A Limit on the Redshift due to Interaction with Electromagnetic Radiation

IN a recent letter[1] Pecker *et al.* discussed the possibility that a part of the "cosmological" redshift could result from the interaction of photons with an interstellar radiation field. Although this suggestion is old[2,3], it has recently regained prominence with the discovery of the 3 K blackbody radiation. Pecker *et al.* discussed a formula for the energy loss of the propagating photon, ν_1,

$$-\delta\nu_1/\nu_1 = \Delta(\nu_2)n_2\delta l \qquad (1)$$

where $\Delta(\nu_2)$ is the coupling constant between the propagating photon and the radiation field of frequency ν_2, n_2 is the number density (cm^{-3}) of the photons at ν_2, and δl is the length of the interaction path, in cm. Assuming that $\Delta(\nu_2)$ is independent of ν_2, they suggested an experiment to determine an upper limit for its value. The proposed experiment, measuring by the Mössbauer effect the energy loss of gamma rays traversing a laser beam, is very difficult to perform. But another Mössbauer experiment was performed a number of years ago to test just this question. In that experiment[4], gamma rays were propagated through a microwave cavity filled with photons of 9,234 MHz ($\lambda \approx 3$ cm) radiation; the fractional energy shift of the gamma rays due to the microwave field was found to be $0.4 \pm 6.0 \times 10^{-16}$, corresponding to a value of $\Delta(\nu_2) < 10^{-33}$ cm^{-1}. This limit is far smaller than the value $\Delta(\nu_2) \approx 10^{-30}$ cm^{-1} proposed in ref. 1 from the analysis of solar redshift data.

We note that the 3 cm wavelength of the microwave radiation used in the experiment of ref. 4 lies near the peak ($\lambda_{max} \approx 0.1$ cm) of 3 K blackbody radiation. Thus the microwave experiment establishes a useful and reliable upper limit for $\Delta(\nu_2)$, provided the Doppler form of equation 1 is valid. This limit is far too small to account for the observed cosmological redshift which requires[1] $\Delta(\nu_2) \approx 10^{-30}$ cm^{-1}.

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R. L. COHEN
G. K. WERTHEIM

Bell Laboratories,
Murray Hill,
New Jersey 07974

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Consequences of a Universal Cosmic-ray Theory for γ-ray Astronomy

THE problem of the origin of cosmic rays is well known; but in spite of considerable advances in knowledge concerning energetic extra-terrestrial objects in recent years, no satisfactory solution has appeared. It is not clear, even, whether the important sources are within the Galaxy or outside it[1,2].

Here we consider the possibility of reviving a theory due to Hillas[3] in which the observed shape of the primary spectrum up to about 3×10^{19} eV is explained in terms of an evolving sources model with constant spectral index at production, and interactions with the microwave background radiation. Such a model can explain the sharp change of slope at 3×10^{15} eV inferred from measurements of the sizes of extensive air showers, as well as the high degree of isotropy which is maintained up to at least 10^{19} eV (ref. 4).

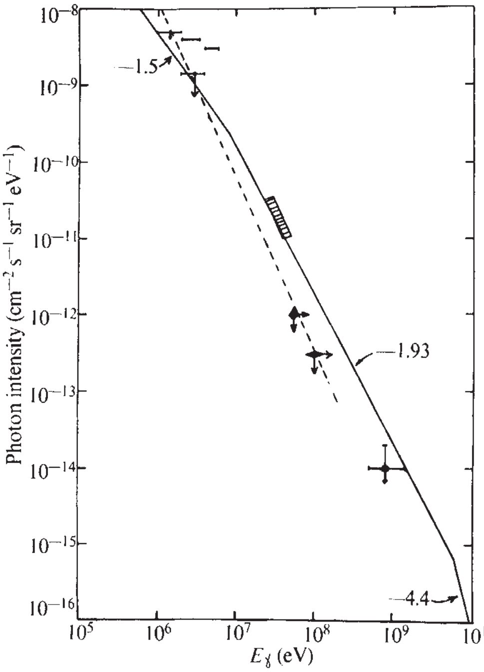

Fig. 1 The expected γ-ray spectrum (solid line). ◆, Ref. 9 (OSO-3); ♦, ref. 8 (COSMOS-208); ✚, ref. 8 (PROTON-2); ├┬┤, ref. 10 (COSMOS-163); ├─┤ ref. 11 (ERS-18); - - - - -, ref. 10 ($E^{-2.4}$ fit to experimental data); ▥, ref. 12 (balloon experiment).

The objections so far advanced to theories of this type seem to rely on assumptions concerning unknown astrophysical quantities. Thus the problem of a γ-ray excess due to pionization on intergalactic matter[5] can be removed by assuming a low enough density for the inter-galactic medium. An X-ray excess is clearly expected if the proton/electron ratio is equal to its local value, but in the absence of evidence to the contrary the possibility that this ratio may be large enough in metagalactic sources to remove the discrepancy cannot be ruled out.

A more fundamental objection would arise if it could be shown that the energy lost in forming the observed primary spectrum above 3×10^{15} eV (which appears initially in the form of electron pairs in this type of theory) will result in a γ-ray flux inconsistent with measurements of the diffuse γ-background. The mechanisms involved are inverse-Compton effect on the microwave background and pair-production on the starlight background, the latter occurring within the Hubble radius for γ-ray energies above about 10^{11} eV for reasonable estimates of the starlight background (see, for example, ref. 6). It is assumed that the starlight intensity does not increase with z—such changes as might be expected do not affect the results greatly in the energy range of interest to us (10^6 to 10^9 eV).

We have made calculations for a model in which the energetic cosmic rays are protons, with an energy spectrum on production of the form $G(E_p, z)dz = BE_p^{-\gamma} f(z)dz$, where B is a constant, z is redshift and $\gamma = +2.6$. The source efficiency $f(z)$ is taken as

$$f(z) = H_0^{-1} \frac{(1+z)^{\beta}}{(1+z)^2 (1+2q_0 z)^{\frac{1}{2}}} \quad \text{for } z < z_m$$

$$f(z) = 0 \quad \text{for } z > z_m$$

corresponding to the form used by Longair[7] in treating the evolution of powerful radio sources. In the calculations we took $q_0 = \frac{1}{2}$, although the results are insensitive to this parameter.

The proton spectrum expected at the present epoch after the generated protons have interacted with the microwave background has been calculated for various values of z_m and β. Comparison with the measured spectrum yields best-fit values $z_m = 14.3$ and $\beta = 4.3$. (The problem of predicted spectrum falling more rapidly above 10^{19} eV than observed is not considered here.) With these values the rather rapid change of slope of the the primary spectrum near 3×10^{15} eV is well represented.

The values for z_m and β can be compared with those derived by Longair from source counts ($2.3 < z_m < 4$ and $\beta = 5.7$ for density evolution, 3.3 for luminosity evolution). Our value of $z_m = 14.3$ is clearly inconsistent with the radio-source value but this is not catastrophic because cosmic-ray sources and radio sources need not evolve in the same time scale.

We show the expected γ-ray spectrum in Fig. 1. (The sharp changes of slope are consequences of approximations in the calculations.) Most of the energy is contained in the region where the slope is -1.93 so that the energy content per unit logarithmic interval is almost constant and the result is not very sensitive to the adopted parameters of the starlight spectrum.

Also shown are the experimental measurements of the diffuse γ-background from satellite and balloon experiments. The intensities measured by OSO-3, PROTON-2 and COSMOS-208 are clearly below the prediction of the present work. The measurements reported by Meyer-Hasselwander *et al.*[12] agree with our prediction.

On balance the observed intensities are too low and we conclude that what appeared to be a very attractive model is untenable. This conclusion will also apply to a "hybrid" model of the type suggested by Beresinsky and Zatsepin[13] in which galactic origin below 10^{15} eV is combined with a Hillas-type metagalactic spectrum above 10^{15} eV.

Note added in proof. Of course, if the "high" intensities of ref. 12 are confirmed by later work, then the conclusion will be reversed.

A. W. STRONG
A. W. WOLFENDALE

Physics Department,
University of Durham

J. WDOWCZYK

Institute of Nuclear Physics,
Lodz, Poland

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Stability of CO_2 in the Martian Atmosphere and under Radiolysis

THE atmosphere of Mars appears to be predominantly undissociated CO_2 (refs. 1–3). It was possible by assuming very rapid transport downwards to explain the composition of the upper atmosphere, but a problem remained at lower altitudes. More recent determinations[4,5] of the rate of O–CO recombination have, however, given a rate constant two orders of magnitude lower than that used in the calculations for 200 K, the Martian surface temperature. This creates a more severe problem. There are less CO and O_2 than can be accounted for by a mechanism of photolysis and recombination.

$$CO_2 + h\nu \rightarrow CO + O \qquad (1)$$

$$O + CO + CO_2 \rightarrow 2CO_2 \qquad (2)$$

$$O + O + CO_2 \rightarrow O_2 + CO_2 \qquad (3)$$

$$O + O_2 + CO_2 \rightarrow O_3 + CO_2 \qquad (4)$$

$$O_3 + h\nu \rightarrow O_2 + O \qquad (5)$$

An earlier suggestion[2] that further reactions involving CO_3 could explain the results is not correct[1,3].

$$O(^1D) + CO_2 \rightarrow CO_3 \qquad (6)$$

$$CO_3 + CO \rightarrow 2CO_2 \qquad (7)$$

Furthermore, reaction (6) without a third-body or as a radiative process seems highly unlikely, and recent experiments yield no evidence for its existence[6]. It has also been shown that a pure CO_2 atmosphere is photochemically unstable under conditions where O (^{1}D) would be produced[7]. CO_2 does, however, show an apparent stability under reactor radiolysis[8]; isotope-exchange experiments have confirmed that both dissociation and recombination occur. Similar behaviour should be expected on Mars and it is pertinent to look for a common explanation.

The principal difference between photolysis and radiolysis lies in the production of ions under high-energy irradiation. The production of fragments and metastables would be expected to be somewhat similar in both cases. An ionic mechanism may therefore explain the recombination in CO_2. Although it has been shown[9,10] that earlier explanations of radiolytic stability based on negative-ion chemistry were unsatisfactory, positive-ion processes cannot be ruled out at the present time. It is known that, in the absence of CO_2, CO is rapidly oxidized by O_2 under irradiation, and the following mechanism has been proposed[11].

$$O_2{}^+ + CO \xrightarrow{M} CO_3{}^+ \qquad (8)$$

$$CO_3{}^+ + CO \rightarrow CO_2{}^+ + CO_2 \qquad (9)$$

$$CO_2{}^+ + O_2 \rightarrow O_2{}^+ + CO_2 \qquad (10)$$

In CO_2 the terminal positive ion under radiolysis is probably $CO_4{}^+$[10] and the existence of the same species in the Martian atmosphere[12] has been suggested. The following modified positive-ion mechanism could oxidize CO in the presence of CO_2.

$$CO_4{}^+ + CO \rightarrow CO_3{}^+ + CO_2 \qquad (11)$$
$$CO_3{}^+ + CO \rightarrow CO_2{}^+ + CO_2 \qquad (9)$$

$$CO_2{}^+ + O_2 \rightarrow O_2{}^+ + CO_2 \qquad (10)$$

$$O_2{}^+ + 2CO_2 \rightarrow CO_4{}^+ + CO_2 \qquad (12)$$

$C_2O_4{}^+$, clustered $CO_2{}^+$, probably also charge transfers to O_2 (ref. 13).

At altitudes below 70 km on Mars, the positive-ion density is 10^3 cm^{-3} (ref. 12) and the rate of oxidation of CO by positive ions will be $\sim 10^3 (k_{11} + k_9)$ s^{-1}. The rate of production of CO by photolysis[1] $\sim 5 \times 10^5$ cm^3 s^{-1} to give a steady-state density of $500/(k_{11} + k_9)$ molecule cm^{-3}. The observed CO/CO_2 ratio is 0.1% and the CO_2 density falls from 2.25×10^{17} molecule cm^{-3} at the surface to 2.25×10^{15} at an altitude of 60 km, giving a CO density ranging from 2.25×10^{14} to 2.25×10^{12}. If any effects arising from transport are neglected, values of k_{11} and k_9 of the order of 10^{-10} cm^3 molecule^{-1} s^{-1} are needed to explain the observations. The radiolytic problem[10] calls for rates $> 10^{-12}$.