MATTER-ANTIMATTER AND THE ORIGIN OF GALAXIES

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SUMMARY

Baryon inhomogeneities in the early high density stage of the universe account for the origin of galaxies. The inhomogeneity is amplified by baryon pair annihilation as the universe expands and eventually galaxies and antigalaxies are formed. This process is more efficient than the usual process which assumes that the initial conditions of a structured universe are density fluctuations.

Symmetry between particles and antiparticles has inspired the suggestion that there is a particle-antiparticle population symmetry and the universe consists equally of matter and antimatter.[1] The main difficulty with this suggestion is the problem of explaining how structures as large as stars or galaxies can form in a particle-antiparticle medium. In addition, Chiu[2] shows that as the universe expands only a negligible fraction of the baryons survive pair annihilation.

Both these difficulties are overcome if we assume that in the early condensed state of the universe the particle composition is not perfectly homogeneous. It is then possible for separate regions of matter and antimatter to survive and form the foundations of a structured universe. Let $\underline{N}$ ($\overline{N}$) be the number of baryons (antibaryons) in a volume V. The baryon inhomogeneity can be expressed as

$$\Delta N/N = (\underline{N} - \overline{N})/(\underline{N} + \overline{N}), \qquad (1)$$

$0 \leq |\Delta N/N| \leq 1$, where $\Delta N = \underline{N} - \overline{N}$ is the baryon number in V. If necessary, a corresponding fluctuation in the leptons preserves charge neutrality. At high density the interaction time is short in comparison with the age of the universe and to a good approximation there is thermal equilibrium.[3] When the mean particle energy greatly exceeds 1 Gev the density n_i of each kind of particle (having a rest mass small compared with the mean energy) is of the order $(kT/\hbar c)^3$, or

$$N_i = Vn_i \sim V(kT/\hbar c)^3. \qquad (2)$$

Under these conditions the pressure is close to one third the energy density and we have the adiabatic relation VT^3 = constant. The N_i are therefore constant and the initial inhomogeneity $\Delta N/N$ persists unchanged until the mean energy drops below ~ 1 Gev, or $T < \sim 10^{13}$°K. Nucleon pair annihilation then occurs in the manner discussed by Chiu[2]; thus $\underline{N} + \overline{N} \longrightarrow \pm \Delta N$, and consequently

$$\Delta N/N \longrightarrow \pm \Delta N/\Delta N = \pm 1. \qquad (3)$$

The initial inhomogeneity is therefore amplified during expansion and we are left with separate regions of matter and antimatter.

Let $n_o \sim 10^{-6}$ cm^{-3}, $T_o \simeq 3$°K be the present mean nucleon density and microwave radiation temperature[4] of the universe. As we go back in time the conserved baryon number n per unit volume increases as T^3 (neglecting losses to pair production) and therefore

$$|\Delta N| = Vn \sim Vn_o(T/T_o)^3. \qquad (4)$$

Eventually, at high density when $T > \sim 10^{13}$°K, it follows that

$$\Delta N/N \sim \pm n_o(\hbar c/kT_o)^3, \qquad (5)$$

and $|\Delta N/N| \sim 10^{-9}$ is the required amount of initial baryon inhomogeneity.[5] An inhomogeneity as large as this cannot be explained as a statistical fluctuation[3,6] of $|\Delta N/N| \sim N^{-1/2}$ for galactic masses of $|\Delta N| \sim 10^{67}$ nucleons. One possibility is that the fluctuations originate when the universe is at the Planck density[7] of $\rho \sim c^5/G^2\hbar \sim 10^{95}$ g cm^{-3} and classical cosmological theory breaks down.

The origin of galaxies in an expanding universe poses many perplexing problems, and gravitational theory has so far failed to provide a satisfactory explanation for the existence of such structures.[8] If ρ is the density and $\delta\rho$ the perturbation in density, the contrast density is $\delta\rho/\rho = \delta N/N$, or

$$\delta N/N = \delta(\underline{N} + \overline{N})/(\underline{N} + \overline{N}). \qquad (6)$$

The general approach hitherto has consisted mainly of studying this kind of disturbance, and it is now known that the contrast density grows slowly in an expanding universe and therefore relatively large initial amplitudes are necessary to explain the formation of galaxies.

We notice that baryon pair annihilation during expansion gives

$$\delta N/N \longrightarrow \delta\Delta N/\Delta N, \qquad (7)$$

and the contrast density of a fluid of uniform composition, unlike the inhomogeneity (3), is not amplified but remains unchanged. Furthermore, at high density, while the pressure is one third the energy density, $\delta N/N$ oscillates at constant amplitude and does not grow with time according to gravitational theory.[9]

Eventually, when the density has dropped and $kT < kT_1 \sim 1$ Mev, electron pair annihilation starts a 'radiation deluge' in which the energy density of radiation is large compared with that of matter.[3,10] This period lasts while the density of matter is

$$\rho_1 > \rho > \rho_2$$

where $\rho_1 \sim \rho_o(T_1/R_o)^3 \sim 10^{-3}$ g cm^{-3}, $\rho_2 = \rho_o{}^4/(aT_o{}^4)^3 \sim 10^{-21}$g cm^{-3}, $\rho_o \sim 10^{-30}$ g cm^{-3} is the present mean density, and a is the radiation density constant. During this period the contrast density of the radiation oscillates at constant amplitude, and radiative drag maintains $\delta N/N$ also at constant amplitude.[11] Not until $\rho < \rho_2$ and the radiation deluge has subsided can the contrast density at last begin to increase. Under favorable conditions at low pressure we then have[8]

$$\delta N/N \propto (\rho_2/\rho)^{1/3}. \qquad (8)$$

The mean density of galaxies is $\rho \sim 10^{-24}$ g cm^{-3} and in order that $\delta N \rightarrow N$ we must have the large initial value of $\delta N/N \sim 10^{-1}$. Various types of instability,[12] including radiative cooling mechanisms,[13] can reduce the required amount of initial density irregularity; these instabilities will also enhance the density fluctuations which evolve from inhomogeneities of composition that we have already considered.

The idea that the universe consists of structures of matter and antimatter as large as galaxies raises the objection that it is difficult to see how in the first place matter and antimatter can become separated. The logical answer to this objection has been that in any case we do not understand the processes by which galaxies are formed even in the absence of antimatter. The situation now, however, is reversed and it is difficult to see how galaxies can form without also the formation of antigalaxies. Either a compositional irregularity of $\Delta N/N \sim 10^{-9}$ or a density irregularity of $\delta N/N \sim 10^{-1}$ is sufficient to explain the origin of galaxies. The compositional irregularity is compounded from fluctuations of component fluids, and although we do not understand the cause of these fluctuations, it seems reasonable to suppose that they are of the same order of magnitude as the overall density irregularity; that is, $\Delta N/N \sim \delta N/N$. In any event, when density perturbations are important, a baryon inhomogeneity of $\Delta N/N \gtrsim 10^{-8} \delta N/N$ will result in the formation of antigalaxies as well as galaxies.

Because inhomogeneity is the more efficient method of producing a differentiated universe it seems more than likely that the universe consists equally of matter and antimatter. Furthermore, using Jeans' criterion or the virial theorem

$$M \sim (kT_2/Gm)^{3/2}/\rho_2^{1/2}, \qquad (9)$$

where m is the nucleon mass, it is seen that at the end of the radiation deluge galactic masses of $M \sim 10^{10} M_{\odot}$ are gravitationally bound. This result can scarcely apply to a homogeneous fluid because $\delta N/N$ still possesses its initial value and has only just begun to increase.

We conclude that baryon inhomogeneities in the early dense universe are the cause of galaxies; that there are both galaxies and antigalaxies, and that therefore in all probability there is a particle-antiparticle population symmetry in the universe. These arguments do not exclude the possibility that substructures of antimatter (matter) are present in galaxies (antigalaxies). The mutual interaction of these substructures may account for such puzzling objects as exploding galaxies, radio galaxies and quasi stellar sources.

1. M. Goldhaber, Science 124, 218 (1958). H. Alfvén and O. Klein, Arkiv. Fysik 23, 187 (1962). H. Alfvén, Rev. Mod. Phys. 37, 652 (1965).

2. H.Y. Chiu, Phys. Rev. Letters 17, 712 (1966).

3. R.A. Alpher, J.W. Follin and R.C. Herman, Phys. Rev. 92, 1347 (1953).

4. P.G. Roll and D.T. Wilkinson, Phys. Rev. Letters 16, 405 (1966).

5. Pair annihilation of the higher mass baryons increases the amplification. Since $V(NT)^3$ is approximately a constant, it follows $|\Delta N/N| \propto V^{\alpha}$, where $0 < \alpha < \frac{1}{3}$. Thus at the Planck density: $10^{-29} < \Delta N/N < 10^{-9}$.

6. R.A. Alpher and R.C. Herman, Science 128, 904 (1958).

7. M. Planck, Theory of Heat Radiation (Dover, 1959) p.175. J.A. Wheeler, Annals of Physics 2, 604 (1957).

8. See for example: E. Lifshitz, Journal of Physics (USSR), 10, 116 (1946). W.B. Bonnor, Mon. Not. Roy. Astron. Soc. 117, 104 (1957). E.R. Harrison, 14th International Astrophysical Symposium, Liége, 1966 (in press). A forthcoming review by E.R. Harrison contains a more complete bibliography.

9. R.K. Sachs and A.M. Wolfe, Astrophys. J. 147, 73 (1967).

10. G. Gamow, Rev. Mod. Phys. 21, 367 (1949). R.H. Dicke, P.J. Peebles, P.G. Roll and D.T. Wilkinson, Astrophys. J. 142, 414 (1965).

11. E.R. Harrison, to be published.

12. W.C. Saslaw, Mon. Not. Roy. Astron. Soc., to be published.

13. G.B. Field, Astrophys. J. 142, 531 (1965).

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BIOGRAPHICAL SKETCH

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1966 - Professor of Astronomy, University of Massachusetts. Research in astrophysics and cosmology.

1965-66 National Academy of Sciences senior research associate. Research in astrophysics and cosmology.

-1965 Principal scientist, Rutherford High Energy Laboratory, England. Research in plasma physics and high energy physics.

Altogether, I have approximately 60 publications in the above research areas.