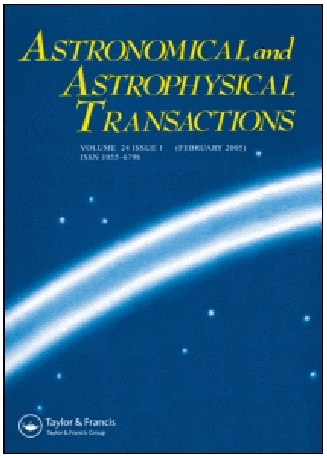

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Spectral-spatial fluctuations of the relic radiation - a new class of objects in the universe

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SPECTRAL–SPATIAL FLUCTUATIONS OF THE RELIC RADIATION—A NEW CLASS OF OBJECTS IN THE UNIVERSE

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In this work a short review of the main ideas and problems connected with studies of post-recombinational stage of the Universe evolution in the range of redshifts z from 1400 to 5 is given. It is shown that the main role in forming observational effects must play the primordial molecules scattering the background radiation in the protogalaxies and protostars moving with pecular velocities. This gives us a possibility to investigate, in principle, fully the initial large-scale distribution of matter in the Universe and to determine the primordial chemical abundance. Moreover, detailed study of predicted effects should give a unique information about the presence and physical parameters of unstable dark matter.

KEY WORDS Cosmology, radioastronomy.

In the standard picture of the Universe evolution there is a period when the matter is in the atom-molecular state, practically without density fluctuations and with a low concentration of free electrons. Diffuse and weak-contrast in density protostars and protogalaxies the main objects at that time. The matter temperature is practically equal to the radiation temperature up to $z = 150$, and then it decreases sharply. The temperature varies within 3000–30 K. The investigation of this stage of the Universe evolution can give answers to many fundamental problems. This paper deals with only two of them: the large-scale structure of matter distribution and the primary chemical abundance. Both of them are presented here quite purely without any distortions of further evolution. Just because of this it is so important to find any way to study thoroughly this stage of the Universe evolution. Besides usually expected effects there are many various predictions on the character of the matter distribution, temperature variations, ionization degree, emission spectrum, etc., resulting from the current considerations on theory of elemental particles, possible existence of primary black holes, etc. Observational restrictions for this or that theory variant seem to be of great interest. From the observational point of view this interval z does not differ from the one under investigations now, $z < 5$, where electromagnetic radiation is also the main source of information, but in a wider spectral range (optical, X-ray, etc.). Therefore we can speak, in some sense, about more distant space and introduce its designation as the super-distant cosmos (SDC). Protogalaxies, galaxy protoclusters, protostars and other objects will constitute the population of the SDC and due to the radiation mechanism they will be observed against the background of powerful relic radiation as faint extended sources. As it will be shown below they will radiate mainly in rather narrow spectral lines and practically without continuum. Just this determines their name, the spectral–spatial fluctuations (SSF), distinguishing them as an intermediate stage between the spatial fluctuations of the relic radiation (RR), being formed at the moment of hydrogen recombination ($z = 1400$), which have the blackbody spectrum with temperature T_r, and current objects (galaxies and stars) whose spectra can be very complex. The procedure of the search for the SSF should contain the elements typical of the search for both the first and the second types of the objects. Below we consider these problems in more detail. One of important questions is the one on the radiation mechanism at this epoch. Numerical theoretical works on the calculation of the protoobject luminosity do not give reliable results. They use mainly the standard mechanisms connected with different sources of energy emission from the protoobject: compression and cooling or the decay of unstable particles. Such mechanisms can be referred to as a set of active ones, i.e. which demand additional sources of matter heating. The standard scheme does not include such sources. But even if one supposes the existence of primary black holes, early stars, etc., then many problems arise as well concerning the conversion of the emitted energy into photons. The fact is that extremely low matter density, low ionization degree, i.e. almost full absence of free electrons, magnetic field, etc. make usual radiation mechanisms–free-free transitions, synchrotron and plasma ones, extremely inefficient. More often, in this connection, are used the radiation processes in lines of excited atoms and molecules at this epoch. However, as a rule, simple components of the medium are used, such as hydrogen atoms and molecules. To excite the hydrogen atom, high energy is needed, and radiation transitions in hydrogen molecule, due to its symmetry, are hardly probable. But the main problem of all the mechanisms, which use the reemission by atoms and molecules, is the extremely low probability of their collisional excitation due to low matter density. A rough estimate of the protoobject luminosity associated with this mechanism shows (see below) that, if not supposing the values of matter density and temperature strongly different from the standard ones, the effective value will be negligibly small. Apparently, just this circumstance generates the sceptical opinion of the observers.

However, there exists a rather simple and well known mechanism of the fluctuation generation of RR , which can be used for the formation of the SSF. This is the Doppler effect which leads to variations of observed temperature of a protoobject with peculiar velocity (Dubrovich, 1977a, 1981). It is a passive mechanism, since for its realization it is not necessary to have any internal energy sources, and the existence of an external radiation is of great importance. Relic radiation, being to a high degree homogeneous, isotropic and rather intense one, is very good for this role. From common considerations, however, it is obvious that only some deviation in physical conditions from the thermodynamical equilibrium and the interaction of the RR and matter can cause some distortions. Peculiar motion of the matter in the system of coordinates, in which, the RR is isotropic and homogeneous, is one of the examples of nonequilibrium. The interaction of the matter and radiation appears due to some mechanisms of scattering or absorption of photons by atoms or molecules. The interaction was important at the epoch of hydrogen recombination at $z = 1500$. Peculiar motions of separate matter elements existed there also, and interaction with the RR was caused by the scattering of photons at free electrons. After the hydrogen recombination, when the number density of free electrons has sharply decreased (by 3–4 orders of magnitude), and the efficiency of the interaction in this channel became practically zero. This allowed to draw a conclusion on the transparency of the Universe for the electromagnetic radiation at $z < 1000$. However, at present this conclusion needs to be specified. The point is that at $z < 350$ in the Universe at minimum standard conditions there can generate molecules, the main feature of which is (for our purposes) very large cross-section of photon scattering in narrow resonance lines. The values of these cross-sections (different for various molecules) exceed the Thomson cross-section of scattering on free electrons by 10–12 orders. With such a big value of the cross-section, we can obtain high efficiency of matter and radiation interaction even at very small molecule abundances. More detailed consideration on the types of molecules and optical depth estimation τ will be given below, and here we note that RR distortions will be frequency-dependent and equal to

$$\begin{aligned} \delta T/T &\approx v\tau/c, && \text{for the Doppler effect,} \\ \delta T/T &\approx 0{,}01\tau n_e/n_\nu, && \text{for the collisional exitation,} \end{aligned} \tag{1}$$

where $\delta T/T$ is the relative RR temperature distortion, v is the peculiar velocity, c is the speed of light, n_e is the electron density, n_ν is the density of photons in the RR within the thermal Doppler contour of a molecule line ($\delta\nu/\nu \approx 10^{-5}$). We will consider parameters of a more probable distortion, when we will discuss concrete types of protoobjects. Here we only compare the efficiency of this mechanism and that given above of radiation at collisional excitation. At reasonable values of parameters: $v \approx 100\,\text{km/s}$, $\tau \approx 1$, $z \approx 100$, $n_e \approx 10^{-3}\,\text{cm}^{-3}$, $n_\nu \approx 10^4$, we obtain the difference of 4–5 orders of magnitude in favor of the Doppler mechanism.

Now we describe one more mechanism of SSF formation. It is caused by possible nonequilibrium of the RR spectrum and a large cross-section of absorption in molecule lines, but does not require the presence of peculiar velocities. This is the mechanism well known in physics—luminescence. More often it is invoked in the problems on emission of interstellar matter and reflection nebulae. For cosmological problems, this process was considered by Dubrovich (1977b, 1985) and Lyubarckij and Syunyaev (1982). It will be very important if there are unstable particles in the early Universe which decay into photons in a rather wide frequency range. The main point of this mechanism is that high frequency photon, while being captured by a molecule can break into some photons of lower frequency, so that their total energy equals to the energy of the initial photon. The peculiarity of this process (with the powerful RR) is that reverse action is possible, i.e. the absorption of one upper equilibrium photon is supplemented by the absorption of the RR photons and, as a result, one photon of the sum of their energies is produced. Apparently, such a process can occur (in both directions) only when the RR spectrum deviates from the Plank one. The spatial inhomogeneity of the matter distribution is not necessary for it, i.e. it can give isotropic distortions of the RR spectrum. These distortions will look like steps in emission or absorption. Their position in frequency is dependent upon the molecule type, its formation moment, and concrete transition frequencies. However, when a noticeable spatial inhomogeneity is formed, the SSF can be formed due to this mechanism. The effective amplitude does not depend here on the peculiar velocity of the protoobject. The main interest in this case is the convenience of observations of such objects as compared with the search for isotropic spectrum distortions, that requires the RR temperature measurements with a high precision. And for this mechanism, note it once again, the value of $\delta T/T$ is determined only by external factors, but not by the heating of the protoobject. Comparing the both considered mechanisms, it should be expected that the most effective and probable, from the viewpoint of similarity to the standard scheme, is the Doppler mechanism, since peculiar velocities of protoobjects are sure present at matter density fluctuations, and the RR spectrum may not have considerable distortions.

Now we consider those molecules which could be present at that epoch, estimate their abundances and determine the frequency region where they may be observed. It is well known that the primary matter consists mainly of hydrogen and helium; deuterium abundance is 4–5 orders less, then goes lithium (Li), the abundance of which is 9–10 orders less than that of hydrogen. The abundance of heavier elements in the standard scheme of the primary nucleosynthesis is so small that they can be excluded from consideration. Taking into account that at the period z under study, apart from atoms, there exist ions of hydrogen, lithium and free electrons, we can compile a list of more probable molecules: H_2, HD, H_2^+, HD^+, LiH, LiH^+, HeH^+, H_3^+, H_2D^+, H^-. Table 1 presents some important parameters of these molecules for us: the first column: molecule name, the second one: the dissociation potential in eV, the third: recombination moment by Saha (i.e. at complete thermodynamical equilibrium, for more details see below); the fourth: the wavelength λ_0 of the first rotational transition in microns; the fifth: dipole moment in debye (10^{-18} units CGSE), the sixth: numerical coefficient τ_0 in the expression for optical depth, and then—ε-energy coefficient for rotational levels (Dubrovich, 1977a).

The presented recombination moment for all the molecules corresponds to z_r, the moment at which the molecule dissociation by the RR photons stops and begins recombination with a low velocity due to low matter density and small recombination coefficients. Thus, at $z > z_r$ a given molecule does not wittingly exist due to high dissociation rate by the external field. Kinetics of molecule formation is of great interest since it essentially depends on many parameters and is very sensitive to their variations. Most obvious one can see it in the abundances

Table 1

Mol.	D_e *(ev)*	z_r	λ_0 *(μ)*	*d (deb)*	τ_0	ε
H_2	4.478	355	84	0	—	—
H_2^+	2.651	210	170	0	—	15.6
HD	4.514	357	112	5.9×10^{-4}	0.011	23.7
HD^+	2.668	212	227	0.86	2.3×10^4	11.7
LiH	2.429	195	676	5.9	1.1×10^6	3.9
HeH^+	1.85	148	149	1.66	8.7×10^5	17.8
H_2D^+	4.3	340	1920 805	0.6	1.1×10^4	—

of H_2D^+, HD and HD^+ relative to the corresponding doubles containing hydrogen at low (≈10%) matter temperature variations. The abundance of molecular ions varies essentially at appearance of even a weak source of additional ionization. Here two types of influence are possible. The first one is when additional free electrons play the role of a catalyzer and accelerate the process of neutral molecule formation, for instance such as H_2. The second, when the number of protons and such molecules as HeH^+, HD^+ etc. increases. We suppose that the ionization source here is rather faint, so that the relative concentration of ions of different atoms remains to be small, but the absolute variation of the number density of free protons can be comparable with that of some molecule. This circumstance allows to increase the sensitivity of cosmological tests in detection of unstable particles. Indeed, if we search for the products of the particle decay against the background of powerful RR at the level of sensitivity in absolute spectral measurements of the order of 0.1%, we can reach the upper limit of the relative number density of the particles of about 10^{-3} with respect to the total number density of photons in RR. But, if we could be able to determine the abundances of various molecule ions, we could detect variations of the ionization degree of about 10^{-3} relative to the baryon density, which could be produced by photons from decaying particles, whose number should be about 9 orders less than the previous one. Another way to estimate the decaying particle masses can be the determination of the relative abundances of different molecules in case if the energy of decaying photons is not enough for hydrogen ionization, but it lies in the interval of dissociation energies of these molecules. All these tests should be calculated in detail with account for the maximum necessary number of parameters. We stress again that this direction can surpass by sensitivity all direct spectral measurements of the RR. Turning back to the question of the dynamics of molecule recombination, we see that z_r determines only most simple parameters of the matter. Now consider the determination of the optical depth τ in molecule lines. First determine the values given in Table 1. The wavelength at which a primary molecule can be observed is

$$\lambda = \lambda_0(1+z)/(J+1); \qquad J = 0, 1, 2, \ldots, \tag{2}$$

where z is the redshift, and J, the number of the rotational level from which the scattering begins. The optical depth along the scattering is determined mainly by the value of dipole moment d. For H_2 and H_2^+, the dipole moment vanishes and their scattering cross-sections are small. Another important factor which determines the value of τ is the cosmological expansion of the Universe. It is equivalent to the presence of a velocity gradient so the distance at which the optical depth is integrated is determined by the distance at which the photons go out of the contour of line due to the redshift (Ω are ω_b, the total and baryon density relative to the critical one, h_{75} is the Hubble constant relative to 75 km/c, and α_m is the density of molecules relative to hydrogen)

$$\tau = \tau_0\alpha_m\Omega^{-1/2}\omega_b(1+z)^{3/2}h_{75}(J+1)\exp[-\varepsilon J(J+1)/(z+1)]. \tag{3}$$

It follows that only a thin matter layer ($\delta z/z \approx 10^{-5}$) participates in the process of the SSF formation at the moment z. This fact is very important. A large frequency band is overlapping due to the scattering of consequent layers at z. The size of protoobjects is, as a rule, rather big $\delta z/z > 10^{-4}$, i.e., the photon of a given frequency "sees" only a small part of the object. Scattering of the homogeneous matter leads to blurring of the previous fluctuations. If $\tau > 1$ in the lines of any molecule, then blurring will take place from the moment of its appearance z_1 up to the dissociation, z_2, and in the corresponding spectral interval also from $\lambda_1 = \lambda_0(1 + z_1)$ up to $\lambda_2 = \lambda_0(1 + z_2)$. The boundary of the angular scales of the blurred fluctuations is determined by the horizon at the moment z. A particular case if the scattering of hydrogen atoms. Here we have an intermediate variant. Due to the high abundance of hydrogen the optical depth of the order of unity will be reached in L_α out of the precise resonance, i.e. in a L_α wing (Dubrovich, 1987)

$$\tau = 3 \cdot 10^2\, \omega \lambda^2 \lambda_0^2 / (\lambda_0 - \lambda)^4. \tag{4}$$

The wavelength dependence here is not so sharp as at resonance, but not so flat as to neglect it. As a result, for $\lambda < 700\mu$ fluctuation blurring on the scale $\theta < 10'(z = 1400)$ begins, then the boundary over λ is shifted proportionally to $z^{1.30}$ and over θ, proportionally to $z^{-3/2}$. Inside this triangle (on the plane $\lambda - \theta$) the map of fluctuation is different from that outside this triangle. This means, that at superposition of maps at different wavelengths, for instance, for the given scale θ, a coincidence in all the range of λ will occur, except those which fall into the selected triangle. It is analogically for θ. Since real observations can be carried out, apparently, at $\lambda = 300\mu$ (due to a sharp decrease of the RR intensity and the increase of the atmosphere and dust noises in our Galaxy), then the minimum $z = 700$, and $\theta < 30'$. At the same time secondary fluctuations appear, which do not correlate spatially with the primary ones. Due to weak frequency dependence of this effect, its observations can be carried out with the spectral resolution $\delta v / v \approx 0.1$. The blurring of primary fluctuations by the resonance lines of LiH or H_2D^+ can occur in some narrow nonoverlapping bands of λ (Dubrovich, 1993). Then the boundary parameters of these bands give an information on the Li and D abundance and on physical conditions at the corresponding moment z. So, for example, H_2D^+ abundance at $T = 30$ K ($z = 50$) has a maximum which can vary by two times when T varies by 10%. Or, for example, the presence of the secondary ionization stage can sharply change the relative molecule abundance and influence the primary fluctuation blurring. If the optical depth in the homogeneous matter is not sufficient for complete blurring, then in this case a detailed comparison of fluctuation maps at different wavelengths gives unusual information. In this sense all the fluctuations have a spectral-spatial character.

Now consider how must the observed objects look. It is determined by the dependence of τ upon z in the protoobject. For the Doppler mechanism, the peculiar velocity v, in the standard scheme and with allowance for the present data on the galaxy cluster velocities, depends z as $v \approx 600(1 + z)^{-1/2}$ km/s. The dependence of τ on z can be complicated, but to the first approximation it is given by (3). However, due to specific conditions for the length of the way τ is integrated, there is a possibility to increase τ at the moment when Hubble expansion of the protoobject is changed by the compression due to selfgravitation. At this moment the photon will scatter along the whole object, and consequently the decrease of τ will be by the factor equal to the ratio of the object size to the size determined by the line profile width (Zeldovich, 1978). Numerically it equals 2–3 orders. The moment of the expansion stopping and beginning of selfgravitational compression is determined by the object scale and by the value of the primary fluctuations of the metrics. For protostars and protogalaxies this moment is from 30 to 10. Further compression of the protoobject leads to a considerable increase in τ due to the density increase. This effect can be estimated by the upper limit to the matter temperature in the object. The matter is that at compression adiabatic heating occurs and in this case $T \sim n$. On the other hand, the effective cooling of the matter will begin at $T > 10{,}000$ K. But yet earlier, at $T = 2000$–3000 K, the molecules which we consider begin to be destroyed. Thus, the protoobjects can compress 5–6 times in size, i.e. 100–200 times in density that will correspond to the increase of T from 30 K (at $z = 50$) up to 3000 K. τ will increase with this 20–30 times. Thus, at $z = 30$ due to formation of protostars and protogalaxies a sharp increase of τ (2000–3000 times) is possible, that makes this epoch the most interesting from the observational point of view. Apparently such considerable increase of τ will allow to detect other molecules based on heavier elements—B, Be, etc.

The interval $3 < z < 5$ can be interesting for observational check due to the SSF caused by the HeH^+ molecule. At this period, an intense formation of galaxies and ionization of intergalactic matter begins and HeH^+ must be present in all the intergalactic space (Dubrovich and Lipovka, 1992). Hot galaxy radiation energy can be sufficient for hydrogen ionization, but not sufficient for their detection neither in optical nor radio ranges. This is just the situation mentioned above. Therefore, the Doppler mechanism of SSF formation can be the main effect here. Due to the simplicity and universality of the HeH^+ molecule, we can see in its lines the full picture of the matter distribution at $z \approx 5$. Note that the laboratory wavelength of the first rotational transition of HeH^+ are $\lambda = 150\mu$, and the next ones 75 μ and 50 μ. For $z = 5$ they are respectively 900 μ, 450 μ and 300 μ, which agrees well with the standard wavelength range of COBE and other satellites, and most important is that the RR is very strong in this range. The study of this interval of z is very important to see the whole picture of the large-scale structure of the matter. The completeness is provided by both the presence of HeH^+ in any sky area in picture plane and the possibility of obtaining high resolution in radius (at z) due to narrow resonance lines. I.e. we can obtain a complete three-dimensional picture of the large-scale structure at large z, which is practically impossible to obtain with traditional techniques, for instance, using a sample of distant quasars due to their small number. The completeness of the general picture is important for elucidation of fine details of scale spectrum predictions to which give some theories of inflation and decision of the question on fractal character of matter distribution in the Universe. The necessary parameters of the devices to solve this problem should be $\delta\lambda/\lambda \approx 10^{-3}$, $\delta T/T \approx 10^{-4}$, $\theta \approx 1' - 10''$.

The method of the SSF observations is analogous to that used for the search for primary fluctuations formed at $z = 1400$, but in narrow spectral bands. It is necessary to observe in some close spectral channels making clearings from noises in each of them. Then it is necessary to make cross correlation analysis of recordings in these channels to know the contribution of objects of different sizes. If the correlation coefficient changes noticeably depending upon the mutual separation of the channels in frequency, then there is some contribution from the SSF in these observations. The next step should give information on z where these SSSF are located. For this purpose observations should be carried out at some frequency being multiple to the primary one (Dubrovich, 1981). It can be two or 3/2 and so on. The sense is that if the detected SSF are formed due to scattering in the rotational lines, then at one of multiple frequencies the picture of the SSF should repeat. If we see SSF simultaneously from different molecules, then the procedure to separate them is based on the comparison of fluctuation maps at different frequencies. Detection of coinciding details on the maps at multiple frequencies allows to fulfill their more precise study. Precise values of frequencies of the object lines allow to determine the molecule, since at general law of multiplicity of rotating frequencies there are small deviations in the two-atoms molecules from this law being strictly individual for each of them. The value of deviation from the law of multiplicity can comprise some percents in frequency. Thus, there are some ways to find z where this or that molecule exists and continue its detailed studying for determination of cosmological parameters.

The spectral-spatial fluctuations of relict radiation (SSF RR) are a new class of astrophysical objects. Their main properties and manifestations are:

This is a population of the Universe following quasars on the side of large Z. The range of Z is from 5 to 300. Physically these are protogalaxies, protostars, etc. Normally these are extended diffuse objects with the angular size from several arc seconds to dozens of arc minutes.

The main mechanism providing the observation of such objects will be the Doppler change of the temperature of the background radiation due to their motion with pecular velocities and scattering in the molecular lines. It is possible either only emission or only absorbtion in the time of this process.

The main molecules must be: LiH, HeH^+, HD^+, H_2D^+. The main transitions lines are rotating (see Table 1) for $Z < 50$ and rotating-oscillating for $Z > 50$.

The values $\delta T/T \approx 10^{-3}$–$10^{-5}$, the line widths are $\delta\lambda/\lambda \approx 10^{-3}$–$10^{-5}$. The range of the wavelengths is 0.05–1 cm.

It is possible that the fluorescence mechanism supplements the Doppler's one. It is possible that the formation of the SSF depends not on the velocity of a protoobject but on the density contrast with the presence of the global distortions of the RR spectrum caused by unstable particles disintegration or other sources. The range of wavelengths, angular sizes, widths of lines will be the same as in the first case. But the value $\delta T/T$ will be proportional to the initial spectrum distortion, τ and $\delta\rho/\rho$. The compulsory sign of such distortions are absorption and emission presence in the lines of rotating-vibration transitions with the observing of energy law conservation.

The detailed measuring of the abundance of the primordial molecules is a very sensitive method of the search of unstable dark matter.

The method to search for the SSF consists of two stages: a complete survey in several narrow spectral bands and the search for spatially uncoincided diffuse objects, and then the detailed spectral investigation of these objects.

So, we have an opportunity to study a new region of the Universe and obtain new interesting information about it's fundamental parameters.

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