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a Baryon Symmetric Universe**

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Ribbons on the CBR Sky: A Powerful Test of a Baryon Symmetric Universe

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If the Universe consists of domains of matter and antimatter, annihilations at domain interfaces leave a distinctive imprint on the Cosmic Background Radiation (CBR) sky. The signature is anisotropies in the form of long, thin ribbons of width $\theta_W \sim 0.15^\circ$, separated by angle $\theta_L \simeq 1^\circ (L/100h^{-1}\text{Mpc})$ where L is the characteristic domain size, and y -distortion parameter $y \simeq 2.5 \times 10^{-6}$. Such a pattern could be detected by the high-resolution CBR anisotropy experiments planned for the next decade, and such experiments should finally settle the question of whether or not our Hubble volume is baryon symmetric.

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The conventional view is that the Universe possesses a *baryon asymmetry*, and all astrophysical objects are made of baryons. This is quite a reasonable view. Clearly there is a local asymmetry between matter and antimatter: Earth is made entirely of matter, as well as the Moon, as evidenced by the fact that Apollo astronauts took a second small step. On scales beyond the solar system the arguments become less direct and less compelling. About the strongest statement one can make is that if the Universe is baryon symmetric, matter and antimatter must be separated into domains at least as large as the size of clusters of galaxies, $L \sim 20$ Mpc [1].

Although the simplest picture is that the Universe possesses a *global* baryon asymmetry, the possibility of a symmetric Universe in which matter and antimatter are separated into very large domains of equal, but opposite, baryon number has been discussed over the years [2]. As de Rujula has recently emphasized, even if matter and antimatter are segregated on very large scales, $L \sim 20$ Mpc, it may be possible to detect the presence of antimatter [3]. One direct approach is to search for antinuclei in cosmic rays [4]. Another is to look for the products of matter–antimatter annihilations from domain boundaries, e.g., high-energy gamma rays [3]. A third possibility, which is the subject of this paper, is to look for a signature of matter–antimatter annihilations as distortions in the Cosmic Background Radiation (CBR). As we shall describe, the signature is very robust as the physics is straightforward, and further, it allows scales as large as the Hubble length (~ 3000 Mpc) to be probed.

Heat is generated at the domain interfaces due to nucleon–antinucleon ($N-\bar{N}$) annihilations. Around the time of last scattering of the background photons¹ the injected energy cannot be thermalized, and it distorts the Planckian spectrum of the CBR. The spatial pattern of distortions is ribbon-like linear structures with angular width characterized by the photon diffusion length at recombination, $\theta_W \simeq 0.15^\circ$, and separation that depends

¹Throughout the paper “last scattering” refers to the epoch of last scattering of CBR photons, and will be abbreviated “LS.” We assume standard recombination so that $z_{\text{LS}} \simeq 1100$; measurements of CBR anisotropy on angular scales of around 1° make a very strong case for standard recombination [5].

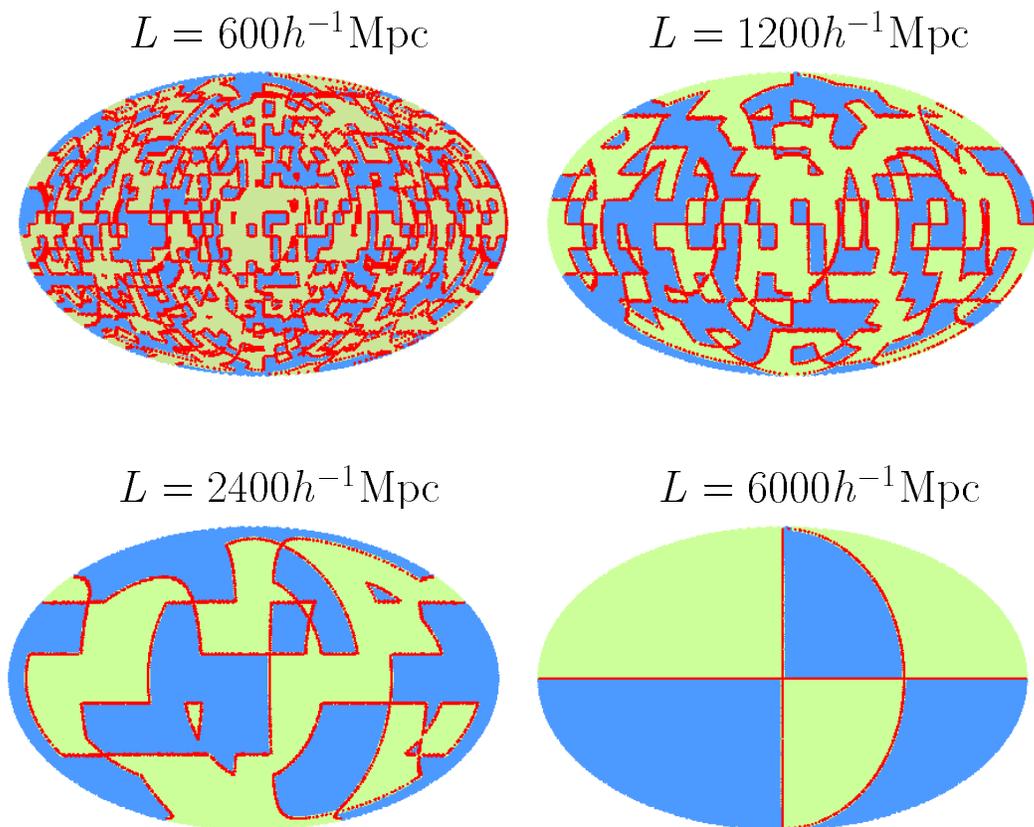


Fig. 1: Realizations of matter – antimatter distortions on the CBR sky for various cubic domain sizes L . Domains of opposite baryon asymmetry are shown in contrasting shadings, with the interfaces between domains highlighted. The spectral distortion of the CBR is confined to these interfaces, which appear as long “ribbons.”

on the domain size, $\theta_L \simeq 1^\circ(L/100h^{-1} \text{ Mpc})$; see Fig. 1. The CBR distortion caused by $N-\bar{N}$ annihilations takes the form of a Sunyaev–Zel’dovich y distortion [6] with magnitude $y \simeq 2.5 \times 10^{-6}$. A y distortion corresponds to a frequency-dependent temperature fluctuation [6]

$$\frac{\delta T(\nu)}{T} = y \left[\left(\frac{\nu}{\nu_0} \right) \frac{\exp(\nu/\nu_0) + 1}{\exp(\nu/\nu_0) - 1} - 4 \right] \longrightarrow \begin{cases} -2y & \nu \ll \nu_0 \\ y(\nu/\nu_0) & \nu \gg \nu_0 \end{cases}, \quad (1)$$

where $\nu_0 = kT/h = 56.8 \text{ GHz}$. At low frequencies the y distortion is independent of ν , and hence indistinguishable from a true temperature fluctuation of magnitude $\delta T/T = -2y$.

The pattern and the amplitude of CBR anisotropy from $N-\bar{N}$ annihilations is interesting because it is not excluded by the present generation of CBR experiments, but should be

within the range of the next round of large-area, high-resolution experiments (e.g., NASA's MAP satellite and ESA's Planck).

We begin with a rough estimate of the y distortion, and then describe a more detailed calculation. In the discussion below, $h \equiv H_0/100 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ and the baryon density is quantified by $\Omega_B h^2$, which big-bang nucleosynthesis constrains to be in the range 0.007 to 0.024 [7]. We take as central values $h = 1/2$ and $\Omega_B h^2 = 0.015$, and display the dependence upon factors like $\Omega_B h^2$, $\Omega_B h$, *etc.*

We assume that some process in the early Universe produced regions of equal and opposite baryon number [8], with $|n_B - n_{\bar{B}}|/n_\gamma \equiv \eta = 4.05 \times 10^{-10} (\Omega_B h^2 / 0.015)$.² If we divide the Universe into cells of comoving size L populated equally with matter and antimatter, then individual cells will be part of larger clusters in a percolation pattern. Interfaces separating matter domains and antimatter domains will have a surface area A that is much larger than L^2 . The magnitude of the y distortion does not depend upon L or A .

Consider matter–antimatter annihilations occurring in the interface regions. Because the electron mass is so much smaller than the nucleon mass, the heat released is dominated by $N-\bar{N}$ annihilations. Nucleon rest-mass energy is released through the production and subsequent decay of pions [1]:

$$N + \bar{N} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \\ \qquad \qquad \qquad \searrow \\ \qquad \qquad \qquad e^\pm + \nu_e (\bar{\nu}_e) + \bar{\nu}_\mu (\nu_\mu). \end{cases} \quad (2)$$

Half the total annihilation energy is in the form of neutrinos, one-third is in the form of $\langle E \rangle \sim 200 \text{ MeV}$ photons, and one-sixth is in the form of $\langle E \rangle \sim 100 \text{ MeV}$ electrons and positrons.

Because neutrinos interact only through weak interactions they deposit negligible energy in the photon gas. It is also easy to see that 200 MeV photons do not significantly heat the

²In Ref. [3], de Rujula has argued on the basis of the uniformity of the CBR sky on large angular scales that the magnitude of the baryon asymmetry must be nearly identical in matter and antimatter domains.

photon gas, since at the time of last scattering the mean free path of a 200 MeV photon, λ_γ , is larger than the Hubble length, H^{-1} :

$$\left(\frac{\lambda_\gamma}{H^{-1}}\right)_{\text{LS}} = \left(\frac{H_{\text{LS}}}{n_e \sigma_C}\right) \simeq 2 \left(\frac{0.03}{\Omega_B h}\right), \quad (3)$$

where σ_C is the Compton cross section.

Significant heating comes only from the 100 MeV electrons and positrons. The scattering of these particles off background photons is much more efficient than scattering of high-energy photons off background electrons because there are roughly 10^{10} background photons for every background electron. The 100 MeV electrons and positrons quickly lose their energy to background photons via inverse Compton scattering, and the upscattered photons slowly lose energy and heat the CBR photons producing the y distortion. As a first approximation, we assume that all the energy carried by 100 MeV electrons and positrons heats the photon gas. This means that the total energy dumped into the CBR per $N\text{-}\bar{N}$ annihilation is $2m_N/6$, where m_N is the nucleon mass.

The $N\text{-}\bar{N}$ annihilation cross section is so large that well after last scattering any nucleon (antinucleon) that drifts into an antimatter (matter) domain is annihilated on a timescale much less than a Hubble time. The transverse thickness of the annihilation region is proportional to the nucleon free-streaming distance at the time of last scattering, approximately $v_{\text{LS}} H_{\text{LS}}^{-1}$. Here, v_{LS} is the nucleon velocity dispersion at the time of last scattering, $v_{\text{LS}}^2 = 3T_{\text{LS}}/m_N$. Expressed as a comoving length, $\lambda_{\text{FS}}(R_{\text{LS}}) \simeq v_{\text{LS}} H_{\text{LS}}^{-1} R_{\text{LS}}^{-1} = 5 \times 10^{-3} (0.5/h) \text{ Mpc}$, where R is the cosmic scale factor, normalized to unity today with $R_{\text{LS}} = 9.1 \times 10^{-4}$. A better approximation for the thickness is $2\lambda_{\text{FS}}(R_{\text{LS}})/\sqrt{3}$, where the factor of 2 comes from the fact that nucleons diffuse into antimatter regions and antinucleons diffuse into matter regions, and the factor $1/\sqrt{3}$ is the projection of the velocity in the transverse direction.

The number density of annihilation pairs is $\eta n_\gamma/2$, and the amount of energy released per annihilation is $2m_N/6$. The amount of heat produced per cross-sectional area A perpen-

dicular to the interface region is

$$\frac{\Delta Q}{A} = \frac{2\lambda_{\text{FS}}(R_{\text{LS}})}{\sqrt{3}} \frac{\eta n_\gamma}{2} \frac{2m_N}{6}. \quad (4)$$

By the time of last scattering the heat deposited by 100 MeV electrons and positrons in the interface region will spread into a larger region. The thickness of this region is governed by photon diffusion around last scattering, and the relevant length scale is the Silk scale, $\lambda_S \simeq 28 (0.0075/\Omega_B h^3)^{1/2}$ Mpc, again expressed as a comoving length [9, 10].

The fractional increase in the energy of the photons in the photon diffusion region, $\Delta Q/Q$, determines the magnitude of the CBR anisotropy. Since $\Delta Q/A$ is spread out over a thickness $2\lambda_S/\sqrt{3}$ (the factors of 2 and $\sqrt{3}$ arise from the considerations discussed above) and the heat energy in photons per area at last scattering is $Q/A = 2.7T_{\text{LS}}n_\gamma (2\lambda_S/\sqrt{3})$, the fractional change is

$$\frac{\Delta Q}{Q} \simeq \frac{2\lambda_{\text{FS}}(R_{\text{LS}})/\sqrt{3}}{2\lambda_S/\sqrt{3}} \eta \frac{m_N/6}{2.7T_{\text{LS}}} = 1.6 \times 10^{-5} \left(\frac{\Omega_B h^2}{0.015} \right)^{3/2} \left(\frac{h}{0.5} \right)^{-1/2}. \quad (5)$$

Since the heat deposited in the annihilation region, which is larger by a factor of $\lambda_S/\lambda_{\text{FS}} \sim 10^4$, is a small perturbation, any backreaction on the annihilation process itself can be safely ignored.

As mentioned earlier, energy from $N-\bar{N}$ annihilation leads to a y distortion, with magnitude $y = \frac{1}{4}\Delta Q/Q$. For frequencies much less than about 100 GHz, the y distortion is indistinguishable from a temperature anisotropy of magnitude

$$\frac{\delta T}{T} = -2y = -\frac{1}{2} \frac{\Delta Q}{Q} \simeq -8 \times 10^{-6} \left(\frac{\Omega_B}{0.06} \right)^{3/2} \left(\frac{h}{0.5} \right)^{5/2}. \quad (6)$$

Note that the ribbons appear *cooler* than the surrounding, unheated regions of the CBR sky. The width of the photon diffusion region determines the angular width of the ribbons,

$$\theta_W \simeq \frac{2\lambda_S/\sqrt{3}}{2H_0^{-1}} \simeq 0.15^\circ \left(\frac{0.03}{\Omega_B h} \right)^{1/2}. \quad (7)$$

The CBR anisotropy from $N-\bar{N}$ annihilations should take the form of linear features, or “ribbons,” of width 0.15° and characteristic separation $\theta_L \simeq 1^\circ(L/100h^{-1} \text{ Mpc})$ set by the domain size. The spatial pattern is illustrated in Fig. 1.

This rough estimate neglects some potentially important effects: the efficiency with which 100 MeV electrons and positrons from annihilations heat the ambient photons, the fact that some heating occurs before last scattering, and the expansion of the Universe. We now refine our calculation of y by including these effects. The net result is a reduction of the rough estimate, by about a factor of two, and a slightly different scaling with the baryon density and Hubble constant.

To begin, let’s follow the energy flow. 1) One-sixth of the annihilation energy goes into 100 MeV electrons and positrons. 2) The 100 MeV electrons and positrons quickly lose energy via inverse Compton scattering off background photons, producing photons of typical energy $E_\gamma \simeq 3\gamma^2 T = 1.2 \times 10^5 T = 2.8 \times 10^{-5} R^{-1} \text{ MeV}$, where $\gamma = E_e/m_e \simeq 200$. We are interested in the interval between the equality of radiation and matter energy densities ($R_{\text{EQ}} = 4.2 \times 10^{-4} h^{-2}$) and last scattering ($R_{\text{LS}} = 9 \times 10^{-4}$), so E_γ is in the range 0.03 to 0.15 MeV. We refer to the photons produced in this step as “secondary” photons. 3) The secondary photons slowly lose energy by Thomson scattering off ambient electrons (with energy loss of about E_γ^2/m_e per scattering). 4) Finally, the electrons produced in the third step rapidly lose energy to the background photons. The last step is the means by which the y distortion arises; the penultimate step is the rate limiting step.

We improve Eq. (5) by integrating over the interval between matter–radiation equality (“EQ”) and last scattering (“LS”):

$$\frac{\Delta Q}{Q} = \int_{\text{EQ}}^{\text{LS}} dR \frac{d\lambda_{\text{FS}}(R)}{dR} \frac{1}{\lambda_S} \eta \left(N_\gamma(R) \frac{\Delta E_\gamma(R; R_{\text{LS}})}{2.7T_{\text{LS}}} \right). \quad (8)$$

The first factor, $d\lambda_{\text{FS}}(R) = [v(t)/R(t)] dt = (v_{\text{LS}} H_{\text{LS}}^{-1}/R_{\text{LS}}) d \ln R$, accounts for the growth of the annihilation interface. The term $N_\gamma(R) \Delta E_\gamma(R; R_{\text{LS}})$ is the nucleon rest-mass energy

liberated into secondary photons when the scale factor was R and transferred to background photons by the time of last scattering. Here, $N_\gamma(R) = (m_N/6)/E_\gamma(R) \simeq 5.7 \times 10^6 R$ is the number of secondary photons per nucleon annihilated and $\Delta E_\gamma(R; R_{\text{LS}})$ is the energy transferred to the background photons by the time of last scattering by a single secondary photon. By integrating from matter – radiation equality to last scattering we neglect the small additional amount of heat produced due to growth of the interface prior to matter–radiation equality.

In the absence of interactions, the energy of a secondary photon would simply scale inversely with the scale factor, and a secondary photon produced when the scale factor was R would have energy at last scattering of $(R/R_{\text{LS}})E_\gamma(R)$. But because the secondary photon loses energy by scattering, its actual energy at last scattering, $E_\gamma(R_{\text{LS}})$, is less. The energy transferred to the background photons by last scattering is this difference, $\Delta E_\gamma(R; R_{\text{LS}}) = (R/R_{\text{LS}})E_\gamma(R) - E_\gamma(R_{\text{LS}})$. In the approximation used previously the energy transfer was taken to be 100% efficient ($E_\gamma(R_{\text{LS}}) = 0$) and instantaneous at last scattering ($R = R_{\text{LS}}$), so $\Delta E_\gamma(R; R_{\text{LS}}) = E_\gamma(R = R_{\text{LS}})$. Combined with the expression for $N_\gamma(R)$, $N_\gamma(R)\Delta E(R; R_{\text{LS}})$ was simply $m_N/6$, and together with the assumption that everything occurs at last scattering led to Eq. (5).

Now we turn to the calculation of the actual energy of the secondary photon at R_{LS} . The evolution of the energy of the secondary photon is determined by two effects, a redshift term and a term due to the transfer of energy to the background electrons (which is then rapidly transferred to the background photons):

$$dE_\gamma = -E_\gamma \frac{dR}{R} - \frac{E_\gamma^2}{m_e} n_e \sigma_T dt, \quad (9)$$

where $\sigma_T = 6.7 \times 10^{-25} \text{cm}^2$ is the Thomson cross section and the factor E_γ^2/m_e is the energy loss suffered by a secondary photon in Thomson scattering. This equation can be integrated,

$$\frac{1}{R_{\text{LS}} E_\gamma(R_{\text{LS}})} = \frac{1}{R E_\gamma} + a \left(\frac{1}{R^{5/2}} - \frac{1}{R_{\text{LS}}^{5/2}} \right), \quad (10)$$

where $a = \frac{2}{5}(n_e \sigma_T / H_0 m_e) = 1.6 \times 10^{-3}(\Omega_B h / 0.03) \text{ MeV}^{-1}$, where n_e is the present density of electrons. We can use this expression to obtain some idea of the efficiency of energy loss of secondary photons. Setting $\Omega_B h / 0.03 = 1$, the two terms on the right-hand-side are equal for $R = R_{\text{LS}}/1.2$, which implies that a secondary photon will lose more than half of its energy by last scattering if it is produced at $R < R_{\text{LS}}/1.2$.

Using the result of Eq. (10) gives

$$\frac{\Delta E_\gamma(R; R_{\text{LS}})}{2.7T_{\text{LS}}} = \frac{2.0 \times 10^{-3}(\Omega_B h / 0.03)(R^{-5/2} - R_{\text{LS}}^{-5/2})}{1 + 4.5 \times 10^{-8}(\Omega_B h / 0.03)(R^{-5/2} - R_{\text{LS}}^{-5/2})}. \quad (11)$$

All the pieces are now in place to integrate Eq. (8); the result can be given as a dimensionless correction factor which multiplies our earlier estimate,

$$\begin{aligned} \frac{\Delta Q}{Q} &= 1.6 \times 10^{-5} \left(\frac{\Omega_B h^2}{0.015} \right)^{3/2} \left(\frac{h}{0.5} \right)^{-1/2} C \\ C &= 2.4 \times 10^{-2} \int_{\text{EQ}}^{\text{LS}} dR \frac{2.0 \times 10^{-3}(\Omega_B h / 0.03)(R^{-5/2} - R_{\text{LS}}^{-5/2})}{1 + 4.5 \times 10^{-8}(\Omega_B h / 0.03)(R^{-5/2} - R_{\text{LS}}^{-5/2})} \\ &\simeq 0.58(\Omega_B h / 0.03)^{0.16} (h/0.5)^{0.6} \end{aligned} \quad (12)$$

where the final expression is a numerical fit to C and indicates that our rough estimate was about 50% too large. Putting it all together, our final result for the temperature fluctuation is

$$\frac{\delta T(\nu \ll 100 \text{ GHz})}{T} = -\frac{1}{2} \frac{\Delta Q}{Q} \simeq -5 \times 10^{-6} (\Omega_B h^2 / 0.015)^{1.6}. \quad (13)$$

In conclusion, if large domains of matter and antimatter are present in the Universe,³ energy released from annihilation at their boundaries around the time of last scattering produces a distinct signature on the CBR sky: A Sunyaev-Zel'dovich y distortion of magnitude 2.5×10^{-6} in the form of thin ribbons on the sky with width 0.15° and separation determined by the domain size L , $\theta_L \simeq 1^\circ (L/100h^{-1} \text{ Mpc})$.

³Note that our analysis does not require equal number of matter and antimatter domains, so long as both are abundant enough to percolate and form large regions.

This distinctive signature could not have been found with the current anisotropy experiments because of a combination of factors: large beam size, small sky coverage or insufficient sensitivity. To illustrate, the COBE Far InfraRed Absolute Spectrophotometer (FIRAS) places the most stringent limit on y distortion, $y < 15 \times 10^{-6}$ (95%) [11]; however, the FIRAS beam size was about 7° , so that if a ribbon were in the beam, the average y distortion over the beam could be as much as 50 times smaller than our estimate. Other CBR anisotropy experiments have greater sensitivity to temperature fluctuations and smaller beam size, but do not cover sufficient sky to be certain of seeing even a single ribbon.

The ribbon feature should be detectable by the high-resolution, full-sky anisotropy maps that will be produced by NASA's MAP mission and ESA's Planck mission, or perhaps earlier by earth-based and balloon-borne experiments with better than sub-degree angular resolution and large sky coverage (e.g., VCA, VSA, Boomerang or TopHat). Because the CBR sky allows us to probe scales as large as the Hubble length and because the physics of this signature is so straightforward, CBR experiments should finally settle the question of the matter/antimatter composition of the observable Universe.

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