Advanced stream search for galaxy clusters with multifrequency microwave data

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Abstract. Based on the data from the Westerbork Northern Sky Survey performed at a frequency of 325 MHz in the range of right ascensions $0^h \leq \alpha < 2^h$ and declinations $29^o < \delta < 78^o$ and using multifrequency Planck maps, we selected candidate objects with the Sunyaev-Zeldovich effect. The list of the most probable candidates includes 381 sources. It is shown that the search for such objects can be accelerated by using a priori data on the negative level of fluctuations in the CMB map with remote low multipoles in the direction to radio sources.

1 Introduction

A great amount of observation data coming from ground-based and space telescopes make it possible to considerably increase a number of members of small populations of astrophysical objects within stream data processing using the correlation analysis. The Planck mission of the European Space Agency (ESA) is one of space experiments, the analysis of whose data still continues. The total amount of data available for scientific analysis makes several terabytes and requires automated processing, searching, and identifying objects with specified characteristics. Still, some of the objects observed in sky maps are missed in the published catalogs. The problem of incomplete catalogs can be solved with the help of new algorithms and codes sensitive to topological, statistical, and spectral characteristics of multi-frequency maps of space missions. In such a way, it will be possible to increase a number of identified objects in the current catalogs and to carry out cosmological studies using all the available data. In the last decade, several surveys have been conducted in observational astrophysics which made it possible to improve the accuracy (better than 1%) of measurements of cosmological parameters. The experiments dealing with measurements of inhomogeneities of the cosmic microwave background map at the NASA WMAP [1] and ESA Planck [2] space observatories stand out among these surveys as well as the Baryon Oscillation Spectroscopic Survey (BOSS) [3] being carried out within the study of baryon acoustic oscillations as a part of the Sloan Digital Sky Survey III [4]. Analysis of the data from these surveys resulted in determination of cosmological parameters with an outstanding level of accuracy and construction of a modern evolutionary model of the Universe from the first split seconds of its

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existence to our days. The study of galaxy clusters observed due to the Sunyaev-Zeldovich effect [5] in the millimeter and submillimeter ranges and also in the X-ray range in which hot gas radiation is observed and simply in the visible range remains one of top directions in cosmological studies. These studies allow us to trace the evolution of masses of clusters and the features of formation of a large-scale structure of the Universe in various cosmological epochs. Significant extension of the list of galaxy clusters in the millimeter range is associated with the appearance of multi-frequency measurements of the microwave radiation such as Planck [6], SPT [7], and ACT [8] experiments. First data from the Planck observatory showed that the documented amount of galaxy clusters (about 1.6 thousand) observed with the help of the SZ-effect, is significantly (by 2 orders) smaller than expected from the data of optical surveys and modeling. Some selection effects can influence the detection of galaxy clusters with the SZ-mechanism. These are: the difficult-to-remove background emission of our Galaxy, point radiation sources, whose contribution to the microwave background covers the depth of the SZ-effect, and the dependence of the radiation amplitude determined by this effect on the mass of clusters which can have a relatively large scatter. It is also important to notice that radio sources are also used to study the distant Universe [9–11]. Due to the set of their physical properties, radio sources are a powerful tool for testing cosmological epochs. They are associated with searching for the most distant active nuclei of galaxies [12, 13], for protoclusters [14], estimating the background object clustering at different redshifts [15], and investigating the gravitational lensing. Taking into account the possibilities of millimeter and submillimeter surveys, the problem of searching for galaxy clusters with radio sources both at small and great redshifts naturally arises with the help of the Sunyaev-Zeldovich effect. In this paper, we check the possibility of detecting the SZ-effect in the vicinity of radio sources from low-frequency WENSS survey [16] using multifrequency microwave maps of the Planck space mission [17]. This work follows our previous paper [18].

2 Planck data

Planck data, thanks to better angular resolution (about 5′) and sensitivity than those of WMAP, allowed one to carry out investigations of both point sources with different populations and extended ones with sizes from several to tens minutes of arc, associated with galaxy clusters. In this regard, when studying galaxy clusters in the microwave range, the Planck space observatory played the most significant role, and the all-sky maps constructed as a result of its operation at nine frequencies of the microwave range (30, 44, 70, 100, 143, 217, 353, 545, and 847 GHz) are the basis for a large number of studies conducted in scientific institutions of different countries. Maps of the Planck space mission1 [19] of the European Space Agency became available to the scientific community in 2013 and immediately became an effective tool in solving many issues of galactic and extragalactic astronomy. In addition, catalogs of detected sources radiating in the millimeter and submillimeter range of the galactic and extragalactic origin were presented. Archives of the Planck mission (Planck Legacy Archive–PLA2) contain both maps of radiation components and lists of detected objects including galaxy clusters with the thermal Sunyaev-Zeldovich effect. The SZ-effect is associated with the inverse Compton interaction of CMB photons and free electrons of hot gas of galaxy clusters. As a result of scattering, the effective spectrum deviates from the black body one. The only arbitrary parameter is the comptonization parameter Y_{SZ} which is described simply by the amplitude. The microwave spectrum of the galaxy cluster observed as a result of the SZ-effect leads to a negative signal at frequencies of 30-143 GHz and a positive signal at frequencies above 217 GHz. This feature is a unique observational manifestation that allows one to distinguish it among other background variations. Since the effect is weak, it can be detected only for the brightest galaxy clusters. For fainter objects, the Y_{SZ} map becomes sensitive to both modeling parameters and systematic errors. The task of detecting and studying galaxy clusters based on the Sunyaev-Zeldovich effect is one of the most important among those scheduled in the Planck mission, as well as in other modern CMB studies with a good angular resolution [20–22]. The SZ-effect has a number of advantages when studying galaxy clusters. The comptonization parameter Y_{SZ} which is used to measure the integrated gas pressure along the line of sight and the amplitude of the SZ-signal does not undergo cosmological attenuation with respect to the surface brightness. This makes the SZ-effect a powerful method of searching for galaxy clusters at great redshifts. From the total SZ-signal integrated over the angular size, the total thermal energy of the gas is directly measured and, consequently, the mass with which the temperature of the gas is expected to correlate. Based on the results of 29-month observations of the Planck mission, a catalog was prepared containing 1653 galaxy clusters and cluster candidates, in which the SZ-effect appears. Of these, 1203 are confirmed by optical observations. The presented catalog covers an area occupying 83.5% of the sky and is the largest and most complete including 1094 objects with known redshifts up to $z \sim 1$. The masses of clusters are distributed over a fairly wide range–$(0.1 - 1.6) \times 10^{15} M_{\rm sun}$.

3 Algorithm development

3.1 Object selection

We develop the method previously proposed [23] for selecting galaxy cluster candidates using catalogs of radio sources and maps of cosmic microwave background radiation. The principle of the method is using cosmological properties of formation of powerful extragalactic radio sources. Such objects belong to a population of the highest-luminosity galaxies which makes it possible to study them at large redshifts and, therefore, to use them as probes of the state of the Universe in other cosmological epochs. An extremely important point in the study of these sources is the fact that their parent galaxies are giant elliptical galaxies (gE) which, generally, can be used as standard rulers and clocks [11, 24, 25]. Although, it should be noted that the most powerful radio sources are galaxies in the period of great merging, as a result of which gEs are formed, as well as the fact that not all gE galaxies are parent objects for powerful radio sources. Another point related to giant elliptical galaxies is that their study is important when investigating the evolution of stellar systems at large redshifts, searching for distant galaxy groups or galaxy protoclusters in the center of which they are located, and studying the processes of merging and interaction which can be indicated by the noticeable activity of their nuclei. The epoch, during which the peak of galactic mergers takes place, continues in the Universe of an age from 1.5 to 4 billion years which corresponds to redshifts from 5 to 1.2 in the standard ΛCDM cosmological model (a model with the dominating dark energy and cold dark matter). For example, in paper [14] devoted to the study of the environment of distant radio galaxies from observations of Ly-α, the redshift was measured and a conclusion was made about their belonging to a protocluster using the data on the density of objects. It was shown that 75% of radio galaxies with $z > 2$ are associated with protoclusters. Hence, the authors have estimated that approximately 3×10^{-8} of emerging clusters fall into the interval of $2 < z < 5.2$ for a comoving cube with a 1-Mpc side with an active radio source. However, it is very likely that in a given range of redshifts, the number of galaxy protoclusters can be greater, since the active radio source simply may not be observed. Thus, based only on data from radio surveys (radio source catalogs and microwave background maps) one can select objects–galaxy cluster candidates. Using the WENSS (the Westerbork Northern Sky Survey) survey catalog conducted in the northern sky with the help of the Westerbork radio telescope in the Netherlands is no coincidence. The WENSS surevey [16] was performed at a frequency of 325MHz and is characterized by a maximum flux density of about 18 mJy (which corresponds to approximately 5σ). Angular resolution of the radio interferometer is $54'' \times 54''\text{cosec}\delta$, where δ is the declination. The survey covers the northern part of the sky above 29o by declination. High sensitivity at low frequency allows us to identify radio sources with data from surveys conducted at higher frequencies. This, in turn, makes it possible to select sources with steep radio spectra associated with distant radio galaxies [14, 26, 27]. Thus, the use of a low-frequency catalog of radio sources in searching for objects with the Sunyaev-Zeldovich effect helps one identify distant galaxy cluster candidates. First searches for the effect using the WENSS data were carried out in papers [28, 29], while here we develop the proposed approach. The WENSS survey area is about 10000 square degrees, and the catalog contains 21134 radio sources. We used the data of the first two hours. In the range under study, there are 16384 objects. Figure 1 shows the analyzed area.

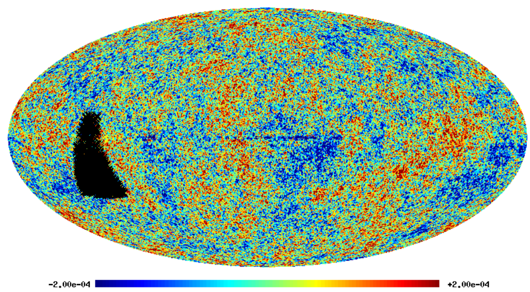

Figure 1. Cosmic microwave background map of SMICA Planck in the galactic coordinates. The black color shows the coverage with radio sources of the analyzed WENSS survey area in boundaries by the right ascension: $0^h < \alpha < 2^h$.

3.2 Selection algorithm

The algorithm for selecting candidates includes several stages:
1) Cutting-out the area in the vicinity of radio sources of the WENSS low-frequency catalog citewenss with a side of 30′in frequency maps of 100, 143, 217, 353, and 545 GHz and in the CMB map about six times exceeding the size of the beam pattern at a frequency of 217 GHz (and three times–the search size used in the Planck data analysis [19]).
2) Selection of potential SZ-sources using the standard SExtractor search program [30] within the 7-arcmin radius from the center of the area (with the beamwidth of a radio telescope of the order of 5′) at frequencies of 100 and 143 GHz–with the negative amplitude, and at 353 and 545 GHz–with the positive.
3) Comparison of the amplitude of a detected source at frequencies of 100 and 143 GHz, $|S_{100}| > |S_{143}|$ and check of the presence of a source with the positive amplitude at a frequency of 217 GHz.
4) Control of selected objects with the visual method.
5) Additional control–checking the presence of a minimum on the cosmic microwave background map with low ($\ell \leq 20$) multipoles. Removing low multipoles with signals of statistical anisotropy [32] reduces distortions in the areas, which, in turn, increases the contrast of smaller inhomogeneities. The minimum in the CMB map is observed in the direction of galaxy clusters with the SZ-effect manifested. It is formed as a result of separating the components [31].
To run all the selection stages, specialized scripts were developed with the GLESP package

[33, 34]. The SExtractor code [30] was used to select sources. The formatted all-sky maps in the microwave range in the GLESP standard which were used for image analysis are available on the CMB website[1] [35].

4 Results

4.1 Radio source population

The catalog of radio sources selected according to the proposed method contains 381 WENSS objects from the right ascension range of $0^h \leq \alpha < 2^h$ selected with the additional visual control.

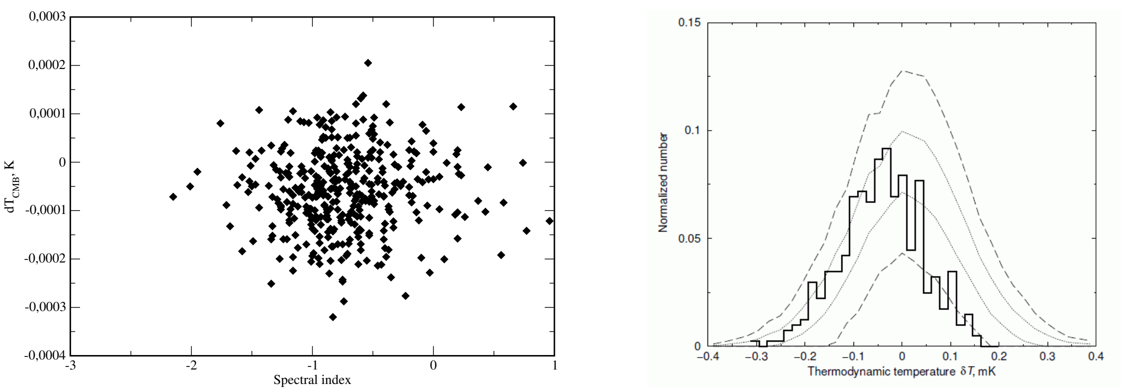

Figure 2. Left: Diagram "spectral index $\gamma_{1.4\mathrm{GHz}}$ – CMB variation $\delta T_{\ell\in[21;2500]}$" for radio sources from the sample under study. Right: Distribution of the fluctuation level in the CMB in the direction to radio sources from the sample under study.We used the CMB SMICA Planck map with multipoles of $20 < \ell \leq 2500$. Dashed lines show the distributions of the $\pm1\sigma$ and $\pm3\sigma$ fluctuation levels in the standard ΛCDM cosmological model from the data of 200 realizations of a random Gaussian CMB map.

Figure 2,left presents the diagram "spectral index γ at a frequency of 1.4 GHz–CMB temperature variation". Distribution of the fluctuation level in the CMB SMICA Planck map with the multipoles $20 < \ell \leq 2500$ in the direction to a radio source is given in Fig. 2,right. The dashed lines show the distributions of the 1σ and 3σ fluctuation levels in the standard ΛCDM cosmological model from the data of 200 realizations of a random Gaussian CMB map. Data are normalized by the number of pixels. Random Gaussian realizations of CMB inhomogeneities were modeled within the ΛCDM cosmology with the help of the special code *cl2map* of the GLESP package [33]. Distribution by spectral indices makes it possible to identify a population of sources with the preferred slope of the radio spectrum describing radiation of an object in a cluster with the observed Sunyaev-Zeldovich effect. The median spectral index of the sample at a frequency of 1.4ĠHz appeared equal to med $= -0.79$. An additional feature of the sample characterizing the population is the negative median signal in the CMB SMICA inhomogeneity map constructed in the multipole range of $\ell \in [21 - 2500]$ in the direction of a radio source (see 2,left). We compared the distribution of responses

[1] `http://cmb.sao.ru`

on the CMB SMICA map in the direction of radio sources with the expected in the ΛCDM cosmological model from the data of 200 random Gaussian CMB realizations (2,right). In addition to the fact that the position of the maximum of the signal response distribution on the SMICA map is shifted in the negative direction beyond the limit of 1σ, it has significant distortions in the area of the positive signal including a lack of positive responses exceeding the 3σ scatter level.

Note that visual control also allows one to separate objects with nontrivial features in the region of positive peaks at low frequencies ($\nu < 217$ GHz). Such topological effects occur, when in the region of the source center in the 1.5 radius of the beam pattern of the radio telescope antenna, the signal has a complex structure. For example, there are two positive peaks. Then the additional local minimum appears which is detected by the algorithm. Thus, in addition to a signal topologically close to the expected one in the case of the Sunyaev-Zeldovich effect, from the algorithm operation results it is also possible to detect radio sources that have the maximum in the studied region at low or all frequencies and often even on the published cosmic microwave background map. Moreover, the objects found were identified with the catalog of SZ-objects of the Planck mission [36] and the data from the catalog of the SDSS survey [37] comprising nearby galaxy clusters with the redshifts $z < 0.42$. Six coincidences with objects from the Planck catalog have been found, in which there are about 1.6 thousand objects, and 19 coincidences with the data on clusters from the SDSS survey. An interesting fact is the detection of 72 radio sources not only on maps built for multi-frequency data but also on the cosmic microwave background map. Thus, according to the results of the study, several important conclusions can be drawn:
1) There are candidate objects with the poorly observed Sunyaev-Zeldovich effect on the Planck mission maps. In the whole sky, they are at least 10- 30 times greater in number than in the published lists. This fact resolves the contradiction between the expected number of galaxy clusters with the SZeffect and their recorded number.
2)There is an effect of a "pit" on the CMBmap when selecting radio sources–candidate SZ-objects. This allows one to independently check the presence of a galaxy cluster in the vicinity of a radio source. Let us note that this negative signal is formed as a residual effect after separation of radiation components without taking into account the a priori information about the presence of a massive galaxy cluster (with the SZ-effect) in this direction in the sky.
3) The parent object is often observed in the fields of radio sources, radiation from which remains on the CMB map obtained as a result of separation of components of the extended background signal. Despite multiple detections of such radio sources on the CMB map, they do not make significant contribution to the definition of cosmological parameters, since they introduce distortions only into the highfrequency part of the angular power spectrum. This region is less significant than the low-frequency region in cosmology determination.
4) Radio sources in galaxy clusters can screen the Sunyaev-Zeldovich effect in the millimeter wavelength range. This reduces the possibility of its detection. The radio spectra were built using the source flux densities measured in different surveys, from the CATS database[2], and the radio spectrum analysis *spg* [38] of the continuous data processing systems at the RATAN-600 [39].

After the automatic selection procedure of possible candidates, 1778 objects (9.9% of the total number) were selected, 381 sources of which (2.1% of the total number) with the most typical contrast signs of the effect were distinguished after visual inspection. It is interesting to notice that the method allowed us to detect 21 of 28 Planck sources that were included into the corresponding catalog of themission, and the visual control based on the contrast of the effect left six of them. Notice that the authors of the paper have the additional catalog

[2] `http://cats.sao.ru`

with the list of objects not presented in this paper because of the "noisiness" of the map with CMB fluctuations. Preliminary estimates show that the number of objects with the Sunyaev-Zeldovich effect can increase up to tens of thousands with careful analysis of microwave background maps which is several times higher than the number of objects obtained from identifications with the SDSS and WISE surveys [40]. It is important to note that the suggested method for searching for galaxy clusters with the SZ-effect using radio sources will also make it possible to search for similar objects with great redshifts ($z > 1$) which cannot be found in [40] due to selection effects.

The sources selected can be further used for optical studies of the environment, estimation of mass and other cosmological properties, for checking the results of standard cosmologicalmodeling. Moreover, new lists of extended radio sources in the microwave range provide new data for accounting when modeling the distribution of extended radio sources over the full sphere [41]. Studies of the radio source vicinities in the WENSS catalog of other ranges of right ascensions, as well as other radio-astronomy surveys, are continued.

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