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SCARS ON THE CBR?

A.G. Cohen[a] and A. De Rújula[b,a] *

[a]*Department of Physics, Boston University, Boston, MA 02215, USA*
[b]*Theory Division, CERN, 1211 Geneva 23, Switzerland*

Abstract

We ask whether the universe can be a patchwork consisting of distinct regions of matter and antimatter. In previous work we demonstrated that post-recombination matter–antimatter contact near regional boundaries leads to an observable (but unobserved) gamma-ray flux for domain sizes of less than a few thousand Mpc, thereby excluding such domains. In this paper we consider the *pre*-recombination signal from domains of larger size.

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*cohen@bu.edu, derujula@nxth21.cern.ch

We recently studied in detail the possibility that space is divided into domains that are equally likely to be made of matter or of antimatter [1]. We computed the nuclear annihilation rate for matter and antimatter near domain boundaries and showed that the resulting relic diffuse gamma-ray flux exceeds the observed cosmic diffuse gamma (CDG) spectrum, unless the domain size is close to that of the visible universe. We thus concluded that a symmetric universe with comparable amounts of matter and antimatter is excluded, unless the typical current size of the domains of uniform composition is $d_0 > 1$ Gpc[1]. In this paper we study the possibility of closing the gap, of less than one order of magnitude, between this scale and the size of the visible universe.

Kinney *et al.* [2] have studied "ribbons" in the temperature of the cosmic background radiation (CBR) that arise at the intersection of domain boundaries with the last scattering surface. This assumes that matter and antimatter came into contact prior to the time at which CBR photons last scattered. In our previous analysis we refrained from making this very natural assumption, because it cannot be argued to be empirically unavoidable.

In this note we *do* assume that matter and antimatter domains were in contact prior to last scattering. If the effects of contact and concomitant annihilation significantly distort the radiation from the last scattering surface, a single domain boundary—or even a fraction thereof—may be detectable. Conversely, the absence of such signatures would complete the proof of our no-go theorem: a universe with comparable amounts of matter and antimatter would be excluded.

We revisit the work of Kinney *et al.* and reach a different conclusion: we find that even the next generation of satellite CBR probes will have a temperature-contrast sensitivity inferior to what is needed to detect the effects of matter-antimatter annihilation on the CBR.

Let $n_B(t)$ and $n_\gamma(t)$ be the baryon and photon number densities, with $\eta \equiv n_B/n_\gamma$. Assume spatially uniform, equal baryon and antibaryon densities prior to last scattering[2] except near domain boundaries, where annihilation leads to depletion. To study the effects of annihilation, we must determine the baryon annihilation rate per unit surface $J(t)$ at the interface between a

[1]Our explicit numbers refer to a "fiducial" choice of cosmological parameters: critical mass density $\Omega = 1$; vanishing cosmological constant $\Omega_\Lambda = 0$; Hubble constant $H_0 = 75$ km/s·Mpc or $h = 0.75$.

[2]For the conventional range of cosmological parameters the approximate times of last scattering and the formation of stable atoms are nearly coincident.

matter and an antimatter domain. The detailed analysis of how this can be done is found in [1]. Here we simply quote the results that are relevant to the problem at hand.

Our conclusions are insensitive to the contamination of nuclear species other than protons in the primordial plasma and to the effects of electron-positron annihilation: we can concentrate on $p\bar{p}$ annihilation. Its direct products are primarily pions (π^+, π^0 and π^-) with similar multiplicities and energy spectra. The end products are gamma rays from π^0 decay, energetic electrons $e^\pm$ from the decay chain $\pi \to \mu \to e$, and neutrinos. The behaviour of relativistic e^+ and e^- is sufficiently similar to justify referring to both as electrons.

The electrons from $p\bar{p}$ annihilation lose most of their energy by Compton scattering off CBR photons. The energy distribution of the upscattered photons straddles an energy domain from the hydrogen binding energy to a few keV, in which the K-shell photoionization cross section is very large. Consequently, these photons keep matter and antimatter close to a fully ionized domain boundary, even well after the time at which recombination would have occurred in a standard cosmology[3].

Annihilation near a domain interface causes a flow to develop as new fluid replenishes what is annihilated. The $e^\pm$ from $p\bar{p}$ annihilation lose a small portion of their initial energies by scattering off ambient electrons in the fluid. This process transfers heat to the fluid, but prior to last scattering the effect on the matter temperature $T(t)$ is small: CBR photons act as a large and efficient heat bath, with a temperature $T_\gamma(t)$ that is not significantly affected by annihilation. Interactions between the matter and the CBR keep the matter temperature $T(t)$ close to $T_\gamma(t)$. This small increase of the electron temperature relative to the photon temperature results in a small distortion away from a thermal CBR spectrum, in the manner first described by Sunyaev and Zeldovich [3]. It is this effect, localized along domain boundaries at last scattering, that must be computed.

Prior to last scattering the motion of the cosmic plasma is damped by the interaction of the ambient charged particles with the CBR. The fluid motion is thus diffusive, described by a time-dependent diffusion coefficient:

$$D_{e\gamma}(t) \equiv \frac{45}{4\,\pi^2\,\sigma_T\,T_\gamma^3(t)}\,, \tag{1}$$

[3]Kinney *et al.* assume a conventional recombination history; at this point our analysis diverges from theirs.

with σ_T the Thompson cross section. The diffusive nature of the process has the welcome consequence that memory of the initial conditions is lost as the fluid evolves. To an excellent approximation the annihilation current $J(t)$ (also computed numerically in [1]) is given by:

$$J(t) \equiv n_B(t)\, v(t) \simeq n_B(t) \sqrt{\frac{5\, D_{e\gamma}(t)}{3\, \pi\, t}}\ , \tag{2}$$

with $n_B(t)$ the proton number density far from the matter–antimatter interface and $v(t)$ an effective velocity defined here for ulterior convenience. The current $J(t)$ is much smaller than the atomic-free-streaming current used by the authors of [2], explaining the bulk of the discrepancy between our conclusions and theirs.

Some of the energy carried off by electrons, $Q \sim 320$ MeV per annihilation, is transferred via the plasma to the CBR. Let ΔH_{LS} be the excess energy per unit volume accumulated in the CBR by the time of last scattering (at a certain location on the last-scattering surface) from the effects of all previous annihilations. The conventional Sunyaev–Zeldovich y-parameter describing the local distortion of the CBR is $y = \Delta H_{LS}/(4\, u(t_{LS}))$, with $u(t_{LS})$ the CBR energy density at the time of last scattering, t_{LS}.

At time t_{LS} the annihilation energy is spread over a distance orthogonal to a matter–antimatter annihilation interface of size $\sim 2\lambda_{LS}$, with λ_{LS} the photon collisional damping scale ($\lambda_{LS} \sim 15$ kpc [4] for our fiducial choice of cosmological parameters). This length scale is also comparable to the resolution that the next generation of satellite CBR probes may achieve. For data acquired with this resolution, and upon neglect of geometrical factors such as the inclination at which the last scattering surface intersects a given domain interface, we may estimate the y-parameter distorsion of the "ribbon". The result:

$$y \sim \frac{1}{8}\, \frac{Q\, n_B(t_{LS})}{\lambda_{LS}\, u(t_{LS})} \int^{t_{LS}} \bar{f}(t)\, v(t)\, dt \tag{3}$$

is dominated by times close to t_{LS}. Here $\bar{f}(t)$ is the average fractional energy deposition in the CBR by annihilation electrons [2]. To complete our calculation we must compute $f(t)$.

An average of nearly four electrons is made per $p\bar{p}$ annihilation, with an energy spectrum peaked at $E_e \equiv m_e \gamma_e \sim 80$ MeV. Prior to recombination, Compton scattering on CBR photons completely dominates over the other electron energy-loss mechanisms (red-shifting and scattering on ambient matter). The spectrum of photons Compton-up-scattered by a single annihilation electron [1] at time t may be approximated by:

$$\frac{dn}{dw} \simeq \frac{8\,E_e}{3\,\pi\,\gamma_e\,\sqrt{3\,T_\gamma\,w^3}}\,\left[1-\frac{w}{3\,\gamma_e^2\,T_\gamma}\right]^{3/2}\Theta[3\,\gamma_e^2\,T_\gamma - w]\,. \tag{4}$$

This approximation is extremely good for the photon energies $w > 10T_\gamma(t)$ that dominate our results[4].

Red-shift and Compton scattering on ambient electrons have comparable effects in making a Comptonized photon lose energy:

$$\frac{dw}{dt} + H(t)\,w = -\,\frac{w^2}{m_e}\,\sigma_T\,n_e(t)\ , \tag{5}$$

with $H(t)$ the Hubble expansion rate and $n_e(t)$ the electron number density $n_e \simeq n_0\,z(t)^3$ (for the large red-shifts of interest we do not make the distinction between z and $1+z$). Let $z_{LS} \sim 1100$ be the last-scattering red-shift. At that time, a photon made at an earlier epoch z would, if it did not interact, have an energy $w\,z_{LS}/z$, but because of the interaction described by the rhs of Eq. (3) it has a lower energy. The difference between these two energies, $w_H(w,z)$, is the photon's contribution to the excess energy density ΔH_{LS} relevant to the CBR spectral distortion. Solving Eq. (5) we find:

$$\begin{aligned} w_H(w,z) &= w\,\frac{z_{LS}}{z}\,f(w,z) \\ f(w,z) &\equiv \frac{a\,w\left(z^{5/2}-z_{LS}^{5/2}\right)}{z+a\,w\left(z^{5/2}-z_{LS}^{5/2}\right)} \\ a &\equiv \frac{2\,\sigma_T\,n_0}{5\,m_e\,H_0}\,. \end{aligned} \tag{6}$$

The mean efficiency $\bar{f}$ in Eq. (3) is the energy-weighted average of $f(w,z)$ over the photon spectrum of Eq. (4):

$$\bar{f}(z) = \frac{1}{E_0}\int_0^\infty f(w,z)\,w\,\frac{dn}{dw}\,dw\ . \tag{7}$$

[4]In [2] a spectrum with a fixed energy $3\gamma_e^2\,T_\gamma$ is used. This results in an overestimate of the energy-deposition efficiency by a factor ~ 5.

Performing the integrations in Eqs. (3) and (7) we obtain $y \sim 3.4 \times 10^{-7}$. The result scales roughly as η^2/H_0 and we have used $\eta = 6 \times 10^{-10}$, $H_0 =$ 50 km/s/Mpc to illustrate the maximal expectation, within errors.

We have neglected a small additional energy deposition by Comptonized photons. Regions lying far from domain boundaries recombine as in a standard cosmology. A moving front develops between ionized and recombined regions as the photon flux progresses, depositing a fraction of its energy as it reionizes the medium. The velocity of the front is $v_f \sim c/(1+\xi)$ where ξ is the ratio of the atomic number density to that of the incident photon flux. Around recombination the details of this process are complicated, and rather than attempting a detailed description, we notice that the energy is deposited over distances larger than the collisional damping scale λ_{LS}. Consequently, an absolute upper bound to the contribution to a y-distorsion can be obtained by using Eq. (3) (in which the energy is distributed in a region of width λ_{LS}) with an assumed energy-deposition efficiency $\bar{f}(t) = 1$. The bound scales as $\eta^{3/2}/H_0$ and has a value $y = 1.4 \times 10^{-6}$ for $\eta = 6 \times 10^{-10}$, $H_0 = 50$ km/s/Mpc.

Our result for the temperature non-uniformity along a matter–antimatter interface is well below the sensitivity levels of currently planned observations. In constraining a baryon-symmetric cosmology, the exquisite detail with which the CBR can be studied is no match for a rough measurement of the diffuse gamma ray background [1].

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