PART I

THE CONTEMPORARY STRUCTURE AND DYNAMICS OF THE UNIVERSE

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OBSERVATIONAL FOUNDATIONS FOR ASSUMPTIONS IN COSMOLOGY

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Abstract. Testing cosmological models is worthwhile as long as the theoretical assumptions, on which these models are based, are true. In this report observational material testing the Cosmological Principle separately for geometry and substratum, is discussed without referring to any given model of the Universe.

1. Introduction

Testing cosmological models is worthwhile as long as the theoretical assumptions on which these models are based are true. Otherwise, model testing, and especially observational determinations of their parameters, such as the Hubble constant and the deceleration parameter, may provide only a formal numerical fit with no physical sense involved. For this reason, apart from testing physical theories (General Relativity, Dicke-Brans theory, etc.) which is a task for physicists, the cosmologist must be interested in verifying the size of regions in the Universe to which the Cosmological Principle may be applied. Thus, cosmological theory must develop against an observational background and must in turn lead to observational tests.

In the present lecture we would like to discuss the empirical support for the assumptions of the Friedmann-Lemaître cosmological models.

2. Neoether as Universal Background

We shall call the postulates determining the symmetries in the energy-mass distribution the Cosmological Principle for the Substratum (CPS), and the postulates determining the symmetries of space-time geometry the Cosmological Principle for the Geometry (CPG). In General Relativity the so-called Mach's Principle is not satisfied (Heller, 1970) and consequently there is no one-to-one correspondence between the energy-mass distribution and the geometry of space-time. It follows that in Relativistic Cosmology, from a logical point of view, one should assume CPS and CPG independently.

We may talk of symmetries in the energy-mass distribution (CPS: homogeneity and isotropy of the substratum) only after distinguishing a certain universal frame of reference in which these symmetries appear in a natural way. The existence of such a particular frame of reference resembles the concept of the ether in classical electrodynamics. For this reason, in a way analogous to the proposition of Trautman (1964, 1968) for classical electrodynamics, one may represent the 'neoether' of Relativistic Cosmology as the rigging vector field:

$$a_\mu = \partial_\mu t. \tag{1}$$

M. S. Longair (ed.), Confrontation of Cosmological Theories with Observational Data, 3–11. *All Rights Reserved.*

This field determines uniquely three-spaces of which it is the rigging.* Vectors (1) are perpendicular to three-spaces $t=\text{const}$. As may be readily noticed, the vector $\partial_\mu t$ is the four-velocity vector of an observer in a frame of reference in which this observer is at rest, i.e.

$$\partial_t x^\mu = (1, 0, 0, 0). \tag{2}$$

It seems that the microwave background radiation may be, within fair accuracy, understood to be the physical realization of the neoether. In the following we assume that this radiation results from the initial fire-ball.

The measurements of Conklin (1972) performed at 3.8 cm for declination +32° aimed at finding anisotropy on large angular scales have led to the discovery of a dipole component in $\Delta T/T$ (measured in the plane of Earth's equator) equal to $(8.5 \pm 3.4) \times 10^{-4}$ with a maximum in the direction of right ascension $10^h 58^m$. This corresponds to the motion of a terrestrial observer with respect to the frame of reference connected with the radiation field with a velocity component in the equatorial plane of about 300 km s^{-1}. These data agree with estimates of the motion of the solar system in the Supergalaxy and indicate that the microwave radiation does not participate in this motion. Conklin's observations do not exclude the possibility that an anisotropy in a direction perpendicular to the equatorial plane exists. Theoretical investigations of several anisotropic models suggest that one should take into account the possibility of the occurence of small scale anisotropies in regions of about 10 deg^2. This concerns especially anisotropic models without spin. Up till now, observations of the microwave background do not provide evidence in favour of such models; however, one should remember that measurements are lacking for large parts of the celestial sphere. Measurements of fluctuations of the background temperature on small angular scales using a scanning technique have allowed only upper limits to be set on ΔT. This value amounts to 1.3×10^{-4} K on a scale 12'.5 for $\lambda = 4$ cm, according to observations made in Pułkovo (Parijskij, 1973). Further measurements (Parijskij, 1973) performed at NRAO for three fields (two about the celestial pole and one at declination +28°) on scales between 3' and 1° at $\lambda = 2.8$ cm have shown that fluctuations in ΔT cannot exceed 0.8×10^{-4} K. For $\lambda = 0.35$ cm, Boynton and Partridge (1973) have obtained as an upper limit to ΔT on a scale of 80" the value 4.3×10^{-3} K at a confidence level of 90%

Extrapolating the isotropy of the microwave radiation to all fundamental observers and representing this radiation field by a rigging vector field, it is easily seen that isotropy of the radiation with respect to any fundamental observer implies constant curvature of the rigging surfaces.

In this manner, the neoether allows in a natural way for the existence of (1) universal cosmic time, (2) orthogonal to the time-lines, three-spaces of constant curvature,

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* The rigging vector field a_μ determines uniquely subspaces of which it is the rigging if and only if:

$$a_\mu = \varphi \partial_\mu \psi \qquad (\varphi, \psi - \text{any functions}). \tag{a}$$

(1) is of the form (a): $\varphi = 1, \quad \psi = t$.

(3) a frame of reference co-moving with the substratum. The postulate of the neoether understood as the rigging vector field may be accepted as the essence of the CPG.

The data cited above provide evidence for an unusually high degree of isotropy of the background on small angular scales. The appearence of small-scale anisotropy would indicate nonuniformities in the density distribution and anisotropy in the motions of matter at the epoch at which the background was formed from the original fire-ball. The lack of anisotropy suggests that during the epoch of interaction of the background with matter, the scale of inhomogeneity of density was small (small in the sense of the value of $\Delta\varrho/\varrho$). As the microwave radiation is usually connected with early stages of the evolution of the Universe, this means that the Cosmological Principle was maintained rather well at those stages. If, moreover, the expansion of the Universe is isotropic (which seems to be supported by the lack of anisotropy on large angular scales), then from the homogeneity of the distribution at the epoch of background formation there follows directly the homogeneity at the present epoch (Collins and Hawking, 1973).

The small value of $\Delta\varrho/\varrho$ at the end of the radiation era is also of importance for the theory of galaxy formation. This is connected with testing the Cosmological Principle for it is precisely the distribution of clusters of galaxies (the substratum) which is to fulfill the symmetries imposed by CPS.

3. Substratum as a Universal Background

Every non-empty cosmological model is filled with a substratum described by a corresponding energy-momentum tensor. From the theoretical point of view the substratum is a set of particles, called in the following discussion fundamental particles, which are distributed in space in a continuous manner. It should be stressed that in the Friedmann-Lemaître models there are no galaxies nor clusters of galaxies but only fundamental particles. For this reason all observables which may be defined for a given model do not concern directly galaxies or clusters but fundamental particles. Hence, defining the actual material system which corresponds to the theoretical concept of a fundamental particle is an essential point when one is concerned with observational testing of cosmological models. One should perform counts, determine redshifts, measure diameters, etc. of such material systems which represent fundamental particles.

In textbooks the opinion is widely propagated that the fundamental particle is represented by a galaxy or a cluster of galaxies. This may be true only at a given cosmological epoch. According to our present views, the substratum picture of the world's evolution remains valid backwards in time up to extremely high densities. In such superdense states no galaxy or cluster of galaxies could exist. It is therefore evident that the definition relating empirical reality to the concept of a fundamental particle has to change with time of cosmic evolution. Speaking most generally, a fundamental particle is such a material system M that (1) the set of all M obeys the Cosmological Principle (CPS), (2) M has the smallest possible linear dimensions (i.e. a cluster of galaxies would not constitute a fundamental particle if the Cosmological Principle were fulfilled on the level of, say, galaxies).

We propose (Heller, 1973) the following definition of a fundamental particle:

(1) A fundamental body is the matter included in a fundamental region.

(2) A fundamental region is the part of the momentary ($t=\text{const}$) three-space resulting from the following procedure:

  (A) We divide the three-space into parts such that:

    (a) their volumes are equal: $V_i = V_k = V$

    (b) their linear dimensions are limited: $L_i \leqslant L$

    (c) the masses contained in them differ by a small value: $|m_i - m_k| \leqslant m_i \delta$

    (d) The energy of gravitational interaction of matter contained in two different parts is small as compared with that of matter within a given part: $|E_{ik}| \leqslant |E_{ii}| \varepsilon$.

  (B) Of all possible partitions (A) we choose that which minimizes L, when δ and ε are fixed.

We postulate that fundamental particles are indentified with the centres of mass of fundamental bodies. In cosmology one has to take into consideration such an extensive domain of three-space that, relative to it, distances between the centres of mass of any two neighbouring fundamental bodies are negligibly small. The last sentence may be considered to be a working definition of the term 'Universe'.

Point (2 A-d) of our axioms defining the concept of a fundamental particle, although important from the theoretical point of view, seems to be non-operational for practical purposes (at the present stage of our knowledge about the world of galaxies), so we shall not discuss it any more.

Our axiomatic definition of the fundamental particle is constructed in such a way that the set of all fundamental particles (i.e. the substratum) is homogeneous *by definition*. Available observational material, however, does not allow us to realize in full the programme contained in our axioms. Therefore, at present, we satisfy ourselves with only rough estimates, which are of course, dependent upon the correct interpretation of the observational data.

4. Observational Data

Unfortunately, the interpretation of observations concerning space distribution and motions depends on the geometry of the Universe which is neither given a priori nor may be investigated in any other way but by measuring the positions and motions of objects under observation. In principle, we thus apply consecutive approximations. First, assuming that we have only to consider flat (Euclidean) geometry, we test the applicability of the Cosmological Principle to the distribution of matter in the Universe to a first approximation. In the second approximation we test the applicability of the Cosmological Principle for a model already applicable to regions established in the first approximation.

It may thus be seen that it is impossible to test the Cosmological Principle without assuming some model.

Testing the distribution in the first approximation consists, in principle, in determining spatial coordinates of stellar objects, and next, in calculating their density distribution. The first problem we encounter is the frame of reference which we want to assume is locally inertial. For purposes of cosmology a sufficiently good zero-point of the frame is the Sun's centre. If one assumes that at present the Sun is not about to meet an invisible mass, then from calculations of the Sun's orbit in the Galaxy it follows that the rate of its velocity change is about 0.7 km s^{-1} per million years, and the change of its direction of motion about 1.5° per million years. Such deviations are negligibly small as compared to the accuracy of measurements which we are interested in. We may also neglect small deviations of the position of the Sun's centre with respect to the centre of mass of the solar system.

For astronomical measurements we use the polar set of coordinates and the problem is divided into establishing the direction of a stellar object (angular coordinates on the celestial sphere) and finding its distance. The determination of angular coordinates is astronomical routine and its accuracy far exceeds the demands of cosmology. It seems moreover that relating these measurements to constant directions determined by the positions of distant galaxies guarantees the inertness of the system. However, one should keep in mind that this is only an assumption following from the use of a given theory. In certain models of the Universe a rotational motion of the whole Universe is possible (e.g. in models of the Gödel type) in which case one should look for other references for fixed directions in order to assure local inertness of the system.

Determination of distances is a much more complicated task for which we are forced to use various methods for different ranges which overlap one another. All these methods are reviewed in Figure 1. For cosmological purposes the red-shift method (method (8) on the Figure 1) is of most importance. However, it is worth remembering that all errors and uncertainties of methods (1)–(7) are transferred automatically to method (8).

As far as testing definite cosmological models is concerned an essential point is whether the redshift appearing in Hubble's law should be interpreted as a Doppler shift or by some other means; this problem is rather irrelevant when testing the Cosmological Principle. For our purposes it is important to distinguish in the redshift the three following terms:

$$z = z_c + z_m + z_p. \tag{3}$$

By z_c we have denoted here the cosmological term which is a function of distance. Its physical nature is irrelevant, the relevant point being the form of its dependence on distance. For not too large distances which appear in the first approximation of the testing procedure we have discussed, we assume nowadays linearity, i.e. Hubble's law. The Hubble constant may be different for different bodies (e.g. different for galaxies and for quasars) as long as it is known. The term denoted z_m is the value of red-shift for a given type of body considered, and is a function of the morphological type of the given body. For example, for a given distance, as suggested, e.g. by Zwicky (1967) and Arp (1966), z_m may depend on the degree of compactness of the galaxy. Finally,

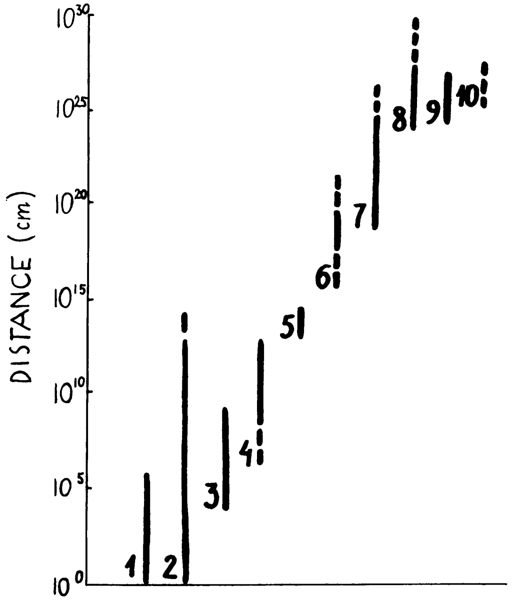

Fig. 1. Review of methods of measuring distances. 1. measuring tapes; 2. radar; laser, etc.; 3. geodesic triangulation; 4. diurnal parallax; 5. determination of solar parallax and parallaxes of further planets by means of celestial mechanics; 6. annual parallax; 7. determination of distances by comparison of absolute and observed magnitudes; 8. red-shift; 9. diameters (explanations in text); 10. off-hand judgment (explanations in text). – Uncertain or unrealized possibilities are marked by broken lines.

z_p is a peculiar term corresponding to all special variations of red-shift, among other factors, resulting from the motions of the bodies.

At present there is heated discussion as to what is the nature and size of the individual terms, which will, no doubt, be reflected in the papers presented at our meeting. No matter what the future outcome of this discussion, which will only lead to a determination of the functional dependences for the first two terms and of the dispersion corresponding to the third, the method of the redshift will probably remain the most accurate method of measuring distances in the Universe, applicable to bodies at any distance as long as they are visible. Its drawback is however its tediousness (the necessity of obtaining well defined spectra). Also, there is much discussion at present as to the numerical value of Hubble's constant, which renders the value of other parameters appearing in the above relations even more uncertain.

Owing to problems associated with method (8), attention is drawn to the method of determining distances from angular sizes (method (9) of Figure 1). One should include here the method of determining distances from the angular sizes of galaxies in clusters, for example the method of Zwicky and Kwast (Kwast, 1970), and methods of measuring distances of clusters alone, e.g. the method of Paál (1971). These methods do not however extend as far as method (8).

Owing to the tediousness of method (8), only a few clusters of galaxies have distances determined from redshifts. The two basic catalogues of clusters of galaxies, those of

Abell (1958) and of Zwicky *et al.* (1960–1968), contain distances of clusters judged on the appearance of their member galaxies (method (10) of Figure 1). These distances, which are determined by off-hand judgement, are, unfortunately, the basis for many statistical studies of the large-scale distribution of matter.

Because of the difficulties with accurate determination of distances as well as selection effects which appear with increasing distance, the investigations concerning the uniformity of distribution of matter are carried out mainly by comparing the visible distribution of objects lying at roughly the same distances for various regions of the celestial sphere.

It is commonly know that it is impossible to observe (both optically and by radio methods but for different reasons) objects lying outside our Galaxy in regions close to the galactic equator. It is usually accepted that interstellar extinction does not introduce in practice errors into the observed picture for galactic latitudes greater than 40°. Actually, the number of galaxies or clusters of galaxies observed, e.g. in Zwicky's catalogue, increases systematically right up to the galactic pole (Zięba, 1973). To make matters worse, close to this pole there lies the supergalactic equator. In the present state of collection and discussion of the data, it is extremely difficult to decide what is the influence of the Supergalaxy (the Virgo Cluster, in Zwicky's terminology) on the counts of distant galaxies and clusters, both through projection of a large number of intrinsically faint galaxies as well as through possible intergalactic extinction associated with the Supergalaxy (Takase, 1972). For these reasons it is as yet impossible to decide whether for investigations of the uniformity of the distribution of galaxies it is better to use two fields close to the galactic poles or rather four fields distant both from the galactic and supergalactic equators (Figure 2). One should moreover take into account the fact that no observational material of the same statistical accuracy exists for both southern and northern celestial hemispheres. In this situation, the equal spacing of clusters of galaxies in various regions of the celestial sphere should be treated as a postulate which does not contradict observation, rather than as a direct result of observation.

The very fact that the Supergalaxy of dimensions ≈ 15 Mpc exists, implies that the Cosmological Principle may not be applied to regions smaller than this dimension. It follows from the works of Zwicky and Rudnicki (1963) that cells of individual galaxy clusters are of dimensions up to 40 Mpc, i.e. 12×10^{25} cm; hence the Cosmological Principle should be applied to regions larger by at least one order of magnitude, that is 10^{27} cm. Here we leave aside the problem of the superclustering of galaxies, as the postulated dimensions of clusters of clusters of galaxies are of the same order of magnitude as those of the cells of galaxy clusters described above. However, one should keep in mind that some workers in this field claim that there exist structures which are larger than clusters of galaxies by an order of magnitude. We should mention here the communication of Herzog of 1967 (unpublished); also the existence of such a superstructure seems to be suggested by certain data on the Jagiellonian Fields (Zięba, 1973). If this is true, if indeed density structures of sizes 10^{27} cm exist, then the Cosmological Principle should be applied to sizes of the order of at least 10^{28} cm.

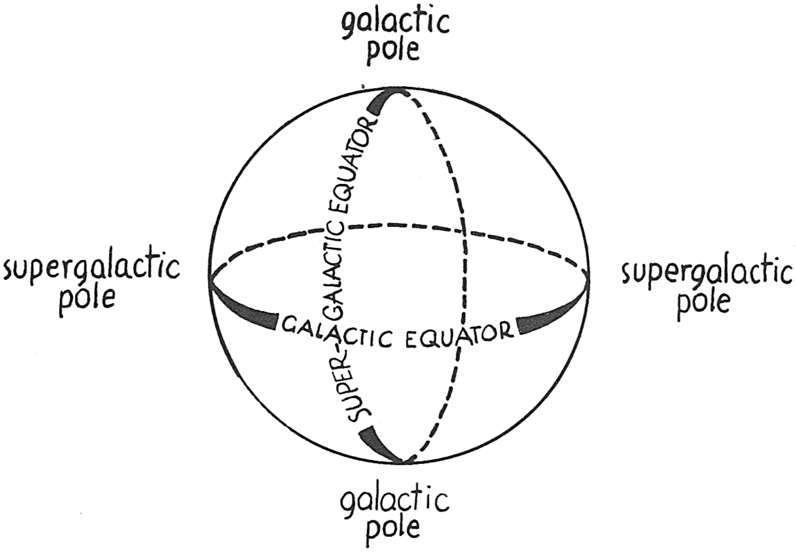

Fig. 2. Situation of observation fields.

This is the size of the whole world of galaxies under investigation.

Further away we have probably the world of quasars. However, due to the controversy concerning these objects, let us, for the time being, draw no definite conclusions about cosmology from them.

For practical reasons it is better to assume that structures of scale 10^{27} cm do not appear in the Universe and to hope that further investigations will not contradict this assumption.

In order to use the Cosmological Principle it is also necessary to determine regions for which averaged velocities are zero with respect to a local frame of reference. Here a pleasant surprise awaits the cosmologist. The dispersion of velocities of stars in galaxies amounts ot hundreds of km s^{-1}. The dispersion of velocities of galaxies in clusters reaches 3000 km s^{-1}. One could expect an even higher dispersion between the velocities of the clusters themselves. Yet plots of red-shift vs luminosity for massive galaxies at the centres of clusters give an almost linear relation. It thus follows that the dispersion of velocities of the nuclei of clusters of galaxies is smaller than the accuracy with which red-shifts are determined. One may therefore believe that clusters of galaxies correspond well to fundamental particles as far as velocities are concerned.

It is well known that the momentum of a particle moving under its own motion with respect to a co-moving frame of reference, varies as R^{-1}. Did clusters of galaxies then possess significant velocities at earlier epochs? Yes, but then, on the strength of the above axiomatic definition, clusters of galaxies cease to be fundamental particles (Heller, 1973).

The problem remains to be solved of the identity of the frame of reference in which the substratum is at rest with the frame of reference in which the background radiation is isotropic.

We thus conclude that at the present epoch one most certainly cannot claim that galaxies correspond to fundamental particles. So, at best, when testing cosmological models, one may treat single galaxies as typical representatives of the fundamental body (cluster?). If the observational curves for galaxies fit reasonably well the theoretical curves (for fundamental particles), it will be one more proof of Nature's kindness towards earthly cosmologists.

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