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The structure of the chromosphere along the northern limb of the Sun according to eclipse observations with RT-22 PRAO AKTs FIAN at a wavelength of 1.4 cm

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Abstract. An acute problem in the study of the solar chromosphere is the following obvious contradiction between the results of radio astronomical measurements of the height (extension) of the chromosphere and model calculations made on the basis of classical standard atmospheric models: the height of the chromosphere according to radio data is significantly greater than the model calculations. This is largely due to the fact that the widely used models are based on UV observations and, in addition, are one-dimensional and do not take into account the strong structural inhomogeneity of the chromosphere. Numerous attempts to "improve" the models by introducing various elements of inhomogeneity and "fit" them to radio data are purely empirical and are not substantiated theoretically. In such a situation, it is important to obtain more accurate and reliable radio observation data. This is all the more important because such data can serve as a basis for testing the recently developed 3D inhomogeneous theoretical models of the solar atmosphere. The article presents new data obtained from observations of a partial solar eclipse on June 10, 2021, using the RT-22 radio telescope of the Lebedev Physical Institute at a wavelength of 1.4 cm: the estimate of the radio radius is not more than 13″. The contradictions mentioned above remain significant.

Keywords: Sun: chromosphere, radio radiation, solar eclipse

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1 Introduction

Back in the late 1940s, I.S. Shklovsky showed that the solar corona is almost completely transparent to the short-wavelength (millimeter and short-wavelength part of the centimeter) radio wave range. This explains the accepted point of view that the observed short-wave radio emission from the quiet Sun arises in the chromosphere. It is important to note that it is generated in thermal plasma due to the bremsstrahlung under LTE conditions, and the Rayleigh-Jeans approximation for the Planck function ensures direct proportionality of the measured brightness temperature of radio emission (T_{b}) to the plasma temperature (T_{e}). Thus, the use of observations of short-wave radio emission from the Sun turns out to be the most convenient means of diagnosing chromospheric plasma (Loukitcheva & Nagnibeda 2000; Loukitcheva et al. 2004). Shklovsky showed that in the presence of a hot corona and a sharp transition from the cold chromosphere to the corona (transition region), characteristic and significant effects should be observed in the short-wave part of the radio range (within the framework of one-dimensional 1D concepts): brightening towards the edge of the solar disk and a bright, more than 100%, ring on the limb (narrow spike on the radial distribution of radio brightness) (Shklovsky 1957). In subsequent decades and in our time, a large number of works, both observational and theoretical, have been devoted to the study of these effects.

Important work on the study of the chromosphere was carried out in the early 1950s based on optical observations of total solar eclipses; these results were collected and summarized by Thomas and Athey in the famous book "Physics of the Solar Chromosphere" (Nagnibeda & Piotrovich 1987). It is interesting that in this book the authors examined in a separate chapter the radio emission of the chromosphere and made a very important conclusion for the topic of the article: in order for the above limb effects to be "suppressed" (and doubts about this have already been expressed), the chromosphere must be inhomogeneous and contain cold absorbent structural elements. There, the authors proposed spicules in the role of such elements, and using the example of a very simple and "primitive" model, they showed this possibility. Subsequently, many researchers proposed more plausible models, including other elements, for example, coronal loops, selecting their parameters so as to obtain good agreement with observations. However all such attempts, despite the apparent success, are made purely empirically and are not theoretically justified.

Observations of limb effects require fairly high angular resolution and have been performed for many years during solar eclipses or with large radio telescopes and interferometers. Unfortunately, the results obtained strongly depend on the actual angular resolution and the method of processing observations (reduction), so the summary of results demonstrates a significant scatter of data (see review Nagnibeda

& Piotrovich 1987). In such conditions, of great interest is the value of the solar radio radius, which characterizes the altitudinal extent of the chromosphere, and the obtaining of which depends much less on angular resolution.

The main problem remains the obvious contradiction between the results of radio radius measurements and model calculations made on the basis of classical standard models of the atmosphere (VAL – FAL), that is, the height of the chromosphere according to radio data (radio radius) is significantly greater than model calculations, despite the strong scatter of observational values. Particularly convincing were the results of measurements made from observations of the total eclipse of July 11, 1991 by different groups of observers in the millimeter range, using different instruments and in different places. The length of the chromosphere turned out to be about 5000 km, which is more than twice the model value (Belkora et al. 1992; Bastian et al. 1993; Ewell et al. 1993; White & Kundu 1994; Nagnibeda & Rozanov 1998). This is largely due to the fact that widely used models are based on UV observations, are one-dimensional, and do not take into account the strong structural inhomogeneity of the chromosphere. Such discrepancies led to a heated debate between supporters of the model of cold and extended chromosphere and the authors of the VAL – FAL models, stimulated moreover by Zirin's polemical article "The Mystery of the Chromosphere" (Zirin 1996).

An important stage in the continuation of research was the development of modern realistic inhomogeneous 3D models of the chromosphere (http://sdc.uio.no/search/simulations) and modeling of solar short-wave radio emission on their basis (Loukitcheva et al. 2015). We simulated limb effects based on the same models (Nagnibeda et al. 2021).

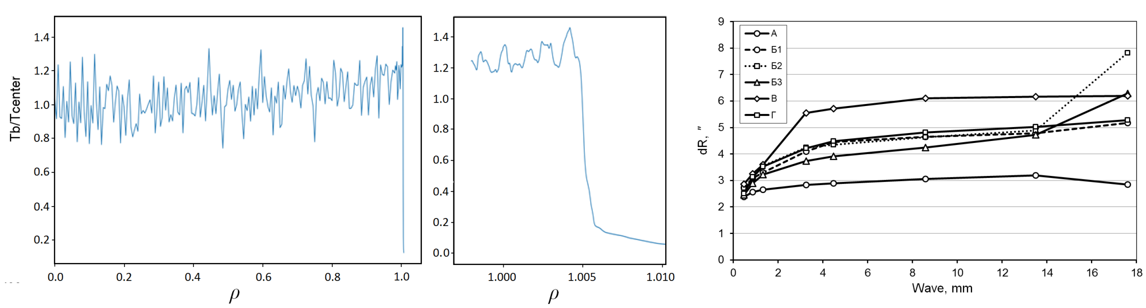

Fig. 1. Simulation results. On the left is the distribution of peak brightness temperature values along the surface of the Sun ($\rho = r/R_{\rm sun}$). In the center is the distribution of Tb at the edge of the Sun. On the right is the dependence of the change in the radio radius of the Sun on the wavelength for models with different types of chromospheric activity.

Qualitatively, the obtained results are similar to those observed ones: preservation of large fluctuations in brightness temperature along the solar surface in the mm wavelength range ("radio granulation"), absence of a sharp peak in brightness temperature on the limb, and a small change in the radio radius with wavelength (Fig. 1). However, the calculated values of the radio radius turned out to be significantly smaller than the observed ones, and the difference increases with increasing wavelength.

To obtain more accurate and reliable radio observation data, it is promising to use the modern unique ALMA instrument. Here it is important to mention observations of the Sun on a separate 12-m radio telescope ALMA, which confirmed previous radio data at short millimeter waves with better resolution (Alissandrakis et al. 2017).

2 Observations

Observations of eclipses make it possible to obtain better resolution even when using small radio telescopes. Theoretically, it can constitute small fractions of arcsec on cm waves. Of course, in real observations, such resolution cannot be obtained due to noise, the level of which is determined by the receiving equipment and control systems of the radio telescope, the state of the earth's atmosphere and the circumstances of the eclipse, etc. On the other hand, if the eclipse zone happens to include observatories with large modern radio telescopes, then their use for eclipse observations significantly improves the quality of the results due to the narrow beam.

Over the past 10 years, four solar eclipses have occurred, and large radio telescopes of Russian observatories fell within the zone of their partial phases. At the initiative of the first authors of the report, in 2021, coordinated observations were organized on large radio telescopes of observatories situated in the eclipse band: IAA RAS (RT-32 and RT-13), PRAO AKTs FIAN (RT-22) and Bauman MSTU (RT-7.5), covering a wide range of wavelengths from 2.5 mm to 13 cm (frequency 3–140 GHz).

The procedure for such observations consists of sequential pointing at a selected area of the solar disk and tracking it during the time when the area is closed or opened by the edge of the lunar disk. Within the scope of this article, we consider the observation of only the limbic regions, represented by contact regions 1 and 4.

Figure 2 shows fragments of the original signal recordings near the 1st and 4th eclipse contacts obtained on RT-22 at a wavelength of 1.4 cm, and the corresponding eclipse configurations. It is evident that the eclipse recordings are noisy, which introduces a noticeable uncertainty into the measured values.

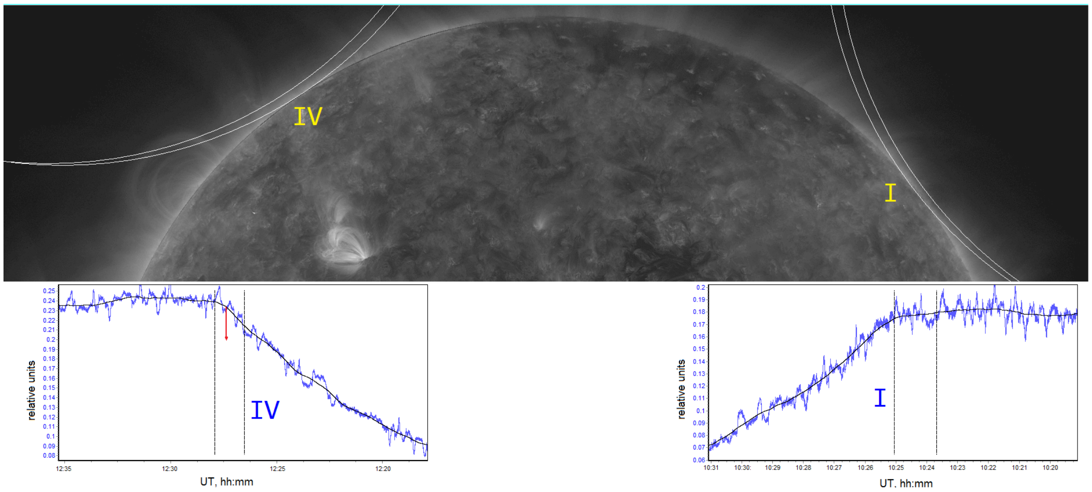

Fig. 2. Recordings near the 1st and 4th eclipse contacts. The vertical lines on the graphs correspond to the positions of the Moon's limb in the top figure. The lines located closer to the center of the disk correspond to the moments of contact. And those located further, to the moments of the Moon's edge reaching the upper boundary of the solar chromosphere.

3 Summary

The height of the edge of the solar atmosphere recorded at a wavelength of 1.4 cm is $\sim 17 - 20''$, but the estimate of the radio radius (measuring on the level 0.5 of full solar signal) based on the break in the IV contact record (red arrow) is less than $13''$. The results obtained are compared with previous measurements of the radio radius collected in Fig. 3, compiled in the paper (Ivanov et al. 2023). It is interesting that the results of our eclipse measurements on different instruments form a clearly distinguished group. Such a difference requires further analysis. One of the possible reasons may be the methodological difference in determining and measuring the radio radius. It is obvious however, that the difference in the estimates of the chromosphere extent obtained in the optical and radio ranges, which has been discussed for many years, remains significant, including the model test calculations that we performed earlier (Nagnibeda et al. 2021) for theoretical inhomogeneous models of the chromosphere and mentioned in Section 1 (Fig. 1). In Fig. 3 they are designated as ENW and CH models.

Within the error limits, the results of observations on the RT-22 PRAO and the RT-32, RT-13 IAA do not generally contradict each other.

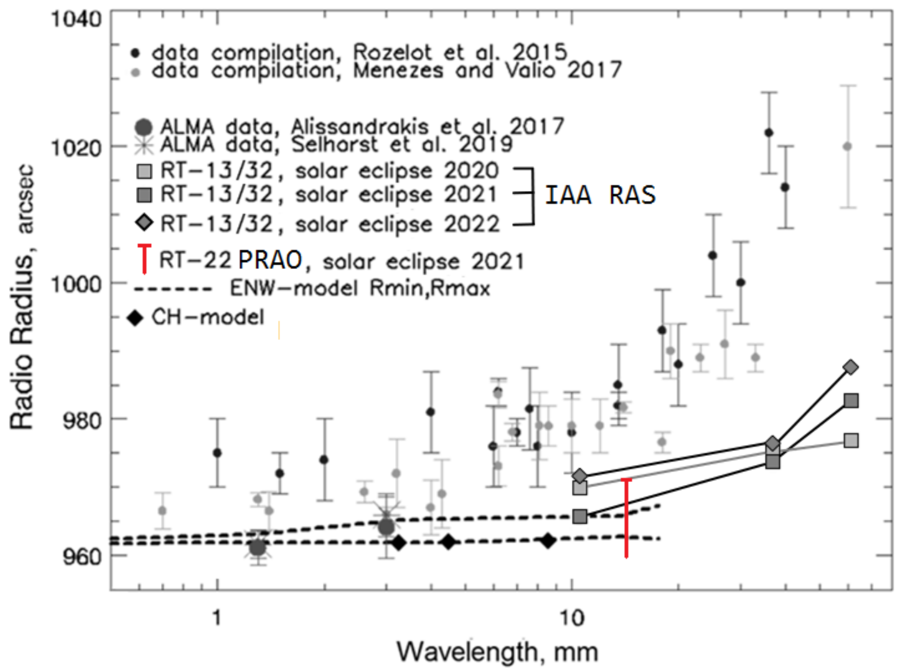

Fig. 3. Comparison of our results with previous measurements of the solar radio radius (Ivanov et al. 2023).

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