubchina O.A. and Korzhavin A.N.* Brightness Temperatures and Electron Density in the Solar Polar Coronal Region on the Basis of MW Observations // Geomagnetism and Aeronomy, 2014, Vol.54, No. 8, pp. 1039-1044.
9. *Nelson L., Reginald, et al.* Electron-temperature maps of the low solar corona: ISCORE results from the total solar eclipse of 29 March 2006 in Libia // Solar Phys., 2009, pp. 347-361.

Table 1. Angular dimensions of the horizontal (rh) and vertical (rv) antenna directivity diagrams,λ - observation wavelength.

λ, cm	1.03	1.38	2.7	6.2	13	30.7
(rh ×rv) ang min.	0.4× 17.3	0.6× 19.3	1.2× 19.4	2.6× 25.0	5.7× 35.8	13.4× 84.4

Table 2. Brightness temperatures of radio emission of the quiet Sun and the maximum values of brightness temperatures of the open limb of the Sun according to observations at a number of wavelengths at the radio telescope RATAN-600 during the maximum phase of the solar eclipse on 29.03.2006.

λ - wavelength of observation, r/Rs - distance of the maximum signal of the open part of the Sun's northwestern limb from the center of the Sun's optical disk in solar radii, Tb - maximum brightness temperature of radio emission from the open part of the Sun's northwestern limb. The averaged (labeled S) values of brightness temperatures (Tb) for the quiet Sun obtained earlier at the BPR and RATAN-600 in the normal observing mode [Borovik et al., 1990].

λ cm	6.2	13.0	30.7
r/Rs	1.005	1.005	1.01
Tb × 10^4, K	2.0	4.5	8.4
(S)λ, cm	6.0	15	31.6
Tb× 10^4, K	2.47	6.3	17.4

FIGURE CAPTIONS

Fig. 1. The course of rays from the Sun during observation at the radio telescope RATAN-600: 1 - during the observation by the "Relay" method on the northeastern sector, 2 - in the normal mode of observation on the southern sector with a periscope.

Fig. 2. Calculated positions of the solar and lunar disks at the moment of observation of the maximum phase of the solar eclipse on 29.03.2006 at the radio telescope RATAN-600.

Fig. 3. Superimposition of the Sun's radio emission record at the wave13 см (RATAN-600) on the image of the Sun in white light [Nelson et al., 2009] during the eclipse on 29.03.2006. 1 - boundaries of the vertical directivity diagram (v.d.n.a.) at wave1.03 cm; 2 - v.d.n.a. at wave13.0 cm. (On the vertical axis - antenna temperatures Ta, on the horizontal axis r/Rs - distance from the center of the Sun's optical disk in radii of the Sun's optical disk).

Fig. 4. Superimposition of records of the Sun's radio emission at wavelengths: λ = (1.03 -30.72) cm, obtained from observations of the maximum phase of the solar eclipse of 29.03.2006 on the radio-tele- scope RATAN-600, on the heliographic grid after subtracting the Moon's radio emission [Golubchina et al., 2008]. The wavelengths of the observations are indicated in the figures. The larger amplitude curve corresponds to an observation at a longer wavelength. The scale of values on the vertical axis - antenna temperature in degrees Kelvin - is shown in the figure by a vertical segment, while the horizontal axis shows r/Rs - distance from the center of the Sun's optical disk in radii of the Sun's optical disk.

Fig. 5. Records of radio emission of the Sun at wavelengths (1.03, 1.38, 2.7) cm during the maximum phase of the solar eclipse at the radio telescope RATAN-600 and the image of the Sun (He II304 A , SOHO). The maximum positions of the antenna temperature (Ta) values of the radio emission signals are identified with the position of the open western sickle of the Sun. The middle arrow indicates the position of the prominence (Pr.). S1 is the position of the rising local source No. 10866; S2 is the position of the Sun and Moon entering the knife-edge DNA of the radio telescope during a solar eclipse.

Fig. 6. Distribution of brightness temperatures (Tb, K) of radio emission at wavelengths (1.03-30.7) cm of the Sun's northwestern sickle, discovered during observations of the maximum phase of the solar eclipse on 29.03.2006 with a distance (r/Rs) from the center of the Sun. Here the designations: (6, 5, 4, 3, 2, 1) correspond to the measurements at λ = (30.7, 13, 6, 2.7, 1.38, 1.03) cm.

Fig. 7. Electron concentration distribution (n_e) from measurements at (1.03, 1.38, 2.7, 6.2, 13.0, 30.7) cm with distances from ~1 Rs to 2 Rs from the center of the Sun's optical disk according to observations of the northern polar region of the Sun during the maximum phase of the solar

eclipse on 29.03.2006.

Fig. 8. Electron concentration distribution for the northwestern limb of the Sun from brightness temperature measurements at the wave 1.03 cm. (min pol, min eq) - distribution of electron concentrations determined from numerous observations of the polar and equatorial regions of the Sun in white light during total solar eclipses during the period of minimum solar activity, (max pol) - from data for the pole during the period of maximum solar activity, and (Baum) - electron concentrations calculated using the Baumbach-Allen formula [Zheleznyakov, 1964].

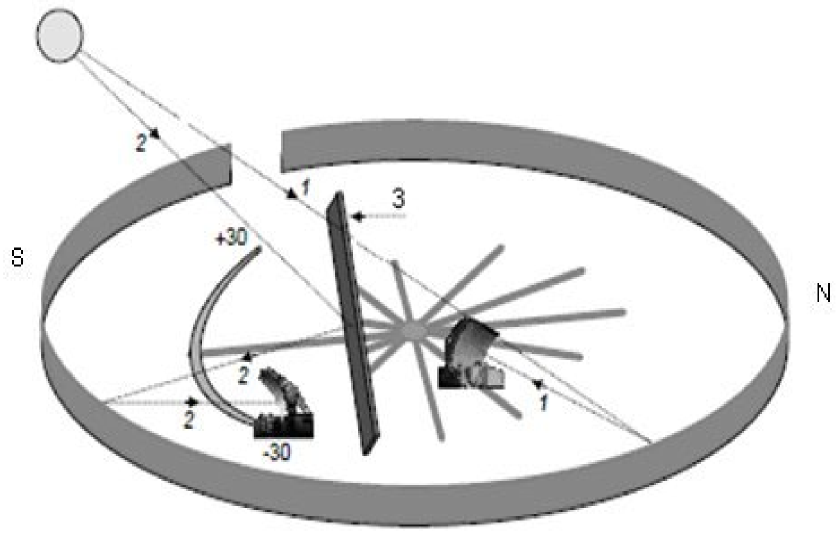

Fig. 1.

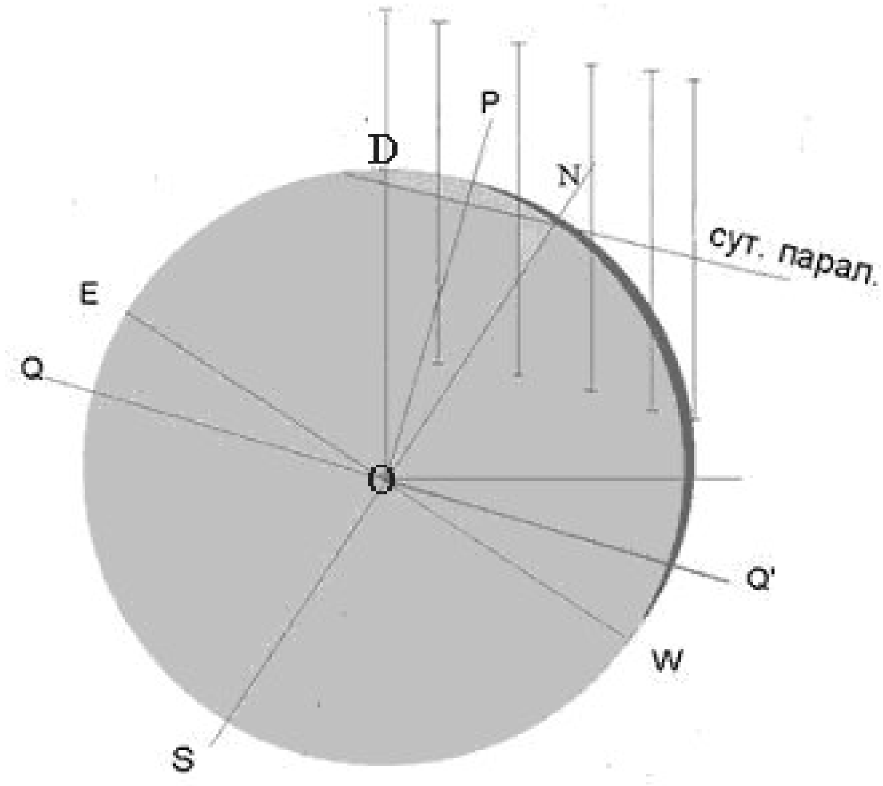
P
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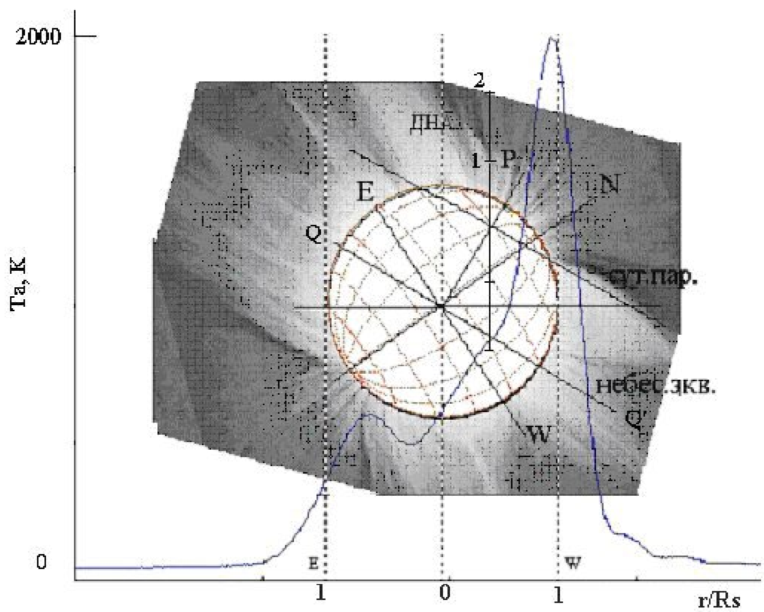
Fig. 2.


2000
Ta, K
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1
P
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1
r/Rs

Fig. 3.

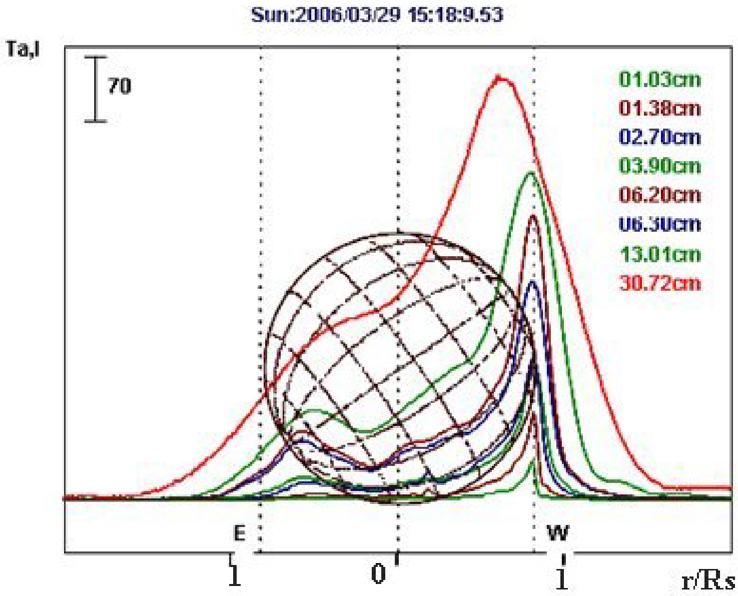
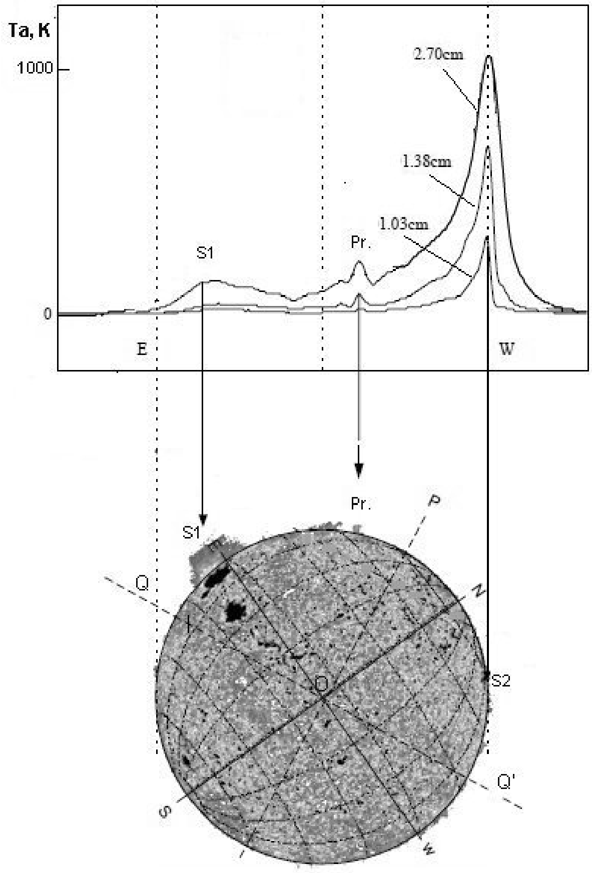

Sun:2006/03/29 15:18:9.53
Ta,I
70
01.03cm
01.38cm
02.70cm
03.90cm
06.20cm
06.30cm
13.01cm
30.72cm
E
W
1
0
1
r/Rs

Fig. 4.


Ta, K
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0
2.70cm
1.38cm
1.03cm
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Pr.
E
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S1
Pr.
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S
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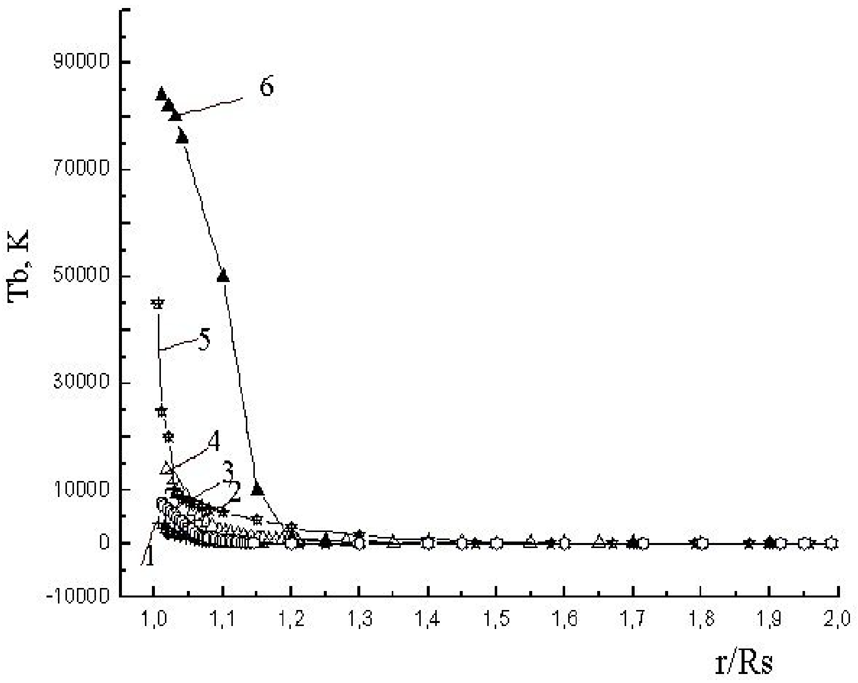
Fig. 5.



Tb, K
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6
5
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1,8
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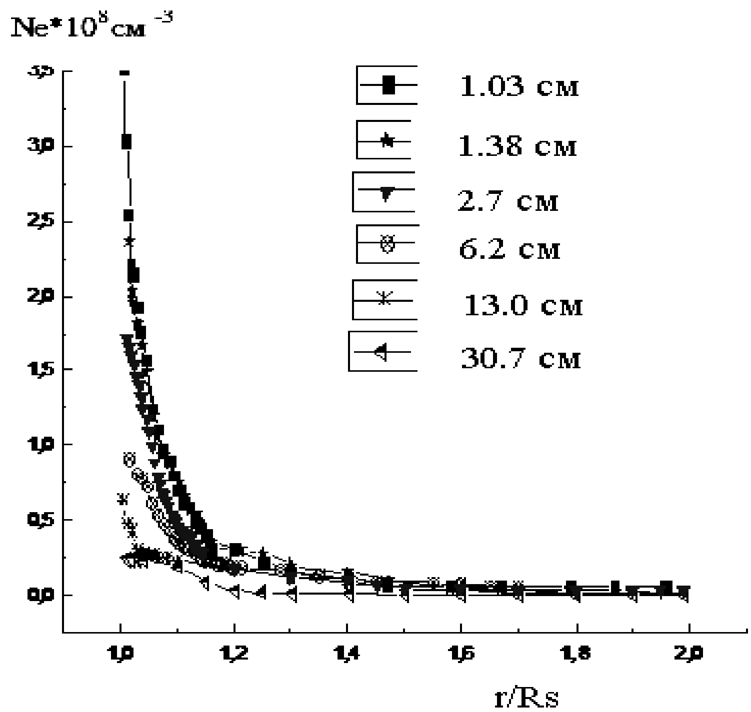
2,0
r/Rs

Fig. 6.



Ne*10^8см^-3
1.03 см
1.38 см
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6.2 см
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3,0
2,5
2,0
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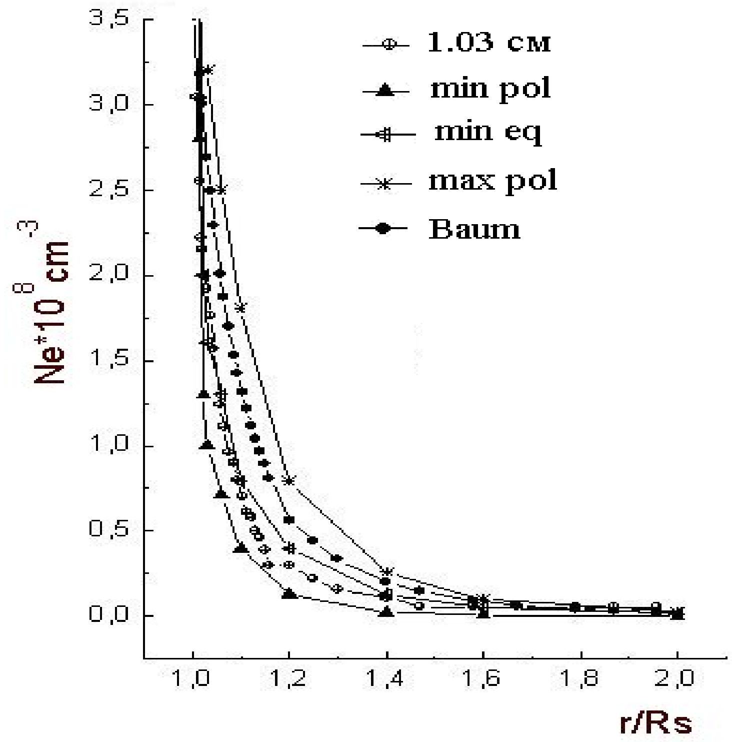
r/Rs

Fig. 7.



3,5
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1,0
0,5
0,0
Ne*10^8 cm^-3
1.03 см
min pol
min eq
max pol
Baum
1,0
1,2
1,4
1,6
1,8
2,0
r/Rs

Fig. 8.