A&A 387, 379–382 (2002)
DOI: 10.1051/0004-6361:20020371

Astronomy & Astrophysics

The Rees-Sciama effect and the primordial nucleosynthesis

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Received 21 November 2001 / Accepted 12 February 2002

Abstract. It is known that, theoretically, the Rees-Sciama effect may cause arbitrarily large additional redshifts in the cosmic microwave background radiation due to transparent expanding voids having sizes comparable with the size of horizon. Therefore, again theoretically, eventual huge voids existing immediately after the recombination may essentially change the predictions of the theory of big bang nucleosynthesis. If this eventuality holds, then the dark matter can be dominantly baryonic and, simultaneously, one can be in accordance with the predictions of primordial nucleosynthesis theory. Studying this eventuality one arrives at the result that the observed extreme isotropy of the cosmic microwave background radiation rejects the existence of any such huge voids, and hence this eventuality does not hold.

Key words. cosmic microwave background – dark matter – early Universe – cosmology: miscellaneous

1. Introduction

The Rees-Sciama effect (Rees & Sciama 1968; for a detailed survey see Mészáros & Molnár 1996; Zaldarriaga et al. 1998; Sakai et al. 1999 and the references therein) causes an additional non-Friedmann shift of the photons of cosmic microwave background radiation (hereafter CMBR) due to the changing gravitational field of transparent expanding structures being between the last scattering surface and us. These structures may be either overdensities (cf. superclusters) or underdensities (cf. voids), and also the additional shift may be both redshift or blueshift, respectively.

This effect may clearly be important in galaxy formation scenarios, where the initial perturbations during the recombination play a cardinal role, and these perturbations may be deduced from the observed anisotropies of CMBR. The importance follows from the fact that, due to the Rees-Sciama effect, the observed anisotropies of CMBR need not entirely be caused by the inhomogeneities of non-relativistic matter during the recombination, and the later transparent structures may also cause anisotropies in CMBR (see Mészáros 1994 for more discussion of this question).

In addition, surprisingly, this effect can have a connection to completely different cosmological topics. For example, Mészáros & Molnár (1996) show an interesting connection between this effect and the observations of Lauer & Postman (1994), where the peculiar velocity of the Earth and the maximum of the dipole anisotropy of CMBR were found to have different directions. Mészáros & Molnár (1996) show that – theoretically and surprisingly – the dipole anisotropy of CMBR may also be caused by the Rees-Sciama effect. Nevertheless, further observational data exclude this possibility. The importance of that work was recognized even by the editors of Sky & Telescope Magazine (Sky & Telescope 1997).

A similar surprising connection is the subject of this article. It discusses the connection between this effect and the primordial nucleosynthesis. Interestingly, this connection may have an essential impact on the character of dark matter of Universe (at least, in principle), because this dark matter can dominantly be baryonic. Because the character of dark matter is one of the most important open questions of present-day Cosmology, it is doubtlessly true that the subject of this article is highly topical.

The paper is organized as follows. Section 2 succinctly summarizes the known facts about the Rees-Sciama effect. In Sect. 3 the connection between this effect and the primordial nucleosynthesis is formulated. Section 4 shows that observations reject this connection. Finally, in Sect. 5, the results of paper are summarized.

2. Survey of the Rees-Sciama effect

In this Section, we summarize briefly the known facts concerning the Rees-Sciama effect.

The majority of the several papers (see Mészáros & Molnár 1996 and references therein) dealing with this effect discusses the case of a single spherically symmetric overdense region. There are only a few articles that discuss the case of a single void (Thompson & Vishniac 1987; Mészáros 1994; Mészáros & Molnár 1996).

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Summarizing the main results of the topic one may conclude: a) The effect is independent of wavelength, and therefore the black-body spectrum remains, and only the corresponding temperature is changed due to the crossing of photons across a transparent structure; b) The void causes an additional redshift (i.e. the temperature of CMBR is smaller than the Friedmann value); c) The overdense region causes both additional redshift and blueshift, and the profile of this change is calculable either analytically or numerically; d) Effects from several voids and superclusters along the path of the photons of CMBR should simply be summed; e) The order of the effect is $|\delta T/T| \sim (|\delta\rho|/\rho)(y/d_{\rm hor})^{\beta}$, where T is the temperature of CMBR, δT is its change, $\beta \simeq (2.5–3.0)$, ρ is the Friedmann density, $\delta\rho$ is its departure from this value; y is the size of the object causing the additional shift, and $d_{\rm hor}$ is the size of horizon. It is essential to note that δT and T are the present-day observable values; the remaining quantities are understood for the time, when the object is crossed by the CMBR photons. It is also necessary to note that $|\delta\rho|/\rho \sim 1$ may also occur; i.e. the structures can be highly non-linear. The effect is increasing roughly cubically by the size of object. To illustrate, consider a spherical empty void with diameter $\sim$100 h^{-1} Mpc at $z \ll 1$; i.e. in the cosmological sense very recent (z is the redshift, and $H = 100\ h$ km/(s Mpc) is the Hubble parameter). Then the effect is of order $|\delta T/T| \sim 10^{-5}$ (Mészáros 1994). It must also be noted that – at least theoretically – this effect need not be so small. For example, Rees & Sciama (1968) in their original paper discuss a hypothetical case, when the effect is of order $|\delta T/T| \simeq 2\times10^{-3}$. It is even possible that the effect can be of order unity; again in principle. For example, assume that a void with $|\delta\rho|/\rho \simeq 1$ having a present-day size $\simeq$300 Mpc existed already during the recombination epoch. Because during the recombination epoch its physical size is $\sim$1000 times smaller, at that time $d_{\rm hor}$ was at the same order. In this hypothetical case this void would give an effect of order unity.

3. A possible impact on the character of dark matter and on the primordial nucleosynthesis

Surprisingly, in principle, the Rees-Sciama effect may lead to a new argument supporting the baryonic character of dark matter based on the theory of primordial nucleosynthesis. As far as it is known, this connection was never mentioned yet.

The key idea of this connection is the following. About 90% of matter in the Universe is dark, and recently is widely accepted that this dark matter is dominantly non-baryonic (Peebles 1993). The key argument against the baryonic character of dark matter is based on the theory of nucleosynthesis. This argument follows from the coincidence between the prediction of this theory and the observed abundances of H, D, ^{3}He, ^{4}He and ^{7}Li. A few years ago it was believed that this coincidence was fulfilled for the ratio $\eta = n_{\rm b}/n_\gamma = (1.6\pm0.1)\times10^{-10}$, where $n_{\rm b}$ is the number density of baryonic matter, and n_γ is the number density of photons of CMBR (Dar 1995). Later it was suggested (Turner et al. 1996; Cardall & Fuller 1996; Steigman et al. 1999) that this small and relatively precise value was not correct. For example, Steigman et al. (1999) obtain a much bigger value for this ratio from the primordial nucleosynthesis; the value $\eta \gtrsim 6\times10^{-10}$ is favored, and even the value $\eta = 13\times10^{-10}$ is not excluded. On the other hand, a value as small as $\eta \simeq 2\times10^{-10}$ is not yet excluded either. Recently one has $n_\gamma = 410$ cm^{-3}, and $n_{\rm b} = 1.124\times10^{-5}\ \Omega_{\rm b}h^2$ cm^{-3}, where $\Omega_{\rm b}$ is the ratio of baryonic density to the critical one (Peebles 1993; p. 103). Hence, one has $n_{\rm b}/n_\gamma = 2.74\times10^{-8}\ \Omega_{\rm b}h^2$. To be in accord with the earlier values of the theory of nucleosynthesis it must be that $\Omega_{\rm b}h^2 = (5.8\pm0.4)\times10^{-3}$; while with the highest allowed value of Steigman et al. (1999) $\Omega_{\rm b}h^2 \simeq 4\times10^{-2}$. The newest studies (see Coc et al. 2001 and the references therein) give $\Omega_{\rm b}h^2 = (1.5\pm0.3)\times10^{-2}$, i.e. $\eta = 4\times10^{-10}$. Different observations suggest that $\Omega_{\rm M} \simeq (0.1–0.4)$, where $\Omega_{\rm M}$ is the ratio of total density of non-relativistic matter to the critical density (Bahcall & Fan 1998). (Note here that for the purpose of this paper it is completely irrelevant, if the cosmological constant is zero or non-zero (Riess 2000).) This means that one must have $\Omega_{\rm M}/\Omega_{\rm b} \simeq (2.5–80)h^2$, i.e. for the allowed $h \simeq (0.6–0.75)$ (Freedman et al. 2001) the ratio $\Omega_{\rm M}/\Omega_{\rm b}$ must be $\simeq$(1–50). The first value seems to be excluded; only in the case of the lowest allowed $\Omega_{\rm M}h^2$ case with the highest allowed value of η can this occur. Because about 90% of matter is dark, the situation is straightforwardly solvable, if one assumes that this dark matter is dominantly non-baryonic.

For the sake of completeness it must be added here that – beyond the argument based on the primordial nucleosynthesis – there are two other different and independent arguments for the non-baryonic character of the dark matter. The first argument is based on the observed anisotropies of CMBR (see, cf., de Bernardis et al. 2001 and references therein). The obtained value $\Omega_{\rm b}h^2 = (0.022\pm0.004)$ clearly needs a dominantly non-baryonic dark matter. In addition, if one assumes that the dark matter is dominated by baryonic dark matter then any galaxy formation theory is in doubt. (For example, Peebles 1993 in Chapt. 25 "Baryonic Dark Matter" considers the adiabatic dark matter scenario as "only of historical interest" and also the isocurvature dark matter scenario is taken as an "unattractive" scenario.) The second argument follows from the observations of Lyman-α forest at high redshifts giving $\Omega_{\rm b}h^2 = (0.035\pm0.015)$ (see Hui et al. 2001 and references therein). However, the discussion of these arguments is not a subject of this article.

Consideration in primordial nucleosynthesis is based on the key assumption that $\eta = n_{\rm b}/n_\gamma =$ constant during the whole expansion of Universe. In the Friedmann models both $n_{\rm b}$ and n_γ must not depend on spatial coordinates; they depend only on time t. Because the functional dependence on time should be the same for both densities – specifically one should have $n_{\rm b} \sim n_\gamma \sim a(t)^{-3}$ ("the comoving densities of CMBR photons and baryons, respectively, are constant"; $a(t)$ is the expansion function) – the ratio of two densities should be constant (for more details see, e.g., Weinberg 1972). (Departures from $a^3 n_\gamma =$ constant may exist but should be small. For example, departures of order $\sim 10^{-5}$ should surely exist (Peebles 1971; p. 232). $a^3 n_\mathrm{b}$ should be even more constant.) Strictly, the theoretical prediction of n_b/n_γ from the theory of primordial nucleosynthesis is a prediction for this ratio for the first a few minutes of Universe, when the temperature of CMBR is $\simeq(1-10)$ MeV (Dar 1995).

In addition, it is automatically assumed that the ratio n_b/n_γ does not change in the later stages of Universe. Trivially, if n_b/n_γ = constant was not true in early times, then this standard assumption would be essentially modified.

Some attempts have been made not to fulfil this assumption. One of that is the case when n_b depends on spatial coordinates. These attempts do not lead to essentially new conclusions (Jedamczik & Fuller 1995).

Contrary to these attempts, assume for the moment that n_b/n_γ is changing drastically with time, but that spatial dependence is negligible. If this is the case, then the baryonic character of dark matter may easily be saved under some specific conditions. Simply, one has to assume that during the era of primordial nucleosynthesis $n_\mathrm{b}/n_\gamma \simeq 10^{-10}$, but recently this ratio is $\simeq(2.5-80)\ h^{-2}$ times bigger. This skip may occur – at least in principle – in three ways: either by increasing the comoving number density of baryons, by decreasing the comoving number density of CMBR photons, or by the combination of both. From the physical point of view only the case when the comoving number of photons is decreasing seems to be allowable.

The key idea of this paper is to remark that such a decrease of the number of photons may occur. This decrease is in principle possible due to a global Rees-Sciama effect of order unity caused by voids having the sizes of horizon. This may be seen as follows.

If CMBR is a blackbody radiation (this is assumed everywhere in this article), then $n_\gamma(t) \propto a^{-3}(t)$. This relation is standardly assumed to be fulfilled with high accuracy during the whole epoch of expansion after the annihilation of electron-positron pairs (Peebles 1971; Weinberg 1972). Assume for the moment that this relation is fulfilled only before recombination, but that does not hold during a short period after recombination. Everything else is identical to the case of the standard Friedmann model. In the standard picture recombination occurs at $a_\mathrm{o}/a(t) \simeq 1000$ (Peebles 1971), where a_o is the present value of expansion function. Assume here that recombination occured later: at $a_\mathrm{o}/a(t) = 1000/q$. The value q should be chosen to have $q \simeq (1-50^{1/3}) \simeq (1-3.7)$. Before recombination the value of $\eta = n_\mathrm{b}/n_\gamma$ was in accordance with the prediction of primordial nucleosynthesis. Nevertheless, immediately after recombination there is a skip in the temperature of CMBR; this temperature is immediately decreasing q-times. As the simplest situation, it may be assumed that this skip occurs instantaneously; i.e. during this decrease of temperature the change of $a(t)$ is unimportant. Hence, if this skip of temperature occurs, it can easily be that $\Omega_\mathrm{M} = \Omega_\mathrm{b}$ today.

All this gives the following idea. Assume that, shortly after recombination, the Universe is filled by sufficiently large voids. This means that immediately after recombination large non-linear structures exist. (It must be stated here that this situation is not precisely identical to the model of Jedamczik & Fuller (1995). They assume non-linear structures already during nucleosynthesis – i.e. during the first a few minutes of Universe. Here no non-linearities are needed before recombination. They are needed only shortly after recombination.) This situation may lead – shortly after recombination – to an additional global redshift; compared with the Friedmann value the temperature of CMBR should decrease q times. Knowing the results of the studies concerning the Rees-Sciama effect, one may conclude that this decrease is possible – at least, in principle.

Of course, several questions emerge for this eventuality; both from the theoretical and the observational point of view. The discussion of these questions is the subject of the next section.

4. Solution: No impact

From the purely theoretical point of view, the eventuality of the decrease of T of CMBR q-times with respect to the Friedmann value seems to be allowed.

Theoretically, two conditions are required to occur for this phenomenon. First, to have this huge Rees-Sciama effect the existence of voids of sizes comparable with the horizon at $z \simeq 1000/q \simeq (300-1000)$, when the recombination occurs, is required. Remarkably, this can happen, because in the baryon dominated galaxy formation scenarios the non-linearities should exist even during recombination (Mészáros 1997 and references therein). Second, recombination should be "delayed" and should occur at $z \simeq (300-1000)$. The "delayed" recombination is in principle again allowed. On the other hand, there are also strange artificial requirements: first, why exactly q times does this additional decrease occur, and not – say – ten or hundred times more? Second, how did these huge voids arise already during recombination? Here one has to add that some objects may exist during recombination (Mészáros 1991; Mészáros 1997; Baccigalupi 1998; Sakai et al. 1999), but not huge voids comparable with the size of horizon. Third, if these huge voids existed at $z \simeq (300-1000)$, why are some objects not seen already at these redshifts? Hence, purely from the theoretical point of view, the huge global Rees-Sciama effect is allowed, but its occurence is strange enough.

Even worse is the situation from the observational point of view. There are at least three counter arguments here. First, voids of the sizes of the horizon at $z \simeq (300-1000)$ should today have sizes of hundreds of Mpc. No such objects are observed; the observed voids have sizes of tens of Mpc. Second, the sizes of these voids

– leading to the global additional redshift defined by q – are highly artificial, because they should have roughly the same sizes. Nothing like this is observed. Third, even if this were the case, it would be practically excluded that in any direction the same huge (of order unity) additional redshift occurs. The observed variance of this effect should be of order $\sim 10^{-5}$ or smaller, because this is the order of the observed variance of $|\delta T|/T$ (Peebles 1993; Zaldarriaga et al. 1998; de Bernardis et al. 2001). In fact, the question of the variance of the Rees-Sciama effect – caused by several objects – was already discussed and solved in detail (Thompson & Vishniac 1987; Sakai et al. 1999). These articles arrive at the result that the variance and the size of the Rees-Sciama effect should have the same order. Therefore, voids with sizes comparable to the horizon at $a_o/a(t) = 1000/q$ should give angular scales at $\simeq q$ degrees (this is the corresponding angular scale for the horizon at these redshifts, Peebles 1993) a variance of order unity in the temperature of the CMBR. This is obviously not observed. This is the key argument against the huge global Rees-Sciama effect.

It seems that any further speculation about the voids having the sizes comparable with horizon scale is hopeless.

5. Conclusions

The purpose of this paper was to discuss the potential impact of the Rees-Sciama effect on the character of dark matter. The first result of this paper is the surprising fact that – in principle – once a global Rees-Sciama effect occurs after the recombination, then the dark matter may be dominantly baryonic. The second result is even more surprising: from the purely theoretical point of view, under highly artificial but physically allowed assumptions, the global Rees-Sciama effect can really occur. Nevertheless, the third result seems to be unambiguous: there is a clear contradiction with the observations, because the extreme observed isotropy of CMBR on the order $\sim 10^{-5}$ excludes the occurence of a global huge Rees-Sciama effect.

One has still to add that – due to the fully negative conclusion – it might appear that the purposes of this paper were useless. The author argues that this is not the case for three reasons. First, any, in principle, allowed connections between two different topics should always be discussed. (In fact, the situation is similar to the case when the Rees-Sciama effect and the Lauer-Postman's observations were discussed together. There negative results were also obtained, but the importance of that discussion was obvious.) Second, from the purely theoretical point of view, the global Rees-Sciama effect is allowed; under artificially strange conditions, but it is allowed. This conclusion alone is remarkable and fully new. Third, it is not excluded that in the future the situation will change due to new observational effects. For example, if reionization (Baltz et al. 1998; Weller 1999) were confirmed at – say – $z \simeq (5-20)$, then the observed extreme isotropy of CMBR would reflect the situation after reionization, and not after recombination; then the key argument against the huge global Rees-Sciama effect would be overcame.

Acknowledgements. The useful remarks of Dr. F. Vrba and of the anonymous referee are kindly acknowledged. This research was supported by Research Grant J13/98: 113200004.

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