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The Observation of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies

Introduction

The x-ray radiation from a number of clusters of galaxies (Coma, Virgo, Perseus) was discovered recently.[1] It is assumed that clusters of galaxies form an important class of powerful x-ray sources, possibly giving the main contribution to the x-ray background radiation of the Universe.[2] What is the nature of these sources? What physical mechanisms give the observed x-ray radiation?

Most likely this is either the bremsstrahlung radiation of hot intergalactic gas or inverse Compton scattering on the relativistic electrons. Again the question arises—what kind of radiation and where is it scattered? The relic photons in the intergalactic space,[3] or in haloes of massive elliptical galaxies,[4] or infrared radiation in the vicinity of nuclei of galaxies?[5] The observations of small perturbation in angular distribution of relic radiation can give an answer to these questions. These observations enable us to distinguish between hot nonrelativistic electron gas (being a bremsstrahlung source) and a less numerous group of relativistic electrons. The hole in the relic radiation—the decreasing of its brightness temperature in the Rayleigh–Jeans spectral region,

$$\frac{\Delta T_r}{T_r} = -2\frac{kT_e}{m_e c^2}\sigma_T N_e l,$$

must be observed in the directions to the source with hot electrons,[6] if the latter are optically thin on bremsstrahlung absorption and Thomson scattering. At large optical depth on Thomson scattering the effect increases strongly. The basic physical mechanism is the transfer of soft photons ($h\nu \ll kT_r$) into short wave regions ($h\nu \gg kT_r$).

The properties of relic radiation

We propose to exploit the 2.7 black-body relic radiation. It is undoubtedly the best source of information on any deviations from the isotropy and homogeneity of the Universe and its characteristic features are astonishing: (1)

Excellent isotropy—independence in the direction $\delta F_\nu/F_\nu$ less than 10^{-3} in all angular scales from 10 angular minutes to 24 hours: (2) Its dominance over the radiation of discrete radio sources (at observations with broad angles) in the centimeter and millimeter wavelength bands of the radio background spectrum: (3) The spectrum follows the Rayleigh–Jeans formula $F_\nu = 2kT_r/\lambda^2$ with great precision (better than 5% or 10%) in the 70 cm–0.3 cm wavelength interval.

These properties are quite enough for the use of relic radiation in the proposed test. And, what is more, the realization of tests on different wavelengths can promote elucidation of the exact spectrum of relic radiation.†

The distortion of relic radiation spectrum via Thomson scattering on thermal electrons

As is well known, Thomson scattering of radiation on the thermal electrons leads not only to a change of the direction of photon propagation (isotropization) but also to the broadening of spectral lines due to Doppler effect. Our problem is the investigation of thermal electrons interacting with spectrally broad radiation having Planckian distribution over frequencies. It is assumed that in the isotropically expanding Universe there is a nonexpanding cloud of Maxwellian electrons with $T_e \gg T_r$.

Neglecting the frequency shift by scattering, we would obtain no effect. Obviously elastic scattering of photons cannot change the equilibrium isotropic radiation. Photons 1 scattered into 1 do not reach the observer but, instead, photons 2 are scattered into the observer (2) and replace the lost 1. The compensation is exact and valid even in multiple scattering situations.

Owing to thermal motion (velocity V) of electrons the frequency is shifted randomly by

$$\frac{\Delta\nu}{\nu} = f\frac{V}{c},$$

where f depends on the angles between the electron velocity and photon propagation before and after scattering; soft photons $h\nu \ll kT_e$ are considered —an excellent approximation in the radio frequency band. Assume electrons moving isotropically (with equal probability in all directions; the Maxwellian distribution in the partial case) in the coordinate system in which the unperturbed radiation is isotropic. At cosmological distance this means that the peculiar velocity of the plasma investigated is neglected. This means that the number of photons whose frequency has been raised ($\Delta\nu > 0$) and lowered ($\Delta\nu < 0$) owing to scattering are equal. In a broad spectrum the first-order effect vanishes. However, a second-order effect, proportional to $\overline{(\Delta\nu)^2}$, i.e. to v^2/c^2, remains. In turn, v^2/c^2 for the electrons is proportional to $kT_e/m_e c^2$.

† This remark is due to Yu. N. Pariysky.

A rather long calculation gives the answer for an arbitrary radiation spectrum in the form†[7,8]

$$F(\nu)_{\text{before}} - F(\nu)_{\text{after}} = y\nu \frac{d}{d\nu} \nu^4 \frac{d}{d\nu} \nu^{-3} F(\nu)_{\text{before}},$$

where $y = (kT_e/m_e c^2)\tau_T \ll 1$; $\tau_T = \int N_e \sigma_T \, dl$, $\sigma_T = (8\pi/3) r_0^2 = 6.65 \times 10^{-25}$ cm^2 is the Thomson cross section.

Inserting the Rayleigh–Jeans initial spectrum $F_\nu = A\nu^2$ into the right-hand side, we obtain

$$\Delta F_\nu = F(\nu)_{\text{before}} - F(\nu)_{\text{after}} = -2yF(\nu)_{\text{before}}.$$

The Planckian spectrum of radiation as a whole is not preserved: its Rayleigh–Jeans part is reduced and its Wien region $h\nu \gg kT_r$ is increased,

$$\Delta F_\nu = y\left(\frac{h\nu}{kT_r} - 2\right) F(\nu)_{\text{before}}.$$

The energy of radiation integrated over all the spectrum increases,

$$\int F(\nu)_{\text{after}} \, d\nu = e^{4y} \int F(\nu)_{\text{before}} \, d\nu, \quad \Delta\mathscr{E} = (e^{4y} - 1)\mathscr{E} = 4y\mathscr{E},$$

but the number of photons is constant,

$$\int \frac{1}{h\nu} F(\nu)_{\text{after}} \, d\nu \equiv \int \frac{1}{h\nu} F(\nu)_{\text{before}} \, d\nu.$$

Qualitatively the results are obvious: scattering has preserved the number of photons. The electron temperature is assumed much higher than the radiation temperature, therefore the general trend is a cooling of electrons and an increase in the radiation energy, with conservation of photon number. This is possible only by means of photon transfer from the low-frequency region $h\nu \ll kT_r$ to the high-frequency region $h\nu \gg kT_r$.

Clusters of galaxies—the best candidate for observation of the proposed effect

In the rarefied intergalactic or interstellar gas the Compton optical depth is small, $kT_e/m_e c^2 \ll 1$, and therefore the effect is small. However, the properties of relic radiation mentioned and the great precision of comparative

† This is the appropriate approximation of the general kinetic equation[9,10]

$$\frac{\partial n}{\partial t} = \frac{\sigma_T N_e h}{m_e c} \nu^{-2} \frac{\partial}{\partial \nu} \nu^4 \left(n^2 + n + \frac{kT_e}{h} \frac{\partial n}{\partial \nu} \right)$$

where $n = (c^2/8\pi h\nu^3) F_\nu$ is the occupation number in photons phase space. In the situation considered, the terms n^2 and n can be neglected as compared with $(kT_e/h)\partial n/\partial \nu$, because $T_e \gg T_r$. Inserting the initial spectrum into the right-hand side of the general equation, we easily obtain the form given above for small distortions of the initial spectrum.

measurements allow us to measure the small-scale fluctuations with a sensitivity unequaled by absolute measurements.

If hot intergalactic gas really exists in clusters of galaxies, there are all the conditions for action of the proposed effect. Thus, for example, the x-ray radiation of the Coma cluster of galaxies is interpreted as the bremsstrahlung radiation of a hot intergalactic gas having $T_e \sim 7 \times 10^7$ °K and the density $N_e \sim 10^{-3}$ cm^{-3}. The linear dimension of the source is estimated to be $l \sim 10^{25}$ cm^{-3}. Multiplying these figures, we find

$$\frac{\Delta T_r}{T_r} = -2y = -2\sigma_T N_e l \frac{kT_e}{m_e c^2} \sim 2 \times 10^{-4},$$

the value accessible for observations. Namely, such effect was recently discovered in Coma by Pariysky.[11]

The deficit of brightness (hole) in the Coma is difficult to understand by any other mechanism! The radiation temperature is 2.7 °K; an arbitrary absorption of radiation is always accompanied by spontaneous emission. If the temperature of the absorber is higher than 2.7 °K, the net result would be an increase of radiation, instead of the observed deficit.

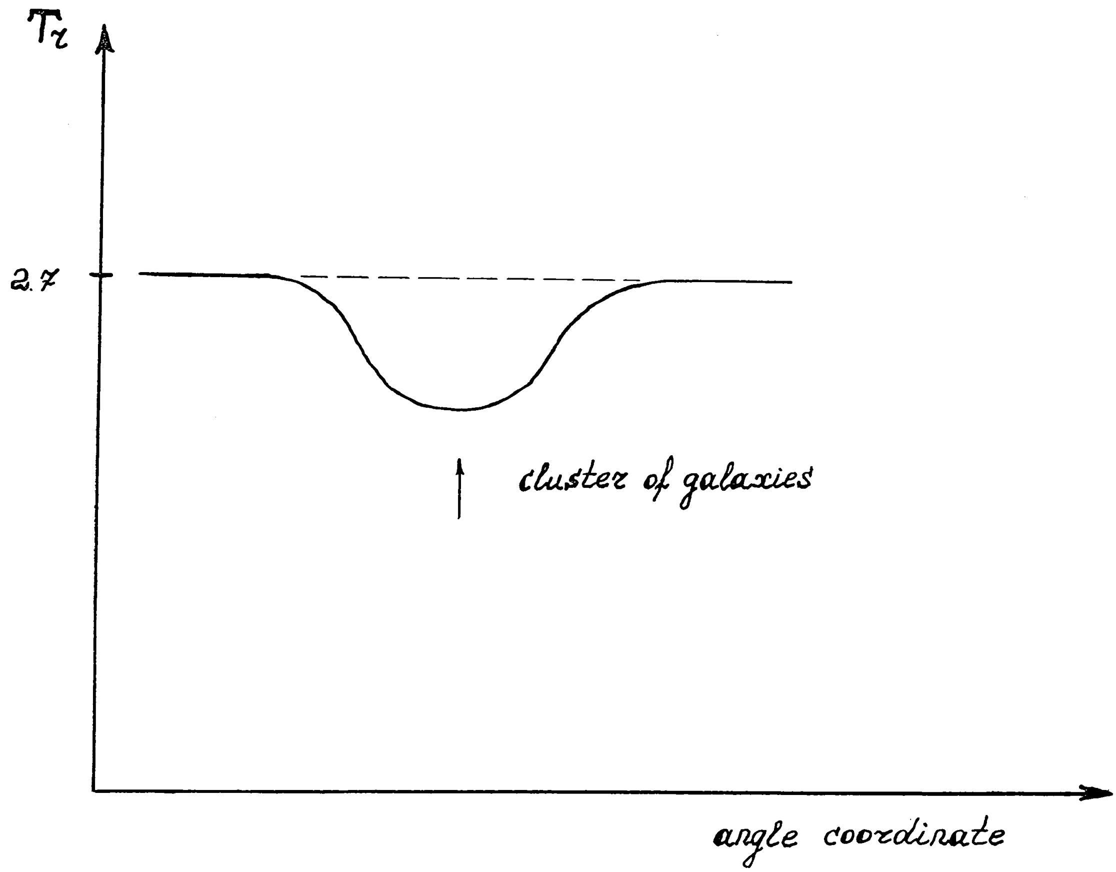

FIG. 1. The "hole" in the microwave background.

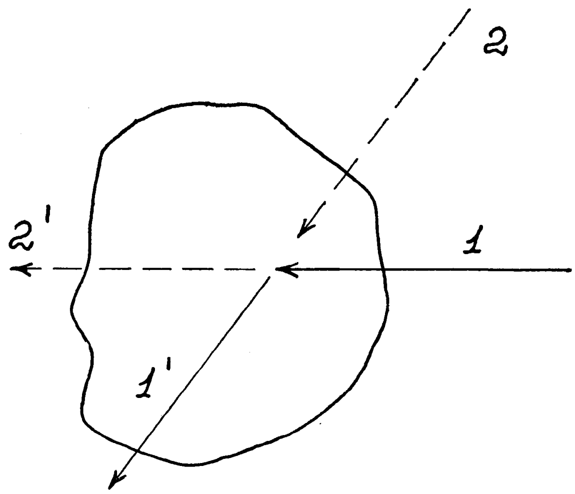

FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

The common radiation of galaxies and radiogalaxies of the cluster must also lead to an increase of radiation intensity in the direction to the cluster. However, in the centimeter band the contribution of galaxies to the background is small, as follows from direct observations (see, for instance, Ref. 12) and this is confirmed by Pariysky's observations.

There is only one other mechanism leading to the "hole" in relic radiation. The receding of the cloud of electrons from the observer leads also to a decrease of relic radiation temperature in the direction of this cloud. The radiation temperature deficit is equal to

$$\frac{\Delta T_r}{T_r} \sim \tau_T \frac{v}{c} \cos\theta = \sigma_T N_e l \frac{v}{c} \cos\theta,$$

where v is the velocity of the cloud in the reference frame connected with relic radiation, θ is the angle between the velocity vector and the direction to the observer. The Doppler change of temperature does not depend on the frequency, contrary to the statement above (diffusion of the photons on the frequency axis due to scattering on hot electrons). Therefore it is possible to distinguish these effects observing the "hole" in the low-frequency, $h\nu < kT_r$, and high-frequency, $h\nu > kT_r$, parts of the spectrum.

Both effects are equal at

$$\frac{2kT_e}{m_e c^2} = \frac{v}{c}.$$

If the observed "hole" in Coma results from its receding, even at $\cos\theta = -1$, the velocity v of its motion in the reference frame connected with the relic radiation must be of the order of 7000 km/s. This value is of the order of the velocity found from redshifts of the lines in the spectra of galaxies in Coma.

However, this velocity is most likely connected with the expansion of the Universe, and the value of v given above contradicts observations.

Conclusion

Thus, the decrease of brightness temperature of relic radiation in the direction of the cluster of galaxies identically testifies to the existence of hot intergalactic gas in clusters. The effect is proportional to the product $\int N_e T_e \, dl$. Knowing the angular dimensions of the "hole" and the distance to the cluster of galaxies, we can identically evaluate $\int \Delta T_r \, d\Omega$ in $\int N_e T_e \, dV$, which in turn gives the full thermal energy of all free electrons in a given object. Most interesting data may be obtained by comparing this information with the data of x-ray observations. The x-ray radiation intensity of the hot gas is proportional to $\int N_e^2 T_e^{-1/2} \, dV$: The x-ray measurements allow us to determine the temperature of the gas. Using all these data it is possible to define the lower bound of the mass of intergalactic gas in the cluster of galaxies and to find its spatial distribution. To confirm our explanation, it would be important to make measurements on different wavelengths. In principle, by refining the measurements, one could extract information on possible deviations of the spectrum from the simple Rayleigh–Jeans formula, which are of extreme cosmological importance.[8]

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