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EVOLUTION OF LOW-FREQUENCY RADIO ABSORPTION IN 3C461

Using the highly accurate and sensitive observations from July 13 to October 13, 2019, with the Giant Ukrainian Radio Telescope (GURT) in the correlation interferometer mode, we have investigated a monotonic trend of free-free absorption parameters from the absolute in-

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tegrated spectrum of 3C461 (Cassiopeia A) measured at low frequencies. The form and peak of this spectrum depend on the magnitudes of the emission measure, the electron temperature, and the average number of charges of the ions for the internal and external absorbing ionized gas toward the supernova remnant (SNR). The most interesting information concerns the evolution of unshocked ejecta inside the SNR. Its emission measure, average number of charges of the ions, and temperature can change with time, and the absorption on the two halves of the shell indicates how the ejecta are heating up. The study of the unshocked ejecta is a requisite step toward a better understanding of radio absorption evolution in Cassiopeia A. The trends from the GURT radio data were analyzed using the Mann—Kendall test and Sen's method. This analysis is the first attempt to detect changes in the absorption parameters inside and outside this evolving SNR using continuous, broadband, and highly sensitive observations. We took into account the possible influence of radio interference on the trend detection results. Our study shows no trend in the absorption parameters. A possible reason for this result could be either the relatively short observation interval, together with the very slow change in absorption parameters, or the uneven nature of the changes in the evolution of absorption. Further measurements of the absolute flux-density spectrum obtained from Cassiopeia A with the help of low-frequency correlation interferometers (implemented on GURT, URAN-2, NenuFAR, and other appropriate radio telescopes) may contribute to the elucidation of the astrophysical processes responsible for thermal absorption in the SNR.

***Keywords**: radio astronomy observations, thermal absorption, supernova remnant, interstellar medium, Mann—Kendall test*

INTRODUCTION

The evolution of supernova remnants (SNRs), from the explosion to the end of the expansion, consists of several different stages [26]: the ejecta-dominated phase, the Sedov-Taylor phase, the snow-plough phase, and the merging phase. Investigations in the radio domain allow us to observe the properties of SNRs, the physical processes within them, and their evolutionary characteristics as well. The features of SNR radio spectra (peak, spectral index, form) differ across the various stages of SNR evolution. Ukrainian researcher Shklovskii [20, 21] was the first to notice a fundamental feature in the evolutionary picture between the flux and radius of an SNR, known as the Σ–D relation. In this regard, the forms of radio spectra are used to determine the evolutionary status of SNRs [24].

Cassiopeia A (3C461, Cas A) is one of the youngest Galactic SNRs, about 330 years old. It is unique for many reasons. Being very bright, Cas A is often used as a calibration source in radio astronomy [3, 14]. On the other hand, its flux decline is rather strong, determined by the age of the object. This has made it possible to study the flux evolution of Cas A for more than 70 years, and the accuracy of radio measurements is constantly growing. Kassim et al. [13] were the first to prove that the radio spectrum of Cas A (<100 MHz) is determined by the thermal absorption of radio emission in unshocked ejecta inside the shell of Cas A, as well as by external ionized gas in the interstellar medium (ISM). To study the various effects that may shape the morphology and spectrum of Cas A at low frequencies, Arias et al. [2] analyzed observations with the Low Frequency Array (LOFAR, see [25]). This method is based on low-frequency maps of Cas A and permits obtaining the emission measure of unshocked ejecta in the SNR. This value can also be found by an alternative method suggested by Stanislavsky et al. [23]. This approach allows measuring the thermal absorption parameters both inside and outside Cas A. These parameters are determined from the integrated radio continuum spectrum of this radio source, recorded by the GURT correlation interferometer with high accuracy and sensitivity. As applied to the spectrum, the absorption parameters are essentially fitting values responsible for its form. The purpose of this paper is to develop the GURT method for probing the unshocked ejecta of CasA evolving over time. It uses relative measurements of the flux density of Cas A with respect to a reference radio source, which is the radio galaxy Cygnus A (Cyg A). At low frequencies, the radio source (3C405) is close in flux density to the Cas A source. Moreover, the radio spectrum of Cyg A is almost unchanged over time.

This paper is structured as follows. We start with a brief description of the experimental facilities, which permit measuring the radio spectrum of Cas A at low frequencies. By comparing this obtained spectrum over several months with its model — which takes into account the absorption of radio emission from the synchrotron source inside Cas A through a large amount of ionized material in Cas A — we find the absorption parameters typical for each day of observations. Their evolution over time is investigated with the help of statistical trend estimators. Finally, we summarize our results and discuss possible explanations for them.

Method. In this study, we use a comprehensive analysis of the radio spectral emission from Cas A. It includes several procedures considered below. The aim is to detect trends in the radio absorption parameters characteristic of the integrated radio spectrum of Cas A.

INTERFEROMETRIC MEASUREMENTS

The GURT radio telescope can be configured as a two-element interferometer [16]. Its geographical location (49.6° N) is very convenient, which ensures our observations of the sources Cas A and Cyg A at almost the same zenith angle at the time of their upper culminations. Using the two GURT sub-arrays with 5 × 5 active cross-dipoles each, the interferometer has a baseline of about 60 meters. To provide a correlation mode, the sub-arrays were connected to a standard backend for the GURT observations [28]. This advanced digital receiver (ADR) has a frequency resolution of 19.073 kHz with a time averaging of about 1 sec. It can measure and record the cross-spectra from both sub-arrays in the frequency range of 8—80 MHz. Thus, the interferometer with a small baseline was implemented and used for the radio observations of Cas A. The advantages of this approach are considered in detail [23] while minimizing its disadvantages.

Each session of radio observations lasted about 7 hours, using the transit of both radio sources. The observation time of each session was divided roughly equally between Cyg A and Cas A. First, the mini-arrays were pointed to the point of Cyg A's culmination, observing Cyg A for about 100 minutes before and after its culmination time. Then, the mini-arrays changed the direction of signal reception to the point of Cas A's culmination in the sky for the next radio observations, lasting approximately 100 minutes before and after its culmination. Although the interferometric observations of Cyg A and Cas A were made from May to October, the largest number of successful sessions were completed from July 13 to October 13. Their schedule is visualized in Fig. 1 and consists of 51 different days of observations. The choice of these days was influenced by the fact that, during the research process, the observation technique was

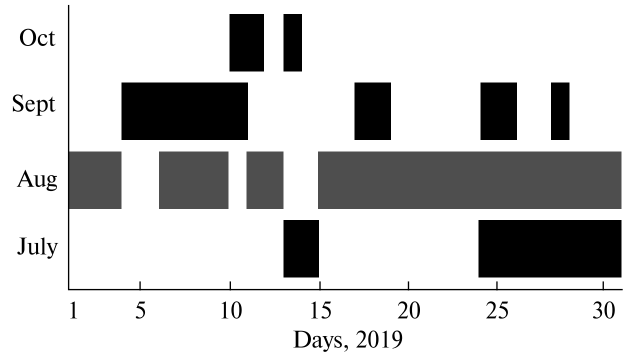

***Figure 1*.** Schedule for the radio observations of Cas A and Cyg A from July 13 to October 13, 2019. The grey bars indicate the available days in the specified period

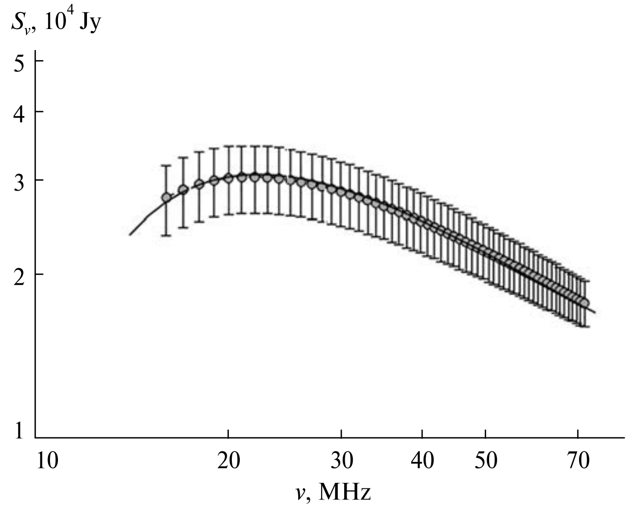

***Figure 2*.** The radio spectrum of Cas A measured at the frequency range 16...72 MHz with the GURT two-array interferometer on July 25, 2019, as an example of observations listed in Fig. 1. The fitting line corresponds to the theoretical model accounting for radio absorption in this SNR with the following parameters: $EM_{int} \approx 37.36$ pc cm^{-6}, $EM_{ISM} \approx 0.16$ pc cm^{-6}, $f_a \approx 0.82$, $T_{int} \approx 100.02$ K, $Z_{int} \approx 2.56$, $T_{ISM} \approx 20.03$ K, $Z_{ISM} \approx$ ≈ 0.53

simultaneously refined, and the performance of the mini-arrays was tested, which were not always favorable due to various technical reasons. Nevertheless, their total number was sufficient for our subsequent analysis. Using the records of radio emission from Cyg A and Cas A, we can find the ratio of flux densities of the radio sources for each day of observations. It should be recalled that the Cyg A radio emission serves as a reference source with a well-known flux density at low frequencies. This allows us to obtain integrated spectra for Cas A from 16 MHz to 72 MHz in 1 MHz steps from day to day. An example of such a radio spectrum is shown in Fig. 2.

FROM THE SPECTRAL DATA TO ABSORPTION PARAMETERS

With the radio spectra of Cas A, we can determine the free-free absorption parameters by fitting the experimental results to a theoretical model. It is these values that we are going to analyze for the presence of changes over time. The model accounts for the absorption inside and outside Cas A, making it possible to align theoretical concepts with experimental results [6]. Now let us discuss it in more detail below.

The synchrotron source inside Cas A generates radio waves characterized by the flux density $S_\nu = AJ_\gamma(\nu/\nu_1)$ depending on three parameters: γ, ν_1, and A. As a model of the synchrotron source, we use a homogeneous cylindrical representation [18] written as

$$J_\gamma(z) \sim z^{2.5}(1-\exp(-z^{-2-\gamma/2})),$$

where $z = \nu/\nu_1$ is the normalized frequency, and γ relates to a power-law distribution of electrons $N(E) = N_0E^{-\gamma}$. Based on the experimental measurements of the Cas A flux density at the frequency of 1 GHz, as well as the magnetic field strength B equal to 0.78 mG [2], we determine $\gamma = 2.52$, $\nu_1 = 6.15$ MHz, and $A = 140500$ Jy.

The synchrotron emission propagates to observers through the SNR and the ISM, where it is absorbed by intervening thermal gas. The absorption includes two components. One of them is internal, conditioned by the unshocked ejecta inside the SNR. The other is external, caused by the ISM around the SNR. Consequently, the full flux density of Cas A takes the following form

$$S_\nu = (S_{\nu,front} + S_{\nu,back}e^{-\tau_{\nu,int}})e^{-\tau_{\nu,ISM}},$$

where $\tau_{\nu,int}$ and $\tau_{\nu,ISM}$ are the optical depths for the unshocked ejecta and the ISM, respectively [2]. Due to the clumpy character of the radio source Cas A, the relative synchrotron brightness contributed from the front and back halves of the SNR, as viewed from Earth, differs. Taking $S_{\nu,front} = f_aS_\nu$, and $S_{\nu,back} = (1 - f_a)S_\nu$, we consider the absorption on the two halves of the shell. Then the optical depth τ_ν is found from the Rayleigh — Jeans approximation [27], namely

$$\tau_\nu = 3.014\times10^4 Z\left(\frac{T}{K}\right)^{-3/2} \times\left(\frac{\nu}{\mathrm{MHz}}\right)^{-2}\left(\frac{EM}{\mathrm{pc}\times\mathrm{cm}^{-6}}\right)g_{ff},$$

where EM is the emission measure, Z is the average number of ion charges, T is the electron temperature of the absorbing medium, and g_{ff} denotes the Gaunt factor given by

$$g_{ff} = \begin{cases} \ln\left[49.55Z^{-1}\left(\frac{\nu}{\mathrm{MHz}}\right)^{-1}\right] + 1.5\ln\frac{T}{K}, \\ 1 \text{ for } \frac{\nu}{\mathrm{MHz}} \gg \left(\frac{T}{K}\right)^{3/2}. \end{cases}$$

Assuming that the flux-density evolution of the synchrotron source in Cas A occurs noticeably slower than the absorption parameters of an ionized gas inside and outside the SNR, the fitting of an experimental radio spectrum to the theoretical curve S_ν under absorption is defined by seven parameters. To find their values, the nonlinear curve fitting in least-squares sense is used. Consequently, we determine a set of values: EM_{int}, EM_{ISM}, f_a, T_{int}, Z_{int}, T_{ISM}, and Z_{ISM} for each observation day. Finally, the ultimate goal of our analysis is to identify the presence and determine features of any trend in these values over time. We will achieve it with the help of statistical tests, as these changes are very small over such a relatively short time interval.

TREND ANALYSIS

Trend detection is one of the most important tools in studying time series data. There are both parametric and non-parametric tests for the trend analysis [9]. Parametric tests are more powerful, but they require more specific conditions regarding the data properties. The time series must be independent and normally distributed. In turn, non-parametric trend tests are applicable for data with any probabilistic distribution. Moreover, they are less sensitive to outliers, although the data under consideration must remain independent. Our measured datasets are not normally distributed, as they can only be positive. Therefore, we prefer non-parametric trend tests.

The Mann — Kendall (MK) trend test [15, 17] is widely used as a non-parametric test to detect significant trends in time series, say x. Its test score does not depend on the presence of missing data (no measurements) or irregularly spaced measurement periods.

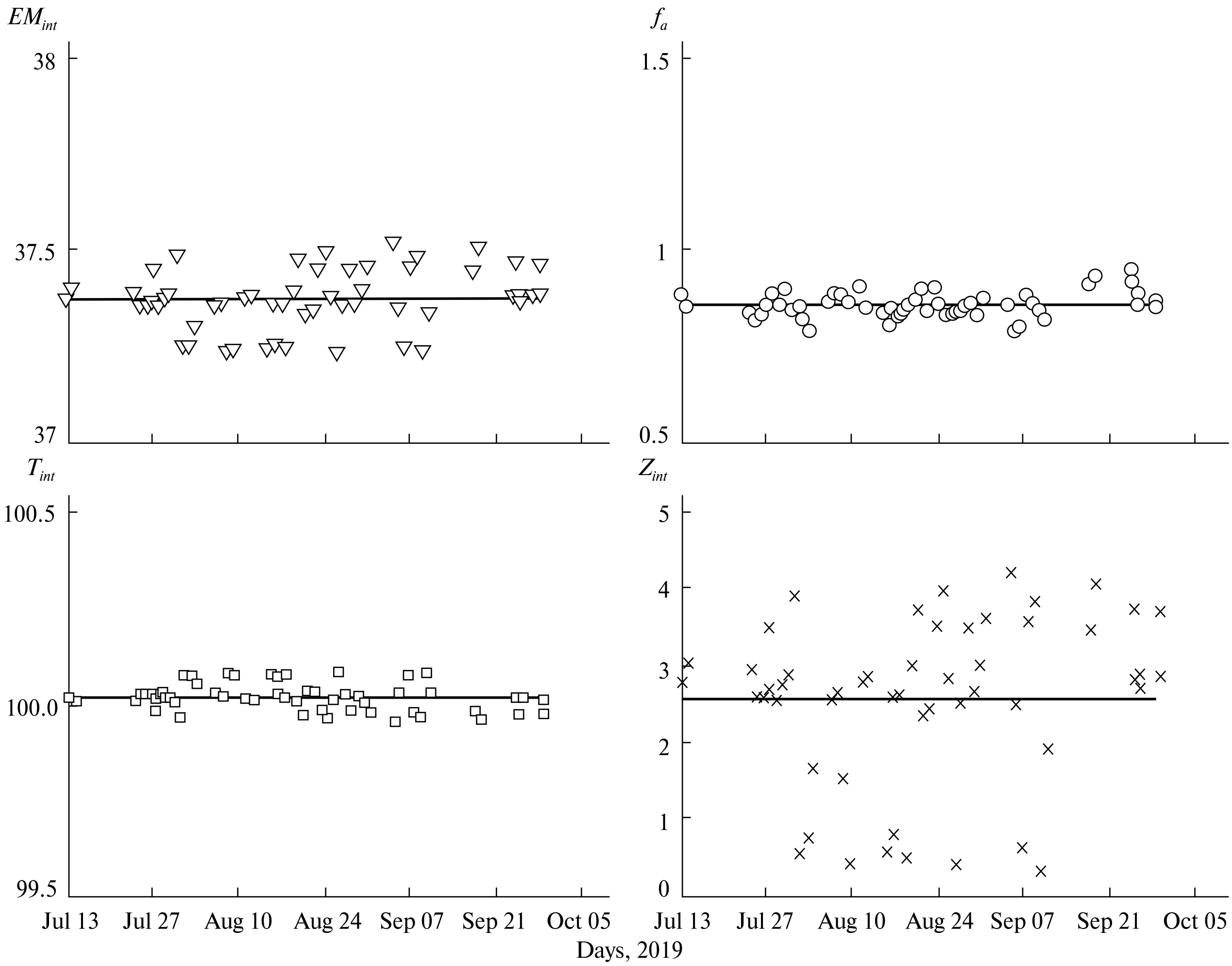

Figure 3. Evolution of thermal absorption parameters in the unshocked ejecta of Cas A, according to the GURT observations from July 13 to October 13, 2019. Lines indicate the rate of change in these values, obtained from the Sen slope estimator

Also, note that for the MK trend test, it doesn't matter if the trend is linear or non-linear. That is why it is very popular in hydro-meteorology [10] and other natural sciences. Among the wide variety of such applications, we recall only cases related to astrophysics. For instance, this test is applied to the examination of the pulsation dynamics of Betelgeuse by studying the characteristics of the light curve prior to a critical transition [8]. Additionally, the MK test was useful for the study of maxima extreme events related to the solar activity cycle [1]. This test examines the sign of all pairwise differences of observed values. It begins with the calculation of the following sign statistic

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) ,$$

where n is the number of data points, and the function $\operatorname{sgn}(x)$ assigns the integer value of 1, 0, or -1 to positive differences, no differences, and negative differences, respectively. If the value S is very high positive, this indicates an upward trend, whereas a very low negative value S corresponds to a downward trend. Throughout the time series, each value is compared with its preceding value, giving $n(n-1)/2$ pairs of sign values. In the case of absorption parameters, the value n is equal to 51, and the number of pairwise comparisons reaches 1275. The variance of statistics S reads

$$VAR(S) = \frac{1}{18}(n(n-1)(2n+5) -$$
$$- \sum_{k=1}^{m} w_k (w_k - 1)(2w_k + 5)),$$

where m represents the number of tie groups of the time series x, and w_k is the number of data of k^{th} tie groups. In a tied group, a set of sample data has the same value. Next, the standardized test statistic Z_{MK} is computed as

$$Z_{MK} = \begin{cases} \dfrac{s-1}{VAR(S)}, & \text{if } S > 0, \\ 0, & \text{if } S = 0, \\ \dfrac{s+1}{VAR(S)}, & \text{if } S < 0. \end{cases}$$

Positive values of Z_{MK} indicate increasing trends, while negative Z_{MK} values show opposite trends. For the results of this analysis to be statistically significant, the original MK test considers two hypotheses: null and alternative. For a given time series, the null hypothesis H_0 assumes it is independently distributed (no trend), while the alternative hypothesis H_1 is that a monotonic trend exists. The trend can be positive, negative, or non-null. The null hypothesis is rejected if the absolute value of Z_{MK} is larger than the theoretical value $Z_{1-\alpha/2}$ obtained from the standard normal distribution, where α is the statistical significance level concerned. Usually, the value $\alpha = 0.05$ is taken. At the 5 % significance level, if $|Z_{MK}| > 1.96$, the null hypothesis of no trend is rejected.

If a significant trend is found, the rate of change can be calculated using the Sen slope estimator [11]

$$\beta = \text{median}\left(\frac{x_j - x_k}{t_j - t_k}\right)$$

for all $k < j$ and $k = 1, 2, ..., n-1$ and $j = 2, 3, ..., n$. Note that the median of those slopes is determined for all pairs of data used to compute the variance value S.

RESULTS

Stationary and non-stationary states coexist in most astrophysical systems [7]. Statistical tests such as the MK test recognize the non-stationary components, which are deterministic, apart from random stationary components. Non-stationarity often arises from the evolution of systems and can have many different sources [22]. Cas A is one such example. It expands in space, but it also interacts with the circumstellar medium (CSM) and eventually with the ISM, generating particle-accelerating shocks. The capability of the MK test to recognize a significant trend lies in how much the non-stationary (trend) components are stronger than the stationary (random) components. Thus, accepting the null hypothesis (no trend) may also indicate changes that are still too small to be detected as a trend.

Thermal absorption parameters, according to the interferometric data recorded from July 13 to October 13, 2019, exhibit fluctuations. This trend analysis shows no trend in the changes in absorption parameters. The evolution of unshocked ejecta inside Cas A happens very slowly so that the emission measure EM_{int}, the average number of charges of the ions Z_{int}, and the temperature T_{int} do not show any trend during three months. Their horizontal slopes are presented in Fig. 3. Such a level of evolution for the thermal absorption parameters permits finding their average values, which were established by Stanislavsky et al. [23].

Although the MK test is quite robust and effective, it still requires that the data be independent. Any fairly strong serial correlation acts against the test's robustness. In particular, its presence can lead to an incorrect interpretation of the null hypothesis of no trend [5]. There is some reason to expect autocorrelation in the obtained data for Cas A. One of them is connected with radio frequency interference (RFI) in spectral data. When RFI is removed from radio records, the missing data points are smoothed by the median or otherwise, which causes a correlation to appear. From the autocorrelation plot of absorption parameters, it follows that there is a slight autocorrelation in the first lag that we can ignore. Nevertheless, even if this effect is not too large, it would be useful to eliminate it. To overcome this issue, two main methods were suggested to eliminate serial correlation [10]. One method uses pretreatment of the data, and the second involves modifying the MK test to improve trend analysis. Using the Python package of different modified MK trend tests [12], the time series of each absorption parameter was examined. After this analysis, the main conclusion (no trend) remains true. This indicates that the serial correlation was rather weak, as expected.

Following Arias et al. [2], the term for internal absorption $f_a + (1-f_a)\,e^{-\tau_{\nu,int}}$ can vary with time. If the cold ejecta were continuously encountering the reverse shock, the ejecta would be heating up. The free expansion leads to a decrease in the density of the gas over time as well as the optical depth τ_ν. However, from our GURT observations, the evolution of internal absorption shows no trend. This analysis does not discard the assumption of Arias et al. [2]. Probably, this detection is typical for the unshocked ejecta in the 2019 epoch, and subsequent longer measurements will bring clarity to this issue.

The temporal interval of observations in this work may be too short to detect trends in external absorption parameters using the MK trend test. This effect could serve as a tracer of the interaction of Cas A with its surrounding medium, namely the ISM, along the line of sight. Recently, the importance of such interactions between SNRs and their environs has been highlighted by Castelletti et al. [4]. However, more robust results for the evolution of ionized material properties outside Cas A require long-term observations of its integrated spectrum.

CONCLUSIONS

We have shown that the GURT method can be used for probing unshocked ejecta in Cas A. Moreover, the highly accurate and sensitive observations with the GURT correlation interferometer allow for the absolute flux-density measurements of radio sources at low frequencies. Emission measure, electron temperature, and the average number of charges of the ions for both internal and external absorbing ionized gas toward Cas A become observational characteristics. This provides a direct link between radio observations and theoretical models. From a wider astrophysical perspective, this method can be applied to other SNRs that are bright enough, young, and located in the Northern Hemisphere. Although our measurements from July 13 to October 13, 2019, do not show any significant trend in the evolution of thermal absorption inside and outside Cas A, this does not mean that it is absent altogether. There may be several reasons for this result. First, the observation interval was too short. More likely, the reason may be the very uneven nature of the changes in the absorption parameters. This interesting feature deserves further observations and comprehensive analysis. The study of the absolute flux-density spectrum obtained from Cas A with the help of low-frequency correlation interferometers (implemented on GURT, URAN-2, NenuFAR, and other appropriate radio telescopes) may contribute to a better understanding of the astrophysical processes responsible for thermal absorption in the SNR. Nevertheless, our observations of Cas A indicate that, on average, the unshocked ionized ejecta has a temperature $T_{int} \approx 100$ K, an average ionization state of $Z_{int} \approx 2.55$, and an average emission measure of $EM_{int} \approx 37.36$ pc cm^{-6}, while the ISM absorption along the line of sight to Cas A is characteristic of $EM_{ISM} \approx 0.17$ pc cm^{-6} for a 20K ISM. Moreover, the value $f_a \approx 0.86$ shows that 86 % of the emission emerging from the region projected against the unshocked ejecta came from the foreground side of Cas A. These values are reasonably consistent with other recent results in the literature [2, 4, 23].

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ЕВОЛЮЦІЯ НИЗЬКОЧАСТОТНОГО ПОГЛИНАННЯ У ЗАЛИШКУ НАДНОВОЇ 3С461

Використовуючи високоточні та чутливі спостереження з 13 липня по 13 жовтня 2019 року на Гігантському Українському радіотелескопі (ГУРТ) у режимі кореляційного інтерферометра, ми дослідили наявність монотонного тренду параметрів вільно-вільного поглинання з абсолютного інтегрального спектру об'єкту 3С461 (Кассіопея А) за допомогою вимірювань на низьких частотах. Форма та пік цього спектру залежать від величин міри емісії, температури електронів і середньої кількості зарядів іонів для внутрішнього та зовнішнього поглинання іонізованого газу у цьому залишку наднової (ЗНН). Найцікавіша інформація стосується еволюції викиду всередині ЗНН, який утворився не внаслідок ударного процесу. Його міра емісії, середнє число зарядів іонів і температура можуть змінюватися з часом, а поглинання на двох половинах оболонки вказує на те, як нагрівається викид. Вивчення змін викиду, який утворився не внаслідок ударного процесу, є необхідним кроком до кращого розуміння еволюції теплового поглинання в Кассіопеї А. Тенденції змін радіоданих ГУРТ аналізувалися за допомогою тесту Манна — Кендалла та методу Сена. Цей аналіз є першою спробою виявити зміни параметрів поглинання всередині та поза цим ЗНН за допомогою тривалих високочутливих широкосмугових спостережень. Ми врахували можливий вплив радіоперешкод на результати визначення тренду. Наше дослідження не показує тенденції до змін параметрів поглинання. Можливою причиною такого результату може бути або відносно короткий інтервал спостережень разом із дуже повільною зміною параметрів поглинання, або нерівномірний характер змін в еволюції поглинання. Подальші вимірювання спектру абсолютної глибини потоку, отриманого з Кассіопеї А, за допомогою низькочастотних кореляційних інтерферометрів (впроваджених на ГУРТ, УРАН-2, NenuFAR та інших відповідних радіотелескопах) можуть сприяти з'ясуванню астрофізичних процесів, відповідальних за теплове поглинання в ЗНН.

Ключові слова: радіоастрономічні спостереження, теплове поглинання, залишок наднової, міжзоряне середовище, тест Манна — Кендалла