A Response to George F. R. Ellis's "Comment on 'Entropy and the second law: A pedagogical alternative' " [Am. J. Phys. 63, 472 (1995)]

Ralph Baierlein
Physics Department, Wesleyan University, Middletown, Connecticut 06459

(Received 8 September 1994; accepted 25 October 1994)

Professor Ellis and I agree on the essential physics, but—for the readers of my article—I would like to emphasize a distinction. One needs to distinguish between (1) a pedagogical exercise to show the power of the second law and (2) a study of whether, *in any way*, one can use the energy in warm sea water to launch projectiles. My intention was to show students that they already knew enough to rule out the astronomer's proposal, a proposal that was extremely general about what might be inside the building, yet specific about what was to happen outside. Professor Ellis notes that my "argument demonstrates the general power of the second law in ruling out such generically defined processes." Thus he and I agree on the validity of my reasoning for item (1), and then he goes on to address item (2), a fascinating piece of physics, although not anything that I would want to discuss at an early stage in the classroom teaching of thermodynamics.

Upper limit on the photon electric charge from the cosmic microwave background

C. Sivaram
Indian Institute of Astrophysics, Bangalore 560034, India

(Received 15 February 1994; accepted 11 November 1994)

In a recent paper[1] it was shown that an upper limit q for the electric charge of radiofrequency photons could be deduced by considering the angular spread of the photons from extragalactic radio sources and the angular resolution of present telescopes. With e being the electron's electric charge, it was thus deduced that

$$\frac{q}{e}<10^{-27.7}. \tag{1}$$

Similar limits were placed for optical and x-ray photons. We point out that comparable stringent limits can be obtained over cosmological scales by considering the cosmic microwave background radiation (CMBR). With a black body temperature $T_B=2.74$ K, this background radiation has a photon number density given by

$$n_\gamma \approx \beta\left(\frac{K_B T_B}{\hbar c}\right)^3 \tag{2}$$

where K_B is the Boltzmann constant, $\hbar$ is Planck's constant, (c the speed of light and β is a numerical coefficient of order unity). If each of these background photons has a charge q then the electric force density exerted would be proportional to $\sim n_\gamma^2 q^2$. If ρ is the average mass density of the universe then the gravitational force density is proportional to $\sim G\rho^2$, where G is the Newtonian gravitational constant.

The condition that the additional force due to the excess charge does not dominate cosmological dynamics then requires the constraint:

$$q^2 \leqslant \frac{G\rho^2}{n_\gamma^2}. \tag{3}$$

Writing $\rho=\Omega\rho_c$, where $\rho_c=3H^2/8\pi G$ (with H being the Hubble constant) then gives: (ρ_c is the critical density).

$$q \leqslant \frac{3H^2\Omega}{8\pi\sqrt{G}\cdot n_\gamma}. \tag{4}$$

Assuming $\Omega=1$, $H\approx 100$ km/s/mpc, and T_B in Eq. (2) as $T_B=2.7$ K, then gives

$$q \leqslant 2\times 10^{-27} e \tag{5}$$

(Note that esu units are used). If we had assumed a low density universe, say $\Omega=0.1$ we would get $q \leqslant 2\times 10^{-28} e$. These bounds are comparable with those obtained in Ref. 1 from different considerations.

[1]G. Cocconi, "Upper limits on the electric charge of the photon," Am. J. Phys. **60**, 750–751 (1992).

