BARYON SYMMETRIC BIG BANG COSMOLOGY

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1. Separation

In a big bang cosmology in which the Universe is initially filled with thermal radiation at a very high temperature the number of nucleon-antinucleon pairs decreases exponentially with temperature when the latter falls below a value such that $kT \sim 1$ GeV. To explain the observed ratio $\eta = N/N_{\text{ph}} \sim 10^{-9}$ where N is the average baryon density and N_{ph} the photon density, nucleons and antinucleons must have been separated in the thermal radiation at a temperature greater than 30 MeV. A mechanism has been suggested which would lead to a phase transition in thermal radiation for $kT > 300$ MeV resulting in two phases with opposite non zero baryon number. The interaction between nucleons and antinucleons at intermediate energy is repulsive according to the mesonic theory of nuclear forces. This can be checked experimentally by measuring with enough precision the energy of X-rays emitted by the protonium atom and this experiment is now under way at CERN. Different models have been made to investigate their consequences and in each case a phase transition has been found above a temperature of the order of 300 MeV (Omnes, 1972; Aldrovandi and Caser, 1973; Cisneros, 1973).

2. Coalescence

When the temperature drops below the critical temperature, the typical size of a region containing only matter is 10^{-4} cm; the model will only be consistent with observations if a coalescence mechanism can lead to regions containing only matter (or only antimatter) of at least galactic size. The system of matter and antimatter constitutes an emulsion (i.e. a three dimensional maze). At the boundary annihilation takes place. A detailed analysis of the interactions through which the annihilation momentum and energy are transmitted to the system consisting of matter plus radiation during the radiative period ($1 \text{ eV} < kT < 30$ keV) shows that a pressure discontinuity is generated across the boundary

$$[p] = 2p_a \frac{\lambda}{R}$$

where p_a is the annihilation pressure, λ the Thomson mean free path of photons and R the radius of curvature. This is essentially the Laplace-Kelvin formula associated with surface tension. It has been shown that the boundary area will tend to decrease and L the typical size of the emulsion will increase (Aldrovandi *et al.*, 1973a).

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3. Evolution of the Baryon-Symmetric Universe

When the temperature falls below the critical temperature matter and antimatter tend to mix again and strong annihilation follows. The basic mechanism here is diffusion and as long as there is equilibrium between neutrons and protons through weak interactions the neutron diffusion will control the annihilation rate. A lower limit for η can be calculated, $\eta > 10^{-9}$ (Aldrovandi *et al.*, 1973b). For a temperature near 1 MeV and lower the neutrons annihilate in a short time and annihilation falls to a much lower level (because of the slower diffusion of protons). No helium and heavier elements is produced (Leroy *et al.*, 1973). Then for $kT < 30$ keV, the coalescence mechanism takes place and L increases as shown in Figure 1.

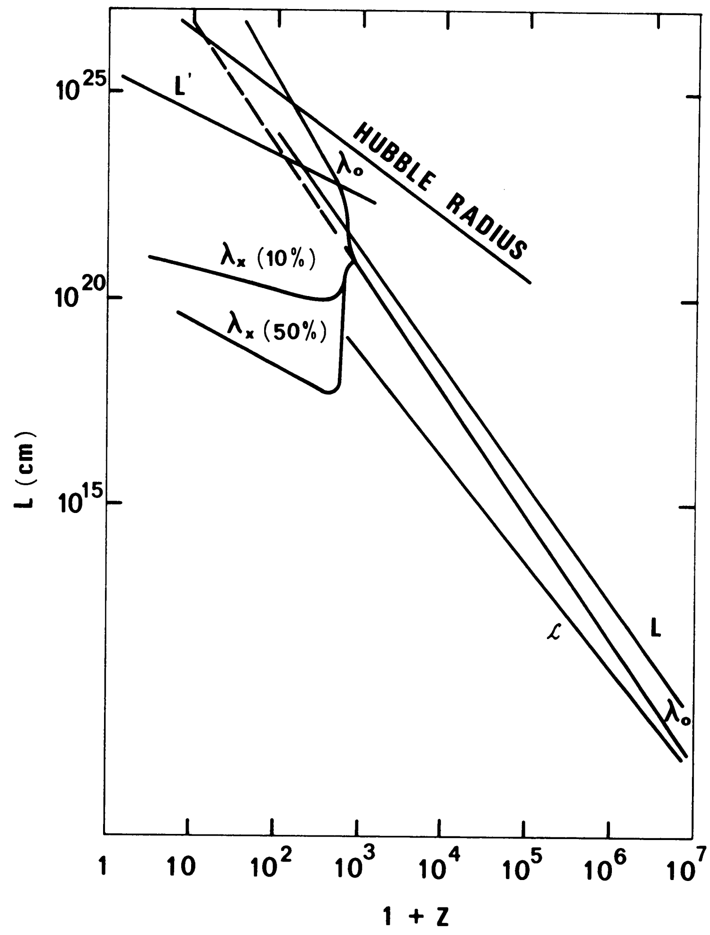

Fig. 1. L is the typical size of the emulsion as computed from the coalescence theory; L' is the typical size of a cell containing one cluster of galaxies; λ_0 is the Thomson mean free path of thermal photons; λ_X is the mean free path of X-rays after recombination expressed as the distance from the boundary at which the photoionization by X-rays given $n_p/n_H = 10\%$ or 50%; z is the cosmological red-shift.

4. Recombination and Galaxy Formation

In this model a large amount of ionizing radiation is produced by the annihilation products; as a result the recombination of the cosmic plasma takes place later and is a very gradual phenomenon. At the same time, the coalescence motions become so fast ($\sim 10^{-2}$ c) that turbulence is generated. The coalescence mechanism has not been fully studied during this complicated period. Nevertheless it is likely that the mass of regions containing only matter are of the order of the mass of a cluster of galaxies when the cosmic gas becomes completely neutral. Preliminary results on the formation of galaxies in this model show that the source of turbulence near recombination and the slow neutralisation might help considerably models of galaxy formation from turbulence in overcoming problems like dissipation and premature collapse (Stecker and Puget, 1972). Magnetic fields are generated along the boundary (Aly,

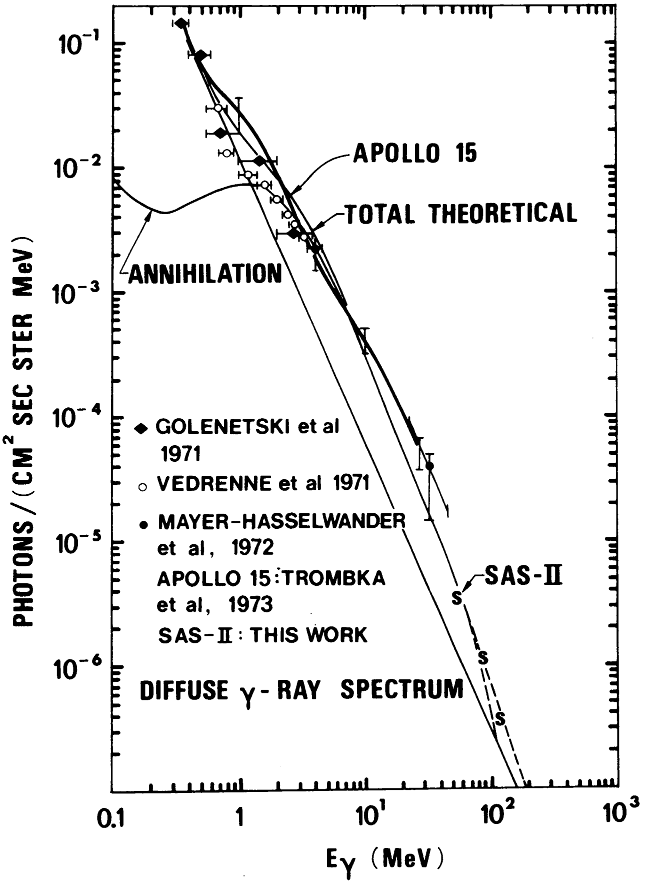

Fig. 2. The curve 'Total Theoretical' is the sum of the predicted annihilated spectrum and of a power law which is an extrapolation of the X-rays background. The dip in the annihilation spectrum below 1 MeV is due to absorption computed here for an Einstein-De Sitter universe.

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1973) and must be taken into account in detailed studies of the galaxy formation problem.

5. Observational Tests

Direct observational tests of this model have been investigated. The best one is the contribution to the diffuse γ-ray background resulting from the decay of annihilation π° at redshifts between 0 and 100. A characteristic spectrum has been predicted and the comparison of recent observations with these predictions gives excellent agreement (Stecker, 1973; Stecker *et al.*, 1971), as shown in Figure 2. The second best observational test is the distortion of the 2.7 K black body radiation spectrum at wavelengths longer than 10 cm (Zel'dovich *et al.*, 1972; Stecker and Puget, 1973).

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DISCUSSION

Steigman: I feel that it is far from established that a phase transition separating matter from antimatter will occur. The calculations which exist are incomplete in the sense that detailed balance is not satisfied; pair annihilation is accounted for but pair creation is not.

Granted that a phase transition may occur, it is necessary to follow the subsequent re-mixing and annihilation in some detail. My calculations have shown that the re-mixing via neutron diffusion is so efficient that for $T \approx 1$ MeV, the nucleon-photon ratio is less than 10^{-16}, orders of magnitude smaller than the observed ratio of $\approx 10^{-9}$.

Referring to the suggestion that the γ-ray spectrum ($E \approx 1$–100 MeV) is due to red-shifted annihilation radiation, it should be noted that the fit to the observed spectrum *does* depend on a parameter – the present density of the Universe. The density determines the red-shift at which the Universe becomes opaque to ~ 100 MeV γ rays and hence determines the energy at which the χ-ray spectrum will turn over. It seems conceivable that by appropriately adjusting the annihilation rate (as a function of epoch) and choosing the density – any γ-ray spectrum can be produced.

Bardeen: If matter-antimatter is separated on a scale of clusters of galaxies at $z \simeq 200$, the large density perturbations ($\delta\varrho/\varrho \sim 1$) would seem to lead to the immediate formation of bound condensations at densities much higher than is consistent with present mean densities of clusters.

Silk: There is considerable uncertainty in the γ-ray observations between 1 and 50 MeV. For example, the Apollo-15 data are obtained with an omni-directional detector, and several corrections must be applied to the raw data, each of which contributes to the uncertainty in the flux. Moreover, even if one tentatively accepts the presence of a bump in the γ-ray spectrum in this energy range, the baryon-symmetric cosmology does not offer a unique interpretation. Among other possibilities, one can mention thermal bremsstrahlung from relativistic plasma surrounding intense infra-red sources in Seyfert nuclei or quasi-stellar sources (cf. the work of Sunyaev).

Zel'dovich: Bardeen's point is that regions of matter and antimatter are separated by regions with $\varrho = 0$ at the interfaces and the overall picture corresponds to $\delta\varrho/\varrho \sim 1$ at the epoch of decoupling which is drastically different from $\delta\varrho/\varrho \sim 10^{-2}$ or 10^{-3} at decoupling which is the assumption of other theories and which seems to be in accord with observation.

Puget obtains $\Delta N \sim N^{1/3}$ instead of $\Delta N \sim N^{1/2}$ by considering the fluctuations at a sharp boundary. However, the sharp boundary seems to be artificial. It is better to define

$$\Delta N = \int (n - \bar{n})\, \mathrm{e}^{-x^2/\lambda^2}\, \mathrm{d}V$$

and

$$N = \int n\, e^{-x^2/\lambda^2}\, \mathrm{d}V \sim \bar{n}\lambda^3$$

in order to characterise the fluctuations. In the Fourier approach one expects that the negative diffusion coefficient corresponding to the phase transition would lead to $n_k \propto k^2$ because $\partial n/\partial t = \Delta n = k^2 n$. For $n_k \propto k^2$ one obtains very much smaller fluctuations on the large scale

$$\Delta N \sim N^{1/6}.$$

The results seem to be sensitive to the exponent.

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