GALAXY FORMATION AND LEMAÎTRE UNIVERSES

Joseph Silk

Institute of Theoretical Astronomy,
Cambridge.

Submitted to Gravity Research Foundation, April 1969.

SUMMARY

We assume the conventional "hot big bang" description of the universe, in which the universe is initially homogeneous, isotropic, and radiation dominated. Then only by adoption of the Lemaître cosmological model with a characteristic stagnation period can one hope to explain the formation of galaxies. We discuss the stability of the Lemaître universe to galaxy formation. The duration of the stagnation period must be less than about one hundred billion years: otherwise catastrophic collapse back to the initial singularity will ensue. Finally, two observable features of the stagnation period are predicted.

Galaxies are the fundamental units of modern cosmological theories. The role of galaxies in cosmology is a vital one, yet galaxies may often be replaced by specks of cosmic dust with the cosmological model left invariant. The postulate of cosmic homogeneity has been a feature common to almost all cosmological models. Recent observational discoveries of the release of vast amounts of energy in remote radio galaxies and quasars have emphasized that an acceptable theory of gravitation must be able to dispense with this drastic simplification. It is the purpose of this essay to describe an attempt to impose structure on cosmological models, so that galaxies may exist and may even be an inevitable phenomenon.

Our discussion is based on Einstein's theory of general relativity. This is necessary because of the inadequacy of the Euclidean formulation of the Newtonian theory of gravitation. The advent of Einstein's theory climaxed an ideological power struggle among cosmologists: as tensor calculus became a necessary tool, so the religious influence waned. However, the complexity of the Einstein field equations has compelled cosmologists to make various simplifying assumptions, if they are to obtain any cosmologies with which to work. We are concerned here with recent attempts to abandon what is perhaps the most drastic of these assumptions, that of the smooth universe. In order to obtain a qualitative picture of the universe one has first to ignore any fine structure, to smooth the universe into a homogeneous paste, invariant in all directions. This assumption of homogeneity and isotropy is customarily referred to as the cosmological principle, according to which precept, if strictly interpreted, there are no lumps in the universe, and therefore no galaxies. Yet it is from galaxies that we derive much of our knowledge about the universe.

Considerable evidence has accumulated, much of it since the discovery of the 3^{o}K microwave background radiation, that the universe is indeed highly isotropic. Thus it appears that in relying on the cosmological principle the main source of error is likely to be the postulate of homogeneity. How, then, to relax this condition and allow the formation (and continued presence) of galaxies?

Two approaches to this problem have been attempted. The empirical approach is to construct a more realistic model of the universe as it now appears, that is to say, a cosmology containing many large lumps. Not only is the universe lumpy now, but in the past the universe (according to Ambartsumian[1]) was even more lumpy, so that galaxies emerge from superdense cores. In other words, the universe would have possessed at least as much complexity, if not more, at earlier epochs than is now apparent.

The alternative approach is to a certain extent complementary. It is postulated that the universe is initially subservient to the cosmological principle, and the question examined is whether complex structures such as galaxies can condense out of the homogeneous cosmic fluid. Most theories of galaxy formation revolve around the concept of gravitational instability or fragmentation, qualitatively described by Newton[2] in 1692.

A detailed formulation of gravitational instability was first given by Jeans[3], who showed that a uniform unbounded static medium will be unstable to fluctuations of wavelength exceeding a certain critical scale (the Jeans length). On smaller scales kinetic pressure exerts a stabilizing influence. Jeans's discussion is not consistent with Newtonian gravitational theory, and a proper treatment, relevant to cosmology, was first given by Lifshitz[4] in 1946, in a paper which has become the gospel of potential galaxy builders.

In normal macroscopic situations involving fluid flow, instabilities are usually exponential in nature: that is, arbitrarily small fluctuations grow into the non-linear regime in a time of the order of the mean flow time. The cosmological environment presents another possibility: fluctuations will grow over many cosmic expansion times until separating out from the substratum.

In isotropic cosmological models with zero cosmological constant, the growth rate for density fluctuations larger than the Jeans length is inversely proportional to the redshift z. Now in a "hot big bang" model[5], matter and radiation decouple as the universe expands at $z \sim 1000$, so that for galaxy formation to have occurred by $z \sim 10$, one percent density fluctuations must be present at decoupling. Studies of dissipative processes during the decoupling epoch further suggest that this requirement would necessitate the presence of ten percent density fluctuations immediately before decoupling[6]. The existence of primordial fluctuations of this magnitude would indicate that the conventional starting point of a homogeneous universe might be inappropriate. Recent studies, in fact, have been made of chaotic initial conditions, with the aim of predicting the survival of various modes against dissipative processes in the early universe.[7] This is no more than a refinement of the primordial chaos, common to many cosmogonies throughout the ages.

However, there remains an alternative possibility which would allow the existence of an initially homogeneous universe, provided that we consider cosmological models with non-zero cosmological constants. Such a constant is a natural consequence of Einstein's theory of gravitation, although there is no Newtonian analogue. Lemaître believed that one such model, the Eddington-Lemaître universe, which expands from a finite radius at which it has spent an infinite time, is especially conducive to galaxy formation. During the static phase, exponential growth of statistical fluctuations would occur. According to Lemaître, the inevitable formation of condensations would initiate the expansion phase of the model[8]. The effect that Lemaître had in mind was due to the decrease in pressure at the onset of galaxy formation, owing to matter being consumed by gravitationally bound condensations. Pressure gradients are negligible on a cosmological scale; only the gravitational influence of pressure is of dynamical importance. Hence a decrease in pressure during the static phase causes the universe to expand.

However Lemaître overlooked more important effects that tend to produce a net increase in pressure. The most significant of these processes seems to be associated with the initial contraction of gravitationally bound condensations. Such systems radiate one-half of their gravitational potential energy during contraction. It may in fact be shown that there is a net increase of pressure following galaxy formation, causing the Eddington-Lemaître universe to collapse.

Of much recent increase in astronomy has been a modified Lemaître universe which retains the "hot big bang" and adds a stagnation period. The earliest epoch at which the stagnation period may occur is determined by a lower limit on the mean density of matter in the universe. One finds that the redshift z_s of the stagnation period must be less than 3.2. It seems remarkable that this upper limit on z_s is close to the largest quasar emission line redshift hitherto observed ($z \simeq 2.36$ for 4C 25.5). Other reasons for astronomical interest in the Lemaître universe include the long time-scale and low present matter density favoured by observations. Furthermore, the model may explain the logN-logS counts of the radio source surveys[9] and unusual coincidences of quasar absorption line redshifts.[10]

It would therefore seem relevant to inquire whether galaxy formation may occur during the stagnation epoch. From similar arguments to those given for the Eddington-Lemaitre model, we find that too long a stagnation period results in instability, followed by a catastrophic collapse back to the initial singularity. To avoid this fate, the duration of the stagnation period must be less than about one hundred billion years. Although this time is not long enough to form galaxies form statistical fluctuations (falling short by a factor of four), the Lemaître model does provide a significant reduction in the requirements on a primordial spectrum of density inhomogeneities. It is only necessary to account for fluctuations of less than one part in a million immediately before decoupling as compared to the ten percent density inhomogeneities required in Friedmann models (with zero cosmological constant).

There are some unique observational consequences of Lemaître models with appreciable stagnation periods. These have to do with the diffuse background radiation. We wish to point out two specific effects, that may enable the duration of the stagnation period to be determined. During the static period prior to galaxy formation, there should be appreciable excitation of the neutral-hydrogen hyperfine transition at 21-cm rest wavelength. We have estimated that the effective spin temperature is less than the black-body radiation temperature, and predict an isotropic absorption feature at 1420 $(1 + z_s)^{-1}$ MHz with band width of order $\sim 10^{-6}\nu$.

The second effect that we have considered is a diffuse gamma-ray flux produced in the early stages of galactic evolution. It has previously been pointed out by Ginzburg[11] that in a Lemaître universe observations of the diffuse gamma-ray flux above 10 MeV due to π^0- decays can be used to set an upper limit on the product of the average net galactic cosmic ray flux and the duration of the stagnation period following galaxy formation. In fact, positron annihilation X-rays can in principle provide a more sensitive test of this quantity, because a relatively narrow line is produced compared to the very broad spectrum of π°-decay gamma-rays. The line would be observable as an isotropic feature at $511(1+z_s)^{-1}$ keV, with a bandwidth of about $3(1+z_s)^{-1}$ keV. The detection of such a line would be strong evidence for great activity (perhaps rapid galaxy formation) at a single, well-defined epoch and so would strengthen the case for a Lemaître universe. With some improvement in the energy resolution of conventional x-ray detectors, we anticipate that observational limits will soon be available for the existence of a stagnation period. Once the X-ray line is mea-ured, and the value of z_s is found, it will be feasible to look for the redshifted 21-cm line, to give a measurement of the duration of the stagnation period. Thus one can conclude that, at least for the Lemaître universe, observations should enable us to probe into primordial epochs, when galaxies were yet unformed. If no evidence is forthcoming for the existence of a stagation period, we shall be compelled to invoke non-gravitational forces to account for galaxy formation[12], or else to return to the idea of primordial chaos.

REFERENCES

1. V.A. Ambartsumian, 11th Solvay Conference (R. Stoops, Brussels,1958).

2. I. Newton, letter to Dr. Bentley quoted by J.H. Jeans, Astronomy and Cosmogony (Cambridge University Press,1929).

3. J.H. Jeans, op.cit.

4. E. Lifshitz, J. Phys. (USSR), 10, 116 (1946).

5. G. Gamow, Vistas in Astronomy, 2, 1726(1956).

P.J.E. Peebles, Ap.J., 142, 1317(1965).

6. P.J.E. Peebles, Proc. 5th Texas Symp. on Relativistic Astrophysics (Dallas, 1968).

7. C.W. Misner, Nature, 214, 40(1967).

C.W. Misner, Ap.J., 151, 431(1968).

J. Silk, Ap.J., 151, 459(1968).

8. G. Lemaître, M.N., 90, 490(1931).

9. N. Kardashev, Ap.J., 150, 2135(1967).

V. Petrosian, Ap.J., 155, (1969).

10. V. Petrosian, E.E. Salpeter, and P. Szekeres, Ap.J., 147, 1222(1967).

I. Shklovsky, Ap.J., 150, L1(1967).

11. V. Ginzberg, Astrophysics and Space Science, 1, 125(1968).

12. D. Layzer, Relativity Theory and Astrophysics, Vol I (American Mathematical Society, 1967).

For further details of the properties of Lemaître universes discussed in this essay, the reader is referred to a paper by K. Brecher and J. Silk (Ap. J., 1969 , in press).

BIOGRAPHICAL DETAILS

Born London, December 1942.
Attended school in London.
Studied at Clare College, Cambridge University 1960-63, obtaining B.A. degree in June 1963, in Mathematics.
Studied at Manchester University, Department of Astronomy, 1963-64.
Graduate student at Harvard University, Department of Astronomy, 1964-68, obtaining Ph.D. degree in June 1968.
Awarded Bowdoin Prize in Natural Sciences, Harvard University, 1968.
Visiting Fellow, Institute of Theoretical Astronomy, Cambridge University, 1968-69.
Publications in fields of relativistic astrophysics, cosmology, and x-ray astronomy.