THE SUNYAEV—ZEL’DOVICH EFFECT ON ELLIPTICAL GALAXIES

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ABSTRACT

The history of discovering of hot gas in galaxies is traced briefly, its main properties are described and the desirability to make them more precise, in particular to obtain additional data on the mass of such gas is pointed out. For this purpose observations of the Sunyaev—Zel’dovich effect on hot gas of coronas of elliptic galaxies are proposed. The absolute and relative disturbances of the cosmic microwave radiation spectrum due to scattering of relic photons by Maxwellian electrons are calculated according the formula of the article [1]. With the example of three elliptic galaxies it is shown that observation of the SZ effect on such galaxies is quite possible. Kinematic SZ effect [2] arising due to peculiar movement and rotation of galaxies is available for observation as well. Such observations combined with X-ray data would make it possible to get more about properties of galactic gas, to obtain additional information on rotation of galaxies, on possible accreting gas flows and on hot galactic wind.

Subject headings: the Sunyaev—Zel’dovich effect, hot gas, elliptical galaxies

Introduction

Effect of distortion of blackbody spectrum of microwave background radiation (CBR) scattered by hot intergalactic gas in galaxy clusters was predicted by Ya.B.Zel’dovich and R.A.Sunyaev in 1969 (known as SZ effect according to Latin alphabet) and since then is widely used in the investigations [1] of properties of this gas and determination of some cosmological parameters, for example, the Hubble constant. Along with thermal effect, kinematical effect was predicted [2] which is produced by the same scattering of relic photons by gas with peculiar motions of clusters relative to CBR. A lot of articles and surveys are devoted to extended description and results of observations of both kinds of effect (for example, [3], [4], [5], [6], [7]).

Recent time SZ effect means not only scattering of CBR by hot gas in cluster galaxies, but also scattering of CBR by other astrophysical objects, for example by outflows of gas from active galactic nuclei and quasars (other examples are given in survey [6]). In this article we suggest to observe thermal and kinematic effect on gas of elliptical galaxies in this article. Effect is about an order lower than on galaxy clusters but nevertheless has access to observations. At the beginning of the article we will briefly discuss a problem of hot gas in galaxies.

Hot Gas In Elliptical Galaxies

For a long time it was assumed that existence of interstellar gas is a feature of disk galaxies, but not elliptical (E) or lens (S0) galaxies, implying cold, neutral gas, the same as in our Galaxy. Situation changed after launching X-ray satellites [8], [9]. X-ray radiation of galaxy clusters (for example, [10], [11], [12], [13]), which was discovered by satellite UHURU in the end of 1970, proved the existence
of hot gas in galaxies and intergalactic medium, which radiates in X-ray. After increasing of angular resolution of X-ray receivers a lot of point sources were discovered [14]. Their contribution to X-ray radiation is important to take into account [15].

It became possible to study in details properties of X-ray radiation from separate galaxies [16], including subtraction of point sources radiation and distinction of hot diffuse gas radiation [17], [18] after launching observatory Einstein in 1978. Hot gas was discovered in five disk galaxies in Virgo cluster [19] and than in elliptical galaxies [20], [21].

Later, using relations between X-ray $L_X$ and optical $L_B$ galaxy luminosities which according to [21], [22] can be presented as $L_X \sim 10^{19} (L_B/L_\odot)^2 \text{erg/s}$, estimations of central electron density $\sim 0.1 \text{cm}^{-3}$, gas temperature $\sim 10^7 K$ and cooling time $\sim 5 \cdot 10^6 \div 5 \cdot 10^7$ years were deduced [23]. By the way, it was concluded that concentration of particles decreases with increasing of distance $r$ from galaxy center according the power law $\sim r^{-\alpha}$, where $\alpha \sim 1 \div 1.5$.

Relatively small cooling time in central regions of galaxies suggests the existence of cooling flows. Dust clouds can remain in cooling flows, infrared radiation of which in E/S0 galaxies is observed by satellite IRAS [24], [25], [26]. From this fact and the data of X-ray observations [20] a conclusion can be made about multiphase of interstellar medium not only in disk galaxies, but in elliptical galaxies too. In connection with construction of X-ray halo models and possible appearances of cooling flows such a multiphase of ISM was considered, for example, in the article [8]. But, as it has been mentioned in series of papers, for example in [27], star formation burst and activity of nucleus make a contribution into balance between the heating and cooling of gas.

Total mass of hot gas in massive elliptical galaxies can reach $10^{10} M_\odot$. According to [28] the abundance of heavy elements including iron increases from $Z_{Fe} \sim (0.2 \div 0.4) Z_\odot$ in periphery till $Z_{Fe} \sim (1 \div 2) Z_\odot$ in the center. As it is shown in papers [29], [30] the amount of gas in galaxies and its X-ray luminosity correlate with their stellar radiation hence with their mass: $L_X \sim L_{opt}^2 \sim M_{stars}^2$. This conclusion is true for galaxy clusters as well [31].

A problem of estimation mass of virialized systems (they can be E-galaxies and evolved galaxy clusters) using properties of diffused X-ray radiation was discussed in several works [32], [33], [31]. It is clear that in order to solve this problem it is necessary to know redistribution of gas density in system along its radius and make some assumptions about the degree of clustering in space, so the solution of problem depends on model. Firstly, difficulty of solution of this problem reveals in investigation of gas components in galaxy clusters which in general are not virialized systems. The evidences of this are observed heterogeneity in surface brightness of diffuse X-ray radiation of hot gas in galaxies [34], [35].

There are other methods of mass estimation of galaxies and galaxy clusters. Firstly, it is a method based on the effect of gravitational lensing [36], [37]. However, this method needs a solution of reverse problem namely recovering of mass distribution in gravitational lens by lensing image. There is another way of mass estimation of extragalaxy systems connected with using integrated thermal SZ effect, offered by discovers of the effect [1]. This method is less sensitive to heating and cooling of gas and does not depend on the redshift of system. The arguments for using this method instead of method based on estimation of mass of galaxy clusters by their X-ray radiation are given in the work [38]. These advantages can appear in the case of investigation of hot coronas of massive spheroid galaxies, virialization of which is quicker and stops earlier, than in galaxy clusters. So such coronas can be observed in X-ray on earlier cosmological times, than galaxy clusters. Though the temperature of virialized galaxies coronas is an order lower, than in cluster gas, and angular size is significantly less than the cluster size, distribution of gas in coronas is more homogeneous, because of quicker merge of galaxies from separate fragments in comparison with clusters. Observational facts give evidences of this. Firstly, there are far quasars presenting active galactic nucleus, when system
of galaxies is far from virialized state and presented as protocluster. Secondly, there is dependence between masses of central black holes and X-ray luminosities of their coronas for massive elliptical galaxies, established in [29], [30], [31].

As have been mentioned above, at the last years effect of distortion of spectrum of CBR, due to scattering of radiation by hot gas was used for investigation of series astrophysical phenomena. For example, there is a discussion about cooling flows in galaxy clusters in the work [39], about wind around bright quasars in the article [40], [41], about young galaxies with powerful star formation burst in the work [27].

In our article we pay attention to possibility of observation of SZ effect on hot gas of spheroidal galaxies, which are not sources of distant radio emission. Such galaxies used to be isolated elliptical galaxies, which were central in groups or not rich clusters. ¹ We consider such observations to be interesting not only for physics of galaxies, but for cosmology by the following reasons.

Firstly, distribution of gas in spheroid galaxies is more regular and symmetrical, and is easier to study, than in clusters. Hence estimations of gas distribution in simplified models are closer to reality.

Secondly, X-ray luminosity function of coronas of galaxies is not exposed such a strong "inverse evolution" as in galaxy clusters. So effects connected with existence of hot gas in galaxies can be observed in large redshifts in comparison with clusters.

Thirdly, different correlations between parameters are traced in elliptical galaxies, because of large degree of virialization. Such parameters can be effective size by the half-luminosity, effective brightness, velocity dispersion on effective size, surface mass density or mass of central black hole [43]. Similar correlations allow us to use such galaxies as "standard candle" or "standard length".

In the following part we will estimate the quantity of effect for three galaxies with known parameters and show that the quantity is significant, so effect can be observed with modern tools.

Estimation of the Effect

1. Mean optical depth of galaxy. Let us estimate a possibility to observe effect by modern and expected tools. Let us accept that galaxy and distribution of electron gas in it has spherical symmetry, radius of galaxy $R$ and typical scale of electron distribution $R_c$. Let us draw a line through the galaxy center from the observer and on distance $s$ from this line and parallel to it the line of sight. Optical depth of galaxy by Thompson scattering along the line of sight is defined by integral over distance $y$ along the line of sight:

$$\tau_e(s) = \sigma_T \int_{-\sqrt{R^2-s^2}}^{\sqrt{R^2-s^2}} n_e \left( \sqrt{s^2+y^2} \right) dy,$$

where $\sigma_T$ - Thompson cross section, $n_e$ - electron concentration on distance $r$ from the center of galaxy.

We assume that electron concentration in galaxy is described by $\beta$-law distribution:

$$n_e(r) = \frac{n_e^0}{\left(1 + r^2/R_c^2\right)^\beta},$$

¹From this point of view, central galaxies in rich clusters can not be used, because they are often sources of strong radio emission with elongated components. Besides, X-ray radiation of corona of central galaxy is hard to separate from elongated radiation of cluster gas. According to work [42] unresolved radio sources on 150 MHz can introduce a distortion into SZ effect up to 10%.
where \( n_e^0 \) - electron concentration in galaxy center. Total amount of electrons, corresponding to such decreasing electron density from the center, is defined as following

\[
N_e = 4\pi n_e^0 \int_0^R \frac{r^2 dr}{(1 + r^2/R^2)^\beta} = \frac{4\pi}{3} n_e^0 R^3 I_e(r_c, \beta),
\]

\[
I_e(r_c, \beta) = \left( \frac{r_c^2}{1 + r_c^2} \right)^\beta F \left( \beta, 1, \frac{5}{2}, \frac{1}{1 + r_c^2} \right).
\] (3)

Here \( r_c = R_c/R \), \( F(a, b, c, x) \) - hypergeometric function. Dependence of integral \( I_e(r_c, \beta) \) of its arguments, which shows the difference between total electron amount with \( \beta \)-law distribution with parameter \( r_c \) and electron amount with homogeneous distribution in the whole volume of galaxy, is shown on the figure 1.

Optical depth in \( \beta \)-law distribution

\[
\tau_e(s) = \sigma_T n_e^0 \sqrt{R^2 - s^2} \int_{-\sqrt{R^2 - s^2}}^{\sqrt{R^2 - s^2}} \frac{dy}{1 + \left( \frac{s^2 + y^2}{R^2} \right)^\beta} = 2\sigma_T n_e^0 \sqrt{R^2 - s^2} \left( \frac{r_c^2}{1 + r_c^2} \right)^\beta F \left( \beta, 1, \frac{3}{2}, \frac{1 - s^2/R^2}{1 + r_c^2} \right).
\] (4)

Averaging of optical depth of galaxy by \( s \) leads to integral

\[
\tau_e = \frac{2\pi}{\pi R^2} \int_0^R \tau_e(s) ds = \frac{4}{3} \sigma_T n_e^0 RL_e(r_c, \beta),
\]

\[
I_e(r_c, \beta) = 3 \left( \frac{r_c^2}{1 + r_c^2} \right)^\beta \int_0^1 u^2 du F \left( \beta, 1, \frac{3}{2}, \frac{u^2}{1 + r_c^2} \right).
\] (5)

Dependence of integral \( I_e(r_c, \beta) \) of \( 0 \leq \beta \leq 2 \) are presented on the figure 2, where \( r_c = R_c/R \) changes from 0.2 till 1.0 with step 0.2. Product \( \tau_e^0 = \frac{4}{3} \sigma_T n_e^0 R \) is a maximum optical depth of
galaxy, i.e. depth taken along its diameter with homogeneous electron distribution in galaxy ($\beta = 0$). Integral shows difference of mean depth from maximum depth. Values of both integrals are similar, $I_\tau$ systematically lower than $I_e$, but maximum relative deviation of values $I_\tau$ from values $I_e$, presented on graphics, is equal 0.1 (with $\beta=1.1$, $r_c=0.2$).

2. Influence of scattering on spectrum of CBR. Parameters of three galaxies, which are interesting for the calculation of effect, are presented in table 1: electron temperature $T_e$ in keV, radius of region $R_c$, luminous in X-ray, in kpc, electron density in galaxy center $n_e^0$ in $cm^{-3}$, recession velocity $V_r$ of galaxies in $km/s$, redshift $z$ and distance from galaxy $D$ in $Mpc$. The whole data is taken from Internet [44].

Let us estimate the changes of intensity of CBR, occurring because of interaction of radiation with electron gas of galaxies. We will use the formula for the SZ-effect, which was found by the authors of the effect in the first approach, supposing that gas in clusters is distributed homogeneously [1]:

$$\Delta I = \frac{2h}{e^2} \left( \frac{k_B T_i}{h} \right)^\frac{3}{2} \frac{\tau_e}{y_e} F(x_i),$$

(6)

$$F(x) = \frac{x^4 e^x}{(e^x - 1)^2} \left( \frac{x}{\tau h(x/2)} - 4 \right).$$

Table 1. Parameters of three elliptical galaxies

| Name     | $T_e$ | $R_c$ | $n_e^0$ | $V_r$ | $z$  | $D$  |
|----------|-------|-------|---------|-------|------|------|
| NGC 499  | 0.9   | 89    | 0.1     | 4400  | 0.014673 | 73   |
| NGC 1332 | 4.3   | 48    | 0.1     | 1525  | 0.005084  | 26   |
| NGC 4291 | 4.3   | 61    | 0.1     | 1750  | 0.005861  | 29   |

Here $x_i = h\nu/(k_BT_i)$ - dimensionless frequency and $T_i = 2.7 K$ - temperature of CBR. Disturbances relative to Plank’s function will be the following:

$$\frac{\Delta I}{I} = \frac{\tau_e}{y_e} e^{x_i/2} \frac{x_i/2}{sh(x_i/2)} \left( \frac{x_i}{\tau h(x_i/2)} - 4 \right).$$

(7)

Usually distortion of Plank’s spectrum is presented through temperature distortion with the formula:

$$\frac{\Delta T}{T} = \frac{\Delta I}{I} \frac{d \ln T}{d \ln I} = \frac{\Delta I}{I} \frac{1 - e^{-x}}{x},$$

(8)
so
\[ \frac{\Delta T}{T_r} = \frac{\tau_e}{y_e} \left( \frac{x_r}{th(x_r/2)} - 4 \right). \] (9)

We will use these formulas for elliptical galaxies. Calculating value of \( \tau_e^0 \) and \( y_e = \frac{mc^2}{k_B T_e} \), we will accept that electron gas is isothermal and parameter \( R_e = R \) (see table 2).

Logarithms of absolute values of intensity of CBR (in units of spectral intensity, i.e. \( \text{erg}/(\text{c cm}^2 \text{Hz}) \)) and logarithms of relative disturbances of temperature as a function of wavelength in mm for three galaxies, characteristics of which are shown in table 1, are presented on figures 3 and 4. Changes of intensity are negative on wavelength larger than 1.3775 cm, so logarithms are taken from their absolute values.

\[ \log |\Delta I| + \log \frac{\tau_e^0}{T_r} \]

Figure 3. Absolute disturbances of intensity of CBR depending on wave length in the directions to three galaxies.

\[ \log \left| \frac{\Delta T}{T_r} \right| + \log \frac{\tau_e^0}{T_r} \]

Figure 4. Relative disturbances of temperature of CBR depending on wave length in the directions on three galaxies.

Disturbances are equal to 0 at the point \( \lambda_0 = 1.3775 \) mm, hence logarithm tend to \(-\infty\). If \( \lambda \to 0 \), then relative disturbances tend to \( \infty \). We remind that relative disturbances do not depend
on $z$, because they are expressed only through the function, depending on $x_t$ - ration of frequency and temperature, which both are proportional to $1 + z$.

Disturbances depend on distance from the galaxy center $r_e$ so on the figures disturbances are presented and they are calculated for maximum optical depths (therefore there are shown additional term - logarithms of ratio of maximum and mean depth along the line of sight). Spectral disturbance of intensity of CBR $\Delta I$ do not change, if we do not account for cosmological expansion and absorption on the line of sight, because temperature and frequency, used in expression for dimensionless frequency are changed at the same way. Intensity decreases as $(1 + z)^2$, because of redshift and different temp of time. This factor is nearly to unity, because redshifts of three galaxies are not large. Intensity is calculated on the unity of space angle, but receiver fixes radiation redshift and different temp of time. This factor is nearly to unity, because redshifts of three galaxies, spectral fluxes of CBR $H_{max} = I_{max}\Delta \Omega$ in maximum disturbance of CBR (on $\lambda_{max} = 0.81$ mm), additional fluxes, because of scattering $\Delta H_{max} = \Delta I_{max}\Delta \Omega$ in Jy are presented in table 2 too. Parts of additional fluxes and relative temperature perturbations are shown in table at the same wave length.

Here are estimations for wave length 0.81 mm, which belongs to Wien spectral region of CBR, where scattering encreases intensity. The largest part of observations of SZ belongs to Rayleigh-Jeans region, in which intensity decreases. It is seen from figures 3 and 4 that in Wien region effect strongly depends on $\lambda$, at $\lambda > 1.38$ mm this dependence is more smooth. For example, to get $\Delta H_{max}/H_{max}$ and $(\Delta T/T_e)_{max}$ at $\lambda = 3$ mm, we have to multiply quantities from table 2 multiply on 0.596, and at $\lambda = 10$ mm - on 0.771.

We will remind that presented quantities are calculated for maximum optical depths of electron gas of galaxies. For the solution of integral characteristics we have to multiply them on $\pi r_e^2/D^2$, which depend on galaxy parameters $r_e$ and $\beta$ and are shown in figure 2. This will decrease the value of effect. For example, for $\beta=1$ and $r_e=0.2, 0.4, 0.6, 0.8, 2.0$ corresponding factors are 0.078, 0.237, 0.370, 0.529, 0.632.

Along with scattering on thermal electrons, macroscopic motions influence on spectrum of CBR: peculiar motion of galaxies and rotation. This additional kinematical SZ-effect leads to the following distortion of spectra [2]:

$$\Delta I = -2\frac{(k_B T_e)^3}{h^2 c^2} \frac{v_t}{c} G(x_t), \quad G(x) = \frac{x^4 e^x}{(e^x - 1)^2},$$

where $V_t$ - radial velocity of electron gas relative to CBR.

We can consider peculiar velocities of galaxies to be not lower than velocities of motion of galaxy clusters, so kinematic effect also can be observed. Calculated values of disturbances of CBR and consideration about their peculiar velocities allow

| Name   | $y_e$ | $\tau_e^0$ | $\Delta \theta$ | $\Delta \Omega$ | $H_{max}$ | $\Delta H_{max}$ | $\Delta H_{max}/H_{max}$ | $(\Delta T/T_e)_{max}$ |
|--------|------|------------|----------------|----------------|-----------|----------------|---------------------------|------------------|
| NGC 499 | 568  | 1.83 · 10^{-2} | 4.19 | 47 · 10^{-4} | 522 | 0.28 | 5.4 · 10^{-4} | 8.14 · 10^{-5} |
| NGC 1332 | 119  | 0.99 · 10^{-2} | 6.36 | 107 · 10^{-7} | 1188 | 1.63 | 1.4 · 10^{-3} | 2.10 · 10^{-4} |
| NGC 4291 | 119  | 1.25 · 10^{-2} | 7.25 | 140 · 10^{-7} | 1554 | 2.70 | 1.7 · 10^{-3} | 2.67 · 10^{-4} |

us to consider that observations of SZ-effect on electron gas in elliptical galaxies are possible with modern tools. Indeed, anisotropy of CBR is observed on level $10^{-5} \div 10^{-6}$ relative to background [5], which exceeds necessary quantity according to figure 4. The same conclusion can be done for absolute
values of distortions, because sensitivity of antennas of modern radio telescopes in millimeter and submillimeter range is about 1 Jy in second [45], hence effect can be observed for the more distant galaxies too. Satellite PLANCK, whose launch is planned in 2008, allows to increase this distances.

Conclusions

We showed that elliptical galaxies are objects, which as galaxy clusters can noticeably distort spectrum of CBR by scattering in hot gas. In spite of the temperature of gas is lower, than in clusters, and galaxies are observed on shorter distances, their properties are known much better, than properties of clusters. Particularly, we can take into account the influence of rotation, unhomogeneous of gas distribution, its temperature and also influence of hot gas flows of different nature. According to [6] the value of thermal effect on galaxy clusters varies from $-3.5 \cdot 10^{-3}$ K till $6 \cdot 10^{-3}$ K, but their are clusters for which the effect is an order higher. In the case of elliptical galaxies the value of effect in Rayleigh-Jeans region is an order lower, for considered galaxies it corresponds to $5 \cdot 10^{-5}$ K, $1.25 \cdot 10^{-4}$ K and $1.59 \cdot 10^{-4}$ at $\lambda = 3$ mm.

The case of scattering CBR by hot gas, outflowing from AGN is not less interesting. Recently a work of E. Scannapieco et al [46] has appeared, in which the influence of hot gas from AGN on small scale distribution CBR is considered and dependence of temperature distortion of CBR from redshift of galaxies is obtained, both thermal and kinematical SZ-effect being considered. In spite of the effect was examined in AGN (not in elliptical galaxies), results are in good accordance. Thus, observations of SZ-effect in elliptical galaxies and AGN (along with observations of these galaxies in other wavebands) can give us additional information about their structure and properties of components, also they will allow us to make more precise parameter of cosmological models.

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