RIVAL THEORIES OF COSMOLOGY

A symposium and discussion of modern theories of the structure of the universe.

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W. B. Bonnor
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FOREWORD

In the spring of 1959, the British Broadcasting Corporation invited Dr. W. B. Bonnor, Professor H. Bondi, and myself to speak in the Third Programme on our different views of modern cosmology—cosmology may be defined as the theory of the origin, structure, and development of the universe as a whole. The resulting talks aroused such interest that the B.B.C. not only decided to broadcast them again but also asked the three speakers to meet together and debate their different viewpoints under the chairmanship of Dr. G. J. Whitrow. This discussion was broadcast towards the end of 1959.

As the questions at issue are for the most part far too recondite to be conveyed really adequately by the spoken word and a single bearing, it seemed desirable, particularly in view of the many and varied inquiries prompted by the talks and discussion, to have the whole series reproduced in more permanent form. This little book has therefore been compiled by the speakers and chairman. Although substantially the same in content as the original broadcasts, the contributors have taken the opportunity to try to clarify and amplify here and there some of their statements, and a certain amount of editing and rearranging of the impromptu discussion has also, we hope, served to clarify it. But if a reader finds obscurity in this subject he may take some comfort in that he is by no means alone and that his feelings are shared by those who have devoted years of study to this sublime problem. The seeming miracle is that there
should be a universe at all, and again one that appears to have an organized structure governed by general laws. It would be too much to expect that the problems it presents are going to prove easy.

I should emphasize that none of the contributors claims for the views expressed here any absolute enduring truth. Cosmologists everywhere are still struggling to find some more certain basis for the theory of the universe than exists at present, and one of the means to such progress lies in the clearer understanding that can emerge from discussion and criticism of rival theories to discover their defects or advantages. It is the business of theory to continue with this while at the same time awaiting and hoping for some great advance in observational technique and discovery, or in some other branch of science, that may precipitate wide revision of our ideas of the universe. We do not know if in this field some great surprise is in store for us, and although it is difficult to believe that there is, we must nevertheless try to keep an open mind and remember that our theories are still at a preliminary stage waiting upon observational evidence for their disproof or precarious survival.

It seemed appropriate here to include pictures of actual examples of the objects that we are talking about when we speak of receding galaxies in the Expanding Universe, but it must be remembered that there may be a great deal of as yet unseen diffuse material between the galaxies, perhaps representing the bulk of all existing matter. Almost all the pictures here reproduced were obtained with the 200-inch telescope on Mt.

Palomar, and it is a pleasure to express our thanks to the Mount Wilson and Palomar Observatories for permission to reprint them here. Thanks are also due to Mrs. Magda Whitrow for compiling the index.

St. John's College
Cambridge
May 1960

R. A. LYTTLETON
# CONTENTS

**FOREWORD**

**LIST OF ILLUSTRATIONS**

I RELATIVISTIC THEORIES OF THE UNIVERSE 1
   by W. B. Bonnor

II THE STEADY-STATE THEORY OF THE UNIVERSE 12
   by H. Bondi

III AN ELECTRIC UNIVERSE? 22
   by R. A. Lyttleton

IV DISCUSSION OF THE RIVAL THEORIES 34
   Chairman: Dr. G. J. Whitrow

SELECT BIBLIOGRAPHY 61

INDEX 63
# Illustrations

**Plates**

<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Messier 51: The first 'spiral nebula' ever to be clearly seen</td>
</tr>
<tr>
<td>2</td>
<td>The spiral nebula in Coma Berenices (NGC 4565)</td>
</tr>
<tr>
<td>3</td>
<td>Messier 101: Example of a spiral galaxy with very open arms</td>
</tr>
<tr>
<td>4</td>
<td>Peculiar external galaxies</td>
</tr>
<tr>
<td></td>
<td>(a) NGC 4631. Edge-on spiral type, but of irregular form. Nebula in Canes Venatici</td>
</tr>
<tr>
<td></td>
<td>(b) NGC 4486. Messier 87. Globular-shaped nebula in Ursa Major</td>
</tr>
<tr>
<td></td>
<td>(c) NGC 4314. Non-typical barred spiral, in Coma Berenices</td>
</tr>
<tr>
<td></td>
<td>(d) NGC 2685. Exceptional form of barred spiral, in Ursa Major</td>
</tr>
<tr>
<td>5</td>
<td>A small cluster beyond the constellation Leo containing four galaxies of widely different types</td>
</tr>
<tr>
<td>6</td>
<td>The cluster of galaxies in the constellation Coma Berenices situated about 300 million light-years away</td>
</tr>
<tr>
<td>7</td>
<td>The rich cluster of galaxies in the constellation Corona Borealis</td>
</tr>
<tr>
<td>8</td>
<td>The vast cluster of galaxies in Hydra</td>
</tr>
<tr>
<td>9</td>
<td>The remotest objects at present detectable with the Great 200-inch telescope</td>
</tr>
<tr>
<td>10(a)</td>
<td>How the relation between red-shift and distance is established for external distant galaxies</td>
</tr>
</tbody>
</table>
Illustrations

10(b) PART OF THE VIOLET END OF THE SOLAR SPECTRUM

11 EXAMPLES OF COLLIDING GALAXIES
(a) The Cygnus source
(b) NGC 4038 and 4039. A pair of galaxies in collision, with evidence of associated streamers of great length
(c) NGC 5426 and 5427. A pair of spiral galaxies probably very nearly in collision
(d) The system NGC 1275 in Perseus

12 NGC 5128 CENTAURUS A: AN EXTRAGALACTIC OBJECT BELIEVED TO CONSIST OF TWO GALAXIES IN DIRECT COLLISION

TEXT FIGURES

FIG. 1 CONJECTURAL DRAWING OF OUR OWN GALAXY SEEN EDGE-ON (Reproduced from R. A. Lyttleton’s The Modern Universe (1956) by courtesy of Messrs. Hodder & Stoughton Ltd.)

FIG. 2 DIAGRAM ILLUSTRATING HOW AN EVOLVING UNIVERSE MIGHT DIFFER FROM A STEADY-STATE UNIVERSE

I

RELATIVISTIC THEORIES OF THE UNIVERSE

By W. B. Bonnor

Until about thirty years ago it was possible to picture the universe as a static collection of stars and nebulae. There was no scientific reason to believe that it had ever undergone any significant change. The discovery that the universe was expanding meant that this simple view had to be given up, and the theories of cosmology which followed suggested that the past and future of the universe must be very different from the present.

The cosmological theories which have found widespread acceptance are those based on the general theory of relativity, and it is this view of the universe I shall discuss. Cosmology here tries to deal scientifically with some of the great issues which have in the past fallen in the domain of speculative philosophy—among them the origin of the universe. Some scientists have maintained that relativistic cosmology implies an act of creation in the finite past. This view I regard as mistaken, and I think it arises from defects in the theories which it is our duty to correct. There is one contemporary cosmology—the steady-state theory of Bondi, Gold, and Hoyle—in which, although creation occurs, it appears in a less unsatisfactory way. The final decision between this theory and those following from general relativity must await more precise observations.
Cosmology is built on two main observed phenomena. First, observations of the distant nebulae (or galaxies, as they are now often called) show that the light we receive from them is redder than that from similar matter in our immediate neighbourhood. This we call the red-shift. The interpretation of this by ordinary physics—called the Doppler effect—is that the nebulae are receding from us at speeds proportional to the magnitudes of their red-shifts.

The second observation of fundamental importance is that the distribution of the nebulae seems to be, on a large scale, the same in all directions of space. This supports an assumption made, in one form or another, by all cosmological theories, and known as the Cosmological Principle. In the cosmology of general relativity, the principle asserts that, at a given time, observers like ourselves on other nebulae would see essentially the same picture of the universe as we do. In making this assumption we ignore local irregularities and think of the universe only on a grand scale.

The Cosmological Principle seems at first sight to conflict with our interpretation of the red-shift—that the nebulae are all receding from our own Milky Way. One might think that this recession implies that we are at the centre of the universe. One of the surprising results of cosmological theory is that there is no contradiction here. Every cosmic observer sees a similar recession of the nebulae, and we are no more at the centre of the universe than our counterparts on other nebulae. The recession of the nebulae is usually known as the expansion of the universe. In general relativity we prefer to think of space itself expanding and carrying the nebulae with it—like leaves in the wind—and not of nebulae moving away from each other through passive and indifferent emptiness. This is not merely a difference of words: the active role of space in dynamics is one of the main ideas which Einstein brought to physics when he created general relativity.

To tackle any physical problem in general relativity, such as the history of the universe, we have to find an appropriate solution of Einstein’s field equations. For cosmology much of the basic work was done between 1917 and 1930 by de Sitter, Friedmann, Lemaître, and Eddington. The field equations do not give a unique answer to the cosmological problem, and there is a large number of solutions, all candidates to describe the actual universe. Each solution is called a model of the universe.

This plethora of world-models is something of an embarrassment to the relativistic theory, and it will be a great relief when a decision between them is reached by observation—as it almost certainly will be within the next decade or so. However, the abundance of relativistic models is not nearly as great as is sometimes thought, provided we rule out those which owe their existence to the notorious cosmological term inserted into the field equations by Einstein in 1917.

At that time nothing was known of the expansion of the universe, and Einstein added the cosmological term to obtain a static world-model. Later it became clear that the original, unaltered field equations were quite capable of describing an expanding universe, and the cosmological term was no longer necessary. In fact,
Einstein himself then abandoned it, and confined his attention to the much simpler models which arise as solutions of the original field equations. This is the best course on grounds of simplicity and economy of hypothesis, and the one which I think we should continue to adopt.

If we agree to abandon the cosmological constant, the more plausible models are of two types. The first type predicts that the expansion will continue for ever: the nebulae which we see will get fainter and fainter, and the average density of matter in the universe will continually diminish. According to the second type of model, the expansion is slowing down fairly rapidly, and will eventually change to a contraction. If this is correct, the distant nebulae will one day approach the Earth instead of receding from it, and to observers of that time the light from them will appear more violet than the corresponding terrestrial light, instead of redder. The prospect of this contraction need cause no anxiety, as it would not begin to happen for many thousands of millions of years.

According to the models of either type, the expansion started about 8,000 million years ago. We can, from the models, estimate the average density of matter in the universe at any given time. We find that this density becomes greater and greater as we go backwards in time towards the moment the expansion started. At that moment itself, the density is infinite. The models suggest no way in which this infinite density could have come about; they give no information about what the universe was like before the

I. Messier 51: The First 'Spiral Nebula' Ever to Be Clearly Seen

The name corresponds to the number of this object in Messier's original list of such nebulous objects. It was first seen by Lord Rosse with his famous 6-foot mirror mounted in the castle grounds at Birr. This galaxy happens to lie flat on to us so that we get the optimum view of its spiral character. The arms, which are mainly hydrogen clouds streaming round, are shown up by the highly luminous stars they contain. The multitudinous tiny dark areas and streaks within the system are due to dust. The object at the bottom of the picture is probably a minor companion system apparently associated in some way with the trailing arm. (200-inch Hale Reflector. By courtesy of the Mount Wilson and Palomar Observatories.)
2. THE SPIRAL NEBULA IN COMA BERENICIS NGC 4565

(NGC = New General Catalogue)

This magnificent specimen of an edge-on galaxy clearly reveals the extraordinary degree of flattening of these objects. The brilliantly luminous central region is here very conspicuous, as also are the extremely numerous dust clouds which combine to give the impression of an obscuring band running the whole length of the general plane of the galaxy.

In our own galaxy, this dust effectively prevents observation of external galaxies by optical means in a belt right round the sky in the region of the galactic equator—sometimes called 'the zone of avoidance'. The central region of our own galaxy is also hidden optically by obscuring dust, but fortunately it can be studied in radio wave-lengths. (200-inch Hale Reflector. By courtesy of the Mount Wilson and Palomar Observatories.)

expansion started. The trail we have been following seems to come to a dead end.

It is for this reason that the start of the expansion is sometimes called the creation of the universe. The conclusion to be drawn from the failure of the models is, it is argued, that all matter, compressed to an enormous density, was created at this time. At the same

FIG. 1. CONJECTURAL DRAWING OF OUR OWN GALAXY SEEN EDGE-ON

The Sun is situated just above the central plane (as indicated) about three-fifths of the way out to the rim. The directions perpendicular to the plane of the Milky Way point to the constellations of Coma Berenices and Sculptor. The dark central band represents the dust clouds, which tend to lie near the galactic plane. This dust obscures and cuts off from observation external galaxies in and near the plane of the galaxy. The small dots away from the galaxy denote the halo of widely-spaced surrounding stars, while the larger white dots represent the globular clusters of stars, of which there are some hundreds or more associated with the galaxy, and show their distribution relative to the galaxy.
moment some sort of explosion took place, and the expansion started.

This view I regard as highly misleading and unscientific. The difficulty to be faced is that at the start of the expansion certain quantities in our differential equations become infinite. This frequently happens with differential equations, and when it does the equation is said to contain a mathematical singularity. A singularity in the mathematics describing a physical problem is usually an indication of the breakdown of the theory, and the physicist's normal response is to try to get a better one.

This procedure has not generally been followed in cosmology, and some scientists have identified the singularity at the start of the expansion with God, and thought that at this moment he created the universe. It seems to me highly improper to introduce God to solve our scientific problems. There is no place in science for miraculous interventions of this sort; and there is a danger, for those who believe in God, in identifying him with singularities in differential equations, lest the need for him disappear with improved mathematics.

To me the correct approach seems to be to admit that the present cosmological models become unsatisfactory if one extrapolates them back the 8,000 million years or so to the start of the expansion. This is not to say that they are inadequate to describe the present, and the immediate past and future; this they are probably capable of doing. But they have to be altered so that they no longer become singular in the distant past.

The first obvious difficulty here is that 8,000 million years is a very long time, and anything we say about what the universe was like then is bound to be tentative, to say the least of it. Cosmology here meets the usual problems of any historical research concerned with the remote past. Some physicists think that the extrapolations involved are so enormous and the conclusions therefore so uncertain that the entire activity is a waste of time. There is something to be said for this view, but my argument against it is that to most people the past history of the universe is such an exciting matter that it is worth speculating about.

Secondly, even if we suppose that the infinite density given by our equations is a mathematical fiction with no physical meaning, it is probable that there was a period of very high density and temperature about 8,000 million years ago. This would be consistent with observed facts, which suggest that the age of our own nebula is somewhere about this figure. It is reasonable to suppose that after the period of intense heat, the nebulae, including our own, formed as the universe cooled. The effect of this period would be to obliterate evidence of what the universe was like before the expansion started. Any relics of a previous epoch would have been reduced to the uniformity of a gas, or even a fluid of atomic particles. For this reason there is little hope of obtaining by direct observations any information about the epochs before the expansion. We have to proceed by more indirect inference. Here the situation is more hopeful. I will describe some possible lines of attack, with special reference to models of the
second type. According to these models the contraction, when it sets in, will eventually gather speed, bringing the nebulae closer and closer together; and if we follow the models to their end they reach a condition of infinite density—in fact, a singular state like the one in which they began. If one is prepared to regard the first singularity as the creation, the second presumably represents the annihilation of the universe.

In my opinion it is more satisfactory to suppose that as the singular state is approached some mechanism starts to operate which slows down the contraction and ultimately reverses it. The universe is thus launched on an expanding phase again, and starts a new cycle of existence. According to this picture, the history of the universe is an unending series of oscillations.

I want to explain two possible mechanisms for reversing the contraction. The first is suggested by a peculiar feature of the theory of relativity. According to Newton's theory the force of gravitation between two bodies is a function of their masses and their distance apart. In general relativity, however, the gravitational field of a body depends not only on its mass but also on the way it is stressed. A thrust or pressure augments the ordinary Newtonian gravitational force, but a tension reduces it. In fact, a body in a sufficiently high state of tension could exert a negative gravitational force—that is to say, a repulsion. A repulsion between particles of matter is just what is needed to reverse the final contraction of the universe. The difficulty is that matter in a gaseous form—such as one would expect to fill the universe at that time—

can exert pressure but not tension. However, matter may show unexpected properties at the high temperature and density which must then prevail. We have little information about this at present, but further knowledge of the behaviour of matter in extreme conditions—such as those inside the stars—may help to decide whether this mechanism is feasible or not.

Another possible way in which the contraction might be reversed is revealed by some interesting recent work by Professor Heckmann of Hamburg. Heckmann supposes that the matter in the universe has a slight rotation. It then seems that the centrifugal force of this rotation is enough to reverse the contraction when the universe becomes very dense at the end of one of its oscillations. In cosmological theories until now it has always been supposed that there is no cosmic rotation, because none has been observed. However, Heckmann has shown that even a slight rotation, such as would be undetectable at present, would be sufficient to prevent the state of infinite density.

These suggestions are tentative, and it may be that neither is correct. Even if we can show definitely that some such mechanism would reverse the expansion, there are difficulties to be overcome. For example if the history of the universe is an infinite series of oscillations, we shall have to look carefully again at the Second Law of Thermodynamics; this law has often been thought to mean that the universe is gradually using up its mechanical energy and converting it irrevocably into heat. This would amount to a sort of running down of the universe, rather as a watch runs
down as it uses up the mechanical energy stored in its spring. The idea of an unending series of equal expansions and contractions is evidently inconsistent with this view. However, it would be wrong to take this too seriously, because it has never been properly shown how the Second Law of Thermodynamics affects the universe as a whole.

There are undoubtedly many difficulties in explaining the start of the expansion. But what I want to emphasize is that this is a matter for scientific investigation, though by indirect and tentative methods. There is no reason whatever for downing tools and handing over to God 8,000 million years ago.

I have been describing cosmological theories founded on general relativity. The steady-state theory, which I referred to earlier, escapes the problem of the start of the expansion; This theory uses the basic ideas of relativity, but modifies Einstein's field equations. According to the steady-state model the universe, considered on a large scale, has always been much the same as it is now: in particular, the average density of matter does not change with the time. However, the observed recession of the nebulæ implies a falling density, and this fact can be reconciled with an unchanging universe only if fresh matter appears to keep the density constant. The steady-state theory proposes that this fresh matter is being continually created out of nothing in empty space. The rate of creation is supposed to be very low, and below the limit of detection by present techniques of measurement.

Although the steady-state theory has no problem of singularities in the finite past, it suffers from one defect so serious that, in my opinion, it is hardly to be considered as an important rival to the relativistic theories. Since matter is a form of energy, the creation of matter out of nothing violates the principle of the conservation of energy. This principle has withstood all the revolutions in physics in the last sixty years, and most physicists would be prepared to give it up only if the most compelling reasons were presented. In fact, when the steady-state theory was originated, about ten years ago, the case for a drastic measure of this sort was rather strong. It then seemed that there was a discrepancy between the predictions of relativistic cosmology and observation. It has since turned out that the observations were wrong, and the relativistic theories are now in satisfactory agreement with the present empirical evidence.

The view I have been putting forward is that the universe has an unlimited past and future. This may seem in some ways as puzzling as if its history were finite. From the scientific aspect, however, this point is really one of methodology. Science should never voluntarily adopt hypotheses which restrict its scope. Sometimes restrictions are obligatory, as for example in the case of the Uncertainty Principle, which restricts the accuracy of certain physical measurements, but unless it is shown that such limitations apply to cosmology we should, I think, assume that our knowledge of the universe can stretch indefinitely into the past and into the future.
II

THE STEADY-STATE THEORY OF THE UNIVERSE

By H. Bondi

In cosmology, one is considering an extrapolation of physics as we know it here to a very much larger scale of phenomenon. What we have learnt in the laboratory is to be applied to the universe at large. Clearly, there are dangers and difficulties in making such an enormous extrapolation. Therefore, it may well be in place to discuss the underlying method—the method of scientific progress—on which all our work is based.

By far the most successful analysis of scientific method is due to Professor Karl Popper. In his view, which I regard as amply borne out by actual scientific procedure, hypotheses are formed in the minds of scientists in a way that is not wholly clear because undoubtedly a substantial element of imagination is involved. The purpose of a theory is to make forecasts that can be checked against observation and experiment. A scientific theory is one that it is in principle possible to disprove by empirical means. It is this supremacy of empirical disproof that distinguishes science from other human activities. We can never regard a theory as proved, because all we can say is that, so far, there have been no experiments contradicting it. A scientific theory, to be useful, must be testable and vulnerable. Cosmology, fortunately, must now be considered to be a science. It is a subject, like any other scientific subject, in which there are means of disproving theoretical forecasts by experiment and observation. It is true that most of these are still rather difficult to make and require expensive equipment and great skill, but this is the way in which we shoot down cosmological theories.

If we now come back to the point I made first, about the enormous extrapolation required in order to apply laboratory physics to the universe at large, then we are immediately up against the question: can we really suppose that physical processes go on elsewhere as they do in our neighbourhood? Clearly, the answer to this question will depend on whether we are in a very special place in the universe or whether ours is a typical one. If our position in the universe in space and time is typical, then we can feel confident that our locally acquired knowledge is applicable elsewhere. If, on the other hand, the universe were very different elsewhere or at other times from what it is here and now, then we would need to know which aspects of our physical knowledge were truly permanent and which of them had just caught a mood of the moment of the universe. If we assume that all the physics we know is unchangeable, although the universe is changing, then we make a possible but quite arbitrary assumption.

Of course, it may be necessary to consider the very difficult problems of the variation of physics in a varying universe; but before we enter the enormous complication of this question, we first try to see whether our universe might not happen to be one that is the same
everywhere and at all times when viewed on a sufficiently large scale. In examining this possibility, we by no means claim that this must be the case; but we do say that this is so straightforward a possibility that it should be disproved before we begin to consider more complicated situations.

We are thus led to consider a model of the universe which is uniform on a large scale, both in space and in time. This model is known as the steady-state model. It is a useful model because in it we can be sure that physics, as we know it here, applies everywhere else. Moreover, as I shall explain later in this talk, it is a model that makes many forecasts that can be checked by experiment and observation. Therefore, it is a testable and, accordingly, a useful scientific theory. It follows immediately from the assumptions of the steady-state theory that the universe must be expanding, for otherwise, as a simple argument shows, we would be drowned by a flood of light from the most distant regions. In order to be consistent with the assumption of uniformity the motion of expansion must be such that there is a velocity of recession proportional to distance. The effect of the recession will then prevent the flood of light. This indeed is the type of motion that is being observed.

Next, if we have such a motion, then it would seem at first sight that the mean density in the universe must be diminishing, because if the distances between the galaxies are increasing all the time, it follows that the same matter now fills a larger volume. However, this would be in flagrant contradiction with the postulate

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**FIG. 2. DIAGRAM ILLUSTRATING HOW AN EVOLVING UNIVERSE MIGHT DIFFER FROM A STEADY-STATE UNIVERSE**

In a given angular sector, at left, the number of galaxies (or clusters of galaxies) per unit volume would be the same at all distances in a steady-state universe.

In an equal sector, at right, if the number of galaxies per unit volume increased with distance—for example, 4 close to us, 5 at $3 \times 10^8$ light-years, 6 at $6 \times 10^8$ light-years, 7 at $9 \times 10^8$ light-years, and so on, as shown—it would mean that the universe is evolving.

Locally two such universes would be indistinguishable because there would be no serious light-time difference.

(For the actual universe we must of course regard the figure as three-dimensional.)
Rival Theories of Cosmology

that the universe is the same at all times. The only way out of this difficulty is to suppose that there is a process of continual creation going on—a process by which, in the enormous spaces between the galaxies, new matter constantly appears. This new matter condenses and forms new galaxies to fill the increasing spaces between the older ones.

Furthermore, every star ages since it converts hydrogen into helium in order to supply the energy the star radiates into space. As each star in the galaxy goes through these changes, the galaxy itself ages. However, the average age of galaxies is kept down since new galaxies constantly form in the increasing spaces between the old ones. It is for this reason, in order to keep the average age constant, that we require the new matter to be laid down in the vast intergalactic spaces. Only in this way can new galaxies be formed so that the average distance between galaxies stays constant, although, because of the expansion of the universe, the distance between existing galaxies is all the time increasing. Old galaxies, as they move farther and farther away, become less and less observable.

The whole picture of the steady-state universe is, therefore, very much like a picture of a stationary human population. Each individual is born, grows up, grows old and dies, but the average age stays the same owing to the fact that, all the time, new individuals are being born. We have, in the steady-state theory, a very similar picture of the universe of galaxies. Old galaxies die by drifting into regions where they are harder and harder to observe, and new galaxies are formed all the time in the spaces between the old ones. In this way, we arrive at a universe that is on the large scale uniform and unchanging. Moreover, it is the only model of this type. Of course, it deviates from ordinary physics in assuming this phenomenon of continual creation of matter which is, indeed, a major infringement of present formulations of physics. Dr. Bonnor has argued that this process of continual creation violates the principle of conservation of energy which has withstood all the revolutions in physics in the last sixty years and which most physicists would be prepared to give up only if the most compelling reasons were presented; but this seems to me to be unsound. The principle of conservation of mass and energy, like all physical principles, is based on observation. These observations, like all experiments and observations, have a certain measure of inaccuracy in them. We do not know from the laboratory experiments that matter is absolutely conserved; we only know that it is conserved to within a very small margin. The simplest formulation of this experimental result seems to be to claim that matter must be absolutely conserved. But this is purely a mathematical abstraction from certain observational results that may contain, indeed are bound to contain, errors.

Now, in fact, the mean density in the universe is so low, and the time scale of the universe is so large, by comparison with terrestrial circumstances, that the process of continual creation required by the steady-state theory predicts the creation of only one hydrogen atom in a space the size of an ordinary living-room once
every few million years. It is quite clear that this process, therefore, is in no way in conflict with the experiments on which the principle of the conservation of matter and energy is based. It is only in conflict with what was thought to be the simplest formulation of these experimental results, namely that matter and energy were precisely conserved. The steady-state theory has shown, however, that much simplicity can be gained in cosmology by the alternative formulation of a small amount of continual creation, with conservation beyond that. This may, therefore, be the formulation with the greatest overall simplicity. There is thus no reason whatever, on the basis of any available evidence, to put the steady-state theory out of court because it requires this process of continual creation. This would be indeed a prejudice, and not a scientific argument.

Finally, as I said at the beginning, we must see how testable this theory is. How many forecasts does it make that can be checked by observation and experiment? There is a whole class of observations based on a very simple consideration. When we see the most distant galaxies that we can observe, then we look at them, not as they are now, but as they were a long time ago, for the light that travelled from them to us took a long time to cover the distance between them and us.

In the case of the most distant galaxies visible in optical telescopes this time is probably around 5,000,000,000 years. If the universe as a whole is evolving in the way Bonnor suggested in the last talk, then, presumably, all the galaxies originated at more or less the same time. In particular, we can definitely say that in such a universe no galaxies originated very recently. According to relativistic theories, then, we see the distant galaxies at an earlier stage in their evolution than the near ones which we see as they are now, more or less. Therefore, one would expect some variations with distance in the appearance of the galaxy, or the colour of light that it sends out, or in the degree of clustering, or possibly in the likelihood that it is a strong emitter of radio waves observable by radio astronomy. Accordingly, if one looks out into space and compares the shapes of distant galaxies with those of near galaxies, or compares in the same manner any other of the characteristics I mentioned, then either one will or one will not find a variation with distance. On the basis of the steady-state theory, time does not matter. A long time ago the universe looked just the same as it does now. Accordingly, no such variation can occur in the picture of the steady-state theory. In the evolutionary pictures one would expect precisely such a variation. Therefore, if these observations are made and any variation is found, then the steady-state theory is stone dead. If no such variation is found, it does not necessarily mean that the evolutionary theories are wrong, because one can always say that the period of time into which we can look back is too short for any such changes to show themselves. Some such observations are within the range of existing equipment, or equipment now in process of being built. Indeed, from the point of view of the steady-state theory we have the very satisfactory situation that although two different
observations of this type have been claimed to disprove the steady-state theory, in both cases it has since been shown that they involved far greater observational errors than had originally been believed. In one case the absence of any such variation has now been established, in the other no definite conclusions can be drawn at present. However, many of these tests may be practicable in the near future.

Next, I want to come to a point of great significance. Most physicists think that all elements were built up from hydrogen by some means or other. In the case of helium, it has been known for years that ordinary stars convert hydrogen into helium. But for a long time it was believed that, in order to make the elements heavier than helium, conditions of density and temperature were required such as could not be found anywhere in the universe as we know it now, not even in the centres of the stars. Dr. Bonnor, in his talk, referred to early stages of high density in the relativistic models. This led to the idea that the birthplace of the heavy elements was this primeval state of the universe. Naturally, we cannot have any such explanation in the steady-state theory. If there ever was a time when it was possible to synthesize heavy elements from hydrogen, then it must be possible to do so now. Everything that ever went on in the universe must, according to the steady-state theory, go on now. It therefore became a crucial question for the steady-state theory whether, in fact, the heavy elements were being synthesized now, contrary to the view held at one time. Inspired by the steady-state theory, such a search has indeed been
going on, and has been entirely successful. We now know that, contrary to the earlier views, the heavy elements are synthesized at present in many reasonably common stars, and that these later burst, and so distribute the elements produced in their centres throughout space. In this way, a theory has been created that is remarkably accurate in accounting for the abundances of the elements. This theory is one of the great achievements of modern physics. Indeed, it is fair to say that, in the twelve years of its existence, the steady-state theory, by inspiring this work, has done more for physics than relativistic cosmology has done in thirty-five years. There are numerous other tests which I shall not describe now. Enough has happened in the twelve years that this theory has existed to show that it gives us a useful way of looking at the universe, a way that inspires new observations and is vulnerable to them.

4. PECULIAR EXTERNAL GALAXIES

External galaxies show a vast range of forms. Hubble's classification begins with almost spherical elliptic galaxies, proceeds along a series of increasing ellipticity, and then divides into a series of spirals of varying degrees of openness of arms and a series of barred or theta-shaped spirals. But there are numerous quite irregular, unclassifiable galaxies too. The precise causes that lead to these widely different forms are still wrapped in mystery. (By courtesy of the Mount Wilson and Palomar Observatories.)
III

AN ELECTRIC UNIVERSE?

By R. A. Lyttleton

It is now more than a quarter of a century since it first became clearly realized that our galaxy is not the whole universe, and that beyond its limits there are countless other galaxies comparable with it in size. This was startling enough: man's personal insignificance had been demonstrated by each previous advance into space, but here was yet another such step on an incomparably larger scale than ever before. But the really surprising thing remained to be established, and that is the now well-known phenomenon that all these galaxies are rushing away from us, and from each other, with speeds that at great distance begin to bear comparison with the speed of light itself.

All sorts of attempts have been made to avoid accepting this expansion, but the suggestions proposed have been largely metaphysical at best, and at worst in conflict with the rest of established science. If we agree to accept the existing order of physics, from which by the way the whole picture of our own galaxy has been successfully and consistently derived, then there seems no escape from accepting the expansion of the universe as an established physical fact.

We do not know for certain yet whether these receding galaxies are being accelerated so that their speeds remain constant so that the fastest moving have simply got farthest away. To settle this would require highly accurate observations of the most distant objects, but it is just for these that observations are weakest, and it turns out that our attitude to the expansion cannot be guided by observation alone, at any rate at present.

Now this question of attitude is a crucial one whenever any new and perplexing phenomenon is discovered. The attitude that any particular person takes will depend on a great multitude of factors. Ask the man-in-the-street what his attitude to the expansion of the universe is and you may receive amusing reactions, almost certainly unscientific, perhaps occasionally even impolite. Try asking a devout clergyman, and he may assure you that it is all the splendid handiwork of God, and that he approves of it. And so on. But why is not the scientist satisfied with simple attitudes of this kind? The answer at bedrock is that he is trying to find an attitude that will help him to understand the universe, and by 'understand it' is really meant to get a theory that will enable other predictions to be made, or the phenomenon 'explained' in terms of already established theory. Someone once said that 'the object of science is to avoid being surprised', but we have not reached that ideal yet, and many more surprises are undoubtedly in store for us before we reach that state of scientific perfection.

Now you may well wonder why in particular should anyone wish to build a new theory of the expanding universe. What is wrong with existing theories based
on Einstein's theory of general relativity? Well, the answer is that these theories are suspect because they do not really achieve anything. Eddington's theory, for instance, begins by more or less arbitrarily introducing certain extra small terms into the Einstein equations, and mathematical models can then be derived that do agree with the expansion and from which we can take our choice. But no extra insight into the universe has resulted from any of them, and it is this extra insight that the scientist is always hoping for. This is the extreme importance of 'theory', for it is only when we have a theory that we have anything to refer observations to, and something to suggest new observations. Observations are meaningless without a theory to interpret them.

Having indicated why there are misgivings about the general relativity 'explanation' of the expanding universe, we come now to the question: What can be done about it? Clearly there is little one can do until one has a new idea about it or a new line of approach. And the new approach that I want now to describe is an electrical one, and not a gravitational one at all.

The idea begins with the proton and electron. These are two of the elementary particles that go to make up matter. They bear opposite electric charges which make them strongly attract each other, and when they are locked together in electrical embrace, they form an atom of hydrogen. The charges of the electron and proton have hitherto been supposed to be exactly equal and opposite, and this must certainly hold to a very high degree of accuracy if all sorts of effects are not to occur that it is known do not occur. The charges can be measured indirectly with fair accuracy, and all the evidence is that the two are equal as near as makes no difference for all ordinary electrical purposes; but even so, there is no experimental evidence for absolutely precise equality. Once this is realized, it becomes of great scientific interest to postulate a small difference that does not upset established results, and see if anything can be explained or predicted thereby.

If the proton has slightly greater charge than the electron numerically, then instead of cancelling out to zero total charge, the proton and electron will give a hydrogen atom a slight positive charge-excess. Imagine now a large spherical distribution of hydrogen atoms. The amount of material in it will depend on the cube of the radius, and so too will the total charge-excess. If a single atom of hydrogen is placed at the surface of such a sphere, it will be subject to two forces opposing each other. First, the material in the sphere will tend to pull it inwards gravitationally, and the bigger the sphere the bigger this force. Second, because of its own very slight charge-excess, the hydrogen atom will be repelled electrically by all the charge-excess within the sphere, and this force also increases in exact proportion with the size of the sphere. The first question is then: How big must the charge-excess be in order that the electric repulsion can overcome the gravitational attraction? The answer turns out to be extraordinarily small—namely, about one part in a million million million! Electrical forces are so very strong compared with gravitation, which is a very weak force, that only this
minute charge-excess is needed to bring about a net repulsion.

If now the whole universe is thought of as a highly rarefied cloud of hydrogen, then the charge-excess would produce a kind of electrostatic pressure urging every atom away from every other atom, and overcoming the attractive tendency that gravitation alone would otherwise give. If, to begin with, we picture the universe in this simple smoothed-out way, which is how general relativity has always been forced to regard it anyway, then the effect of the electric repulsion can easily be worked out, and is found to be exactly of the kind that would cause the universe to expand in just such a way as the observations suggest. That is, the relative velocity of any two selected atoms of hydrogen would always be proportional to their distance apart.

If moreover the density were maintained uniform by continual creation of new matter everywhere in space, then the ratio of velocity to distance would remain constant with time as well, and the smoothed-out universe would have a steady unchanging state of motion of exactly the kind that has for some time been claimed, but never quite established, in the so-called 'steady-state theory' described by Professor Bondi.

Speeds of recession have been measured up to almost a third the speed of light, and if remote parts of the universe move in this way and carry an excess of charge along, there is obviously the possibility that strong currents and magnetic fields may result to an extent inconsistent with observation. So it becomes necessary to tackle the overall electrical problem raised by this motion of expansion, and satisfy ourselves that nothing very awful happens. This can be done by means of a well-known set of mathematical equations associated with the name of Maxwell. But a small and highly important change is required before we can start, for the following reason. If matter is being created in space as hydrogen atoms, or as equal numbers of free protons and electrons, then electric charge will be created along with it. Charge will not be conserved in fact, whereas the classical Maxwell equations imply that it always is. So the equations must be adjusted to begin with by the introduction of some extremely minute terms to allow for the creation of charge. In form, the required terms turn out to be analogous to the famous cosmological terms introduced long ago by Einstein into his field equations and closely associated with the size of the universe.

When the electrical problem is dealt with by means of the modified equations, the solution proves that the outward-streaming motion produces neither a magnetic field nor an electric field despite the motion of the charge-excess. So all is well, and the universe can carry on expanding without throttling itself back by any prodigious electric and magnetic effects, which are not in fact observed anyway.

But what now of the denser condensations of this material, the galaxies and clusters of galaxies through observation of which (and not of any background material) the expansion of the universe has been detected and established. It is only latterly that the possibility of intergalactic matter is coming to be recognized, and it is to a smoothed-out distribution
that the electric expansion theory relates. But if the background material possesses this charge-excess, it will not tend to pull itself together into denser clouds, precisely because the charge-excess overcomes gravitation. How then can galaxies possibly form?

The only condition that could differentiate one part of space from another would be if the material anywhere became ionized—that is, if the electrical bonds holding protons and electrons together as hydrogen atoms should become broken. This always occurs at sufficiently high temperature, and it is this process that enables condensations to form and grow into galaxies purely by gravitational forces. The way this happens is as follows. Once protons and electrons become free particles, the charge-excess acts violently on them, tending to repel the protons out of any region and holding in the free electrons. The result is that the charge-excess can be driven off almost at once. This mobility is a well-known property of conducting material—which is what ionization implies—and so in any ionized region of space there will always result just such an excess number of electrons as would offset the slightly greater charge of the proton. Every element of volume would thereby be rendered strictly neutral electrically. Once this happens, gravitation alone is operative, for the charge-excess disappears, and in such regions condensation into galaxies can occur and continue.

The original charge-excess is so slight, that all that is needed for neutral material is that for every $10^{18}$ protons there should be $10^{18} + 2$ electrons. This would
6. THE CLUSTER OF GALAXIES IN THE CONSTELLATION COMA BERENICES SITUATED ABOUT 300 MILLION LIGHT-YEARS AWAY

Each galaxy contains many thousands of millions of individual stars which are the ultimate source of the light of the galaxy, though much is transmitted and reflected by gas and dust. Various forms of galaxies are to be seen in the cluster with a whole range of orientations relative to the observer. (In the expansion of the universe, a cluster of galaxies is to be regarded as a single unit; the cluster itself maintains its general size unchanged but it recedes as a whole from other clusters also regarded as units.) (200-inch Hale Reflector. By courtesy of the Mount Wilson and Palomar Observatories.)

7. THE RICH CLUSTER OF GALAXIES IN THE CONSTELLATION CORONA BOREALIS

This group of many hundreds of galaxies is at a distance of more than 900 million light-years and is receding as a whole at more than 13,000 miles per second. Individual members have speeds differing more or less from this by a few hundred miles a second because of their motions within the cluster. (The bright round objects with a cross and outlying circle result from overexposed foreground stars in our own galaxy and are nothing to do with the cluster. The cluster is said to be 'in the constellation Corona Borealis', but of course it is in fact far beyond, though in the same direction as the near stars of our galaxy that form this constellation.) (200-inch Hale Reflector. By courtesy of the Mount Wilson and Palomar Observatories.)
8. THE VAST CLUSTER OF GALAXIES IN HYDRA

It contains many hundred members believed to be held together by their mutual gravitational attractions. The individual galaxies are in motion within the cluster with speeds measured in hundreds of miles per second, while the cluster as a whole is receding from us at nearly 40,000 miles per second—more than a fifth the speed of light! The distance of this cluster is nearly 2,600 million light-years. Almost all galaxies appear to be members of clusters, some containing just a few members and others hundreds or thousands. (200-inch Hale Reflector. By courtesy of the Mount Wilson and Palomar Observatories.)

An Electric Universe?

If this turns out to be so, its importance for physics would be immense. But it will not be easy to devise a reliable experiment, because the quantity involved is so minutely small—that is exactly why it has not obtruded itself, and why exact equality has hitherto been assumed without question.

Also, as we have seen, on the electrical theory, the details of what is actually going on at different parts of space would come into the picture to a far greater extent than they do or ever seem likely to do in the general relativity approach—an approach to the problem, by the way, in which Einstein himself had far less confidence than did most of his followers and expositors.

Another interesting point of the theory is that it may explain how the very high-energy cosmic rays can come to be formed and dispatched on their headlong flight through the universe with almost the speed of light. They derive from the protons expelled from the huge ionized regions as they rid themselves of the continually hold for all strictly neutral bodies, including those (if any) we handle. But such a difference is far and away below anything that would patently betray itself in the laboratory.

On this new electrical theory, there is a unique solution of the problem in which the velocity of expansion must be everywhere and always in the same proportion to distance. The theory is able to point to an actual force, in the older Newtonian sense, that would do this, and it immediately suggests that experiments should be devised to see if in fact the charge of the proton is different from that of the electron to the required extent, minute as this is. If this turns out to be so, its importance for physics would be immense. But it will not be easy to devise a reliable experiment, because the quantity involved is so minutely small—that is exactly why it has not obtruded itself, and why exact equality has hitherto been assumed without question.

Also, as we have seen, on the electrical theory, the details of what is actually going on at different parts of space would come into the picture to a far greater extent than they do or ever seem likely to do in the general relativity approach—an approach to the problem, by the way, in which Einstein himself had far less confidence than did most of his followers and expositors.

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arriving slight charge-excess. In the past, no such by-product has even dimly looked like appearing in expanding universe theories, which have not achieved anything more than has been put into them at the start. This, however, is not a criticism of the general relativity theory of gravitation, which applied within the solar system almost certainly represents an improvement on the Newtonian theory. But what has begun to seem far less certain is whether this theory can be modified, by the inclusion of cosmical terms, to apply to the universe as a whole, and this is exactly the question that cosmologists have been struggling with these past thirty years. The advent of a new theory broadens out the discussion, because until some new line of attack was thought of, it was only possible to discuss the matter in limited ways, highly ingenious and complex though these were.

But another thing the theory does is one that particularly interests the theoretical physicists who are much concerned with the ultimate structure of matter itself. To explain the reason for their interest, it is necessary to recall that there are certain pure numbers—indeed, independent of any man-made units of mass, length, and time—that can be constructed out of the constants of the atom and the constants of the universe. For instance: the number given by the ratio of the electric force to the gravitational force between a proton and an electron comes to just about \(10^{38}\)—that is 1 with 39 noughts after it—an immense number. Now take the ratio of two known lengths: first the size of the universe, that is the limiting distance out to which physical

observations could ever be made, and second the radius of the electron; both are known, and the answer is again about \(10^{38}\).

For many years now it has been generally felt that this coincidence is not due to chance, and there are others too. Suppose we take the whole mass of the universe, which can be calculated with fair certainty, and now divide this by the mass of the hydrogen atom—the result may be termed ‘the number of particles in the observable universe’—then, \textit{mirabile dictu}, this comes to \(10^{28}\) to within a small numerical factor, and so is precisely the square of the previous \(10^{38}\). And there are yet others of these amazing coincidences. Can they be pure chance? Physicists do not think so, and the consensus of opinion has long been that they are some profound clue to the relation of the atom to the universe.

Now here has been the physicist’s dilemma: if the expansion of the universe is to be explained theoretically in terms of general relativity, then these numerical coincidences would imply a connection between the structure of the atom and gravitation, because the modern basis of gravitation is within the framework of general relativity. But as yet physicists see no possibility of incorporating the theory of the structure of matter into general relativity, and they have felt much embarrassed by the absence so far of any such feature in their theories.

But if a purely electrical theory of the expansion of the universe such as we have described should prove correct, it would mean that the number \(10^{38}\) is no more than the inverse square of the charge-excess
number, which we have already seen is a moderate multiple of $10^{-18}$ and so is just about right. Also, it will be the force determined by this charge-excess that settles the observable radius of the universe, for the universe ceases for us at such a distance that the recessional velocity has attained to the speed of light. Increase the charge-excess, and the radius of the universe would diminish proportionately in the theory. Gravitation would not come into it, except to the limited extent that it operates to hinder the expansion slightly, though not to such an extent that the numerical coincidences would be affected.

The new electric hypothesis is therefore a priori very welcome to the physicists, since it would get them out of an existing difficulty and leave them free to construct their theories without as yet worrying about gravitation — though, of course, sooner or later gravitation must emerge from theory as an infinitesimal weak residual force emanating from all matter and energy. But this may well be the last refinement of particle theory to be constructed, and it is unimportant compared with other difficulties in understanding the nature of matter.

Finally there is the question people often ask about any new theory: and that is, Is it right? But this is nearly always a question that cannot be answered straight away. Science has become such an indirect matter, with long chains of argument and inference separating hypotheses from observation, or requiring elaborate and ingenious experiment to settle something. And both factors hold in the present case. But if some reliable test could be devised that confirmed the tiny charge-excess, the theory would follow inescapably. So at the moment the theory can only be advanced as a new possibility that must be considered and tested. But on general grounds, it raises fresh hopes in several directions, for it seems to promise just those links between cosmology, quantum theory, and relativity that have for so long been dimly perceived peeping over the horizon.
IV

DISCUSSION OF THE RIVAL THEORIES

Chairman: Dr. G. J. Whitrow

whitrow: I think it would be a good idea if I were first to run over quickly the main points on which we seem to agree. All astronomers today believe that the Milky Way stellar system, of which the sun is an outlying member, is only one of millions of systems of stars, or galaxies, scattered throughout space. These galaxies themselves tend to congregate in clusters, and together these clusters appear to form the framework of the observable universe. Broadly speaking, the whole system of clusters looks much the same in every direction. With modern instruments it is possible to analyse the light from many of these far-off stellar systems. It is now a well-established fact that the more distant the galaxy, the more is its spectral pattern displaced towards the red. This is the so-called extragalactic red-shift. The tendency for this shift to increase with distance is usually known as Hubble's Law.

From time to time various possible explanations of this law have been suggested, but the most obvious explanation, and the one that Hubble himself originally favoured, is that the galaxies are receding from us. The farther the galaxy, the greater its speed. On this view, the red-shift is a simple case of the well-known Doppler effect, such as we observe every day with moving sources of sound. Every test that has been made so far is compatible with this interpretation of the extragalactic red-shift, and there is no reason to regard any other as better founded. All of us here, in common with most astronomers, accept it. Moreover, we all believe that the galaxies not only appear to be receding from us but also from one another.

Granted then that the galaxies are systematically moving apart, the more distant galaxies moving away faster than the others, what is the cosmological significance of this effect, and what is its cause? Does it signify that the universe as a whole is expanding, so that the state of things was different in the remote past from that existing now? Has the universe as we know it a finite history? If so, was there an epoch of world creation? Or should we reject this line of thought and seek instead to reconcile the traditional idea of an unchanging or steady-state universe with the modern idea that the cosmic framework is made up of receding clusters of galaxies? What do you think about this, Bonnor?

Bonnor: The cosmological theory which I support is based on the general theory of relativity. In relativistic cosmology we accept Einstein's equations of the gravitational field, and the problem then is to find a solution of them which represents the universe as a whole. To do this, we have to make certain assumptions. The most important of these is the Cosmological Principle. The form which this principle takes in relativistic cosmology is that at a given time, observers like ourselves on other galaxies would see essentially the same picture of the universe as we do.
Using the Cosmological Principle and Einstein's equations, we get models of the universe which are in satisfactory agreement with present observations. The theory does not lead to a unique model, and one of the things we hope that observers will soon be able to do is to decide between the various possibilities. The more plausible models have several features in common—and here I can give my answer to some of Whitrow's questions. The models all indicate that the universe is expanding; that is, the galaxies are receding from us and from each other. Secondly, as we should expect, since the galaxies are at present receding, the universe is becoming more thinly populated, and so the average density of matter is diminishing. Indeed, it is an essential feature of relativistic cosmology that the past and future of the universe are different from the present.

If we trace the history of the more plausible models backwards in time, we find that the present epoch of expansion started about 8,000 million years ago. One of the problems we still have to solve is what the universe was like before that. I do not think relativity necessarily supports the idea that the universe has a finite history or a creation.

Finally, let me stress that this theory is not constructed ad hoc to deal with cosmology. It is based on general relativity, which is known to be a satisfactory theory on a terrestrial scale and for the solar system. This gives one, I think, an added confidence in it.

Whitrow: Bondi, could you explain your point of view?
Bondi: First of all, I differ from Bonnor in my general attitude to scientific knowledge. What we know bas
Discussion of the Rival Theories

been obtained from scientific experiments on the Earth or in its immediate neighbourhood like the solar system, during an interval which, cosmologically speaking, is a

\( \text{10(a). HOW THE RELATION BETWEEN RED-SHIFT AND DISTANCE IS ESTABLISHED FOR EXTERNAL DISTANT GALAXIES} \)

Each of the successive galaxies at the left has been photographed with the same magnification. As galaxies of similar types are believed to be of much the same size, the decreasing apparent size corresponds almost entirely to increasing distance. The pictures at the right show the spectra of each of these galaxies. (Several hours' exposure are needed to obtain such spectrograms, so weak is the light, especially when dispersed.) The arrows immediately below the spectra indicate the amount of displacement of the K and H lines of calcium from the standard positions when there is no motion of the source of light. This is called the 'red-shift' since it is towards the red end of the spectrum. (The clear vertical lines above and below each spectrum are those of a comparison spectrum, of a source at rest, specially superimposed for measurement purposes.) The distances given are based on the most recent determination of the Hubble constant as about 75 kilometres per second per million parsecs (1 parsec = 3.26 light-years), which makes the accessible universe several times larger than it was thought to be ten or more years ago. (By courtesy of the Mount Wilson and Palomar Observatories).

\( \text{10(b). PART OF THE VIOLET END OF THE SOLAR SPECTRUM SHOWING THE HEAVY K AND H ABSORPTION LINES OF CALCIUM, BESIDES A WEALTH OF DETAIL DUE TO OTHER SUBSTANCES} \)

The lines of any particular element occur always in definite positions within the spectrum, but they are displaced systematically by motion of the source of light, towards the violet if the source is approaching us, and to the red if it is receding. These dark K and H lines occur in a wide variety of stars and, as a result, in the integrated light of a galaxy as a whole. It is by measurements of these K and H lines that the rates of recession of distant galaxies are principally found. (Photo: taken with the 13-foot spectrograph of Mt. Wilson & Palomar Observatories.)
and time, we are led to what is called the steady-state theory. Of course, this does not mean that the steady-state theory must be right; it merely means that the assumptions of the steady-state theory lead to definite statements and predictions of what experiments should reveal. The theory therefore satisfies the essential test of every scientific hypothesis, that it should be possible to disprove it by experiment and observation.

On this basis, then, I would suppose the universe to be in a steady state and to be uniform. Incidentally, this uniformity accounts both for the observed fact that the universe looks the same in all directions—as Dr. Whitrow has mentioned—and for the law of expansion, Hubble’s Law, which he also mentioned. But an expanding universe cannot maintain its density without a process of continual creation of matter. Admittedly, this idea appears, at first sight, to be at variance with what we know from local experience, but I believe that there is no way of reconciling the notion of a universe unchanging in time and uniform in space with the idea of local evolution and ageing without appealing to continual creation.

This continual creation of matter is, however, at a level far too low to have been revealed by the terrestrial experiments on which our usual law of conservation of energy is based. I therefore see no reason to disbelieve it, and on this basis we can construct a useful picture of the universe and one that suggests experimental checks by means of which it could be disproved.

Whitrow: Lyttleton, would you like now to tell us something about your views?

Lytleton: My general view of the cosmological
problem is very similar to Bondi's, which means that at present I am certainly inclined to favour the steady-state description of the universe. But what Bondi and I have done recently is to introduce a new hypothesis into the discussion that could, in fact, answer a question of yours, Whitrow, that we have not yet touched upon, and that is: What is the actual cause of the expansion? If gravitational forces alone were in action, the expansion of the universe would tend to be retarded. But in the new idea that we have been thinking about, gravitation would be overcome by an electric force, a force of repulsion between the atoms of hydrogen that go to make the basic material of the universe. A force of this kind could arise from a slight difference in charge between the electron and the proton, and the difference needed has to be only of the order of one part in $10^{18}$ to counteract the gravitational attraction altogether. If each atom of hydrogen, which consists of one electron and one proton bound together, has an excess charge of one part in a million million over the charge of the electron, then a cloud of hydrogen atoms would tend to fly apart, that is, it would tend to expand in much the way that the universe is observed to do.

However, if this were the whole story, the new idea would take us no farther than the usual relativity theory. But it is also necessary to explain how galaxies and stars can form in this material, which on the earlier basis is simply tending to fly apart. In our latest theory, the answer to this is that the charge-excess in a region of space containing hydrogen will immediately be driven off if the hydrogen atoms within it become ionized, that is if the protons and electrons are free to move independently. Consequently, the material within an ionized cloud will become electrically neutral. Gravitation then takes over entirely and condensations in the cloud could continue to grow: The energy of the background hydrogen that is pulled in from outside will keep these condensing regions at high temperature, and therefore will continue to maintain them in an ionized state, and the process can go on indefinitely.

I should perhaps emphasize that in this theory the galaxies are separating from each other because they are embedded in the expanding gas. They themselves are not electrically charged and are not directly repelling each other. They rather resemble raisins in an expanding cake. By gravitational interaction, the expansion of the gas is communicated to the galaxies, and it is their mutual recession that is actually observed, not that of the background gas, which as yet remains largely unseen.

Whitrow: Your views, Lyttleton and Bondi, are exciting and stimulating, but some of those who adhere to the older point of view are puzzled as to how your hypotheses can be reconciled with laws of nature which they see no good reason to reject. In particular, I believe that you, Bonnor, have some worries in this respect concerning the conservation of energy.

Bonnor: Yes, I think it would be as well to deal with this point right away. According to the steady-state theory, matter is being continually created out of nothing in empty space. Now we know from special relativity that matter is a form of energy, and so it
follows that energy is being created out of nothing. But this infringes what we call the principle of conservation of energy, which has been confirmed by measurement to a high degree of accuracy and so is a principle that physicists in general will not abandon lightly. Bondi's view is that we have no evidence to suggest that the very slight rate of creation required by the steady-state theory does infringe the principle of conservation of energy within the limits of experimental accuracy, but I should have thought that, on grounds of simplicity, it is much better to maintain that energy is accurately and exactly conserved. I think that we must demand a big dividend in return to justify our giving up this fundamental principle.

LYTTELTON: Of course, it is true that the principle of the conservation of energy has survived for a long time, but I think that Eddington put his finger on it when he pointed out that the reason why it has survived so long is simply because in physics energy has come to be defined as that which is conserved. And what has happened is that from time to time new things have been introduced as energy to save this principle.

I do not think myself that the idea of creation violates the principle of conservation of energy. What has been done conceptually in the past is to push an approximately verified law right to the limit, or even beyond, and enunciate it as if it were an absolutely exact law of science. But, in fact, the principle of conservation of energy right down to the last place of decimals is not knowable at all as an exact law, because it has never been established in this precise way. In postulating a rate of creation that is far smaller than the most refined measures of the law of conservation, no conflict with empirical evidence has been introduced at all. On the contrary, I would maintain that this is in accord with one of the typical ways in which science advances. You may remember that at one time in chemistry all the atomic weights were thought to be exact integers, but a great advance occurred when it was pointed out that this was not precisely true.

WHITROW: What have you got to say to that, Bonnor?

BONNOR: Lyttleton says that the principle of conservation of energy is a truism because we define energy in such a way that it is necessarily conserved. It is therefore worth mentioning the history of the neutrino. This was introduced by Pauli about 1932 to save the principle, and for years it was thought by many people to be nothing more than a mathematical fiction for this reason. Yet it is now known that the neutrino exists and is a real constituent of nature. This suggests that the conservation of energy is by no means a truism.

I should like too to repeat my point about simplicity. It is obviously simpler to postulate that energy is precisely conserved, and I am hoping that somebody will explain what dividend we can expect from making the principle of energy more complicated.

BONDI: I believe that we get the dividend in the resulting picture of the structure of the universe. An unchanging universe is simpler than the evolving type of universe that you favour, Bonnor. I think we ought to make it quite clear where the difference between us
lies. You, Bonnor, suppose the universe to be uniform in space. We call this the ordinary Cosmological Principle. What Gold and I postulated was the so-called Perfect Cosmological Principle. According to this, the universe was uniform not only in space but also in time. This unchanging nature in time applies only to the universe as a whole, not of course to the individual constituents, the galaxies, each of which ages in the course of time.

Bonnor: It is true that the ordinary cosmological principle is an assumption, but the perfect cosmological principle is a bigger assumption; and so, if we are trying to economize in hypotheses, I think that the position of relativistic cosmology is rather more acceptable here too.

Bondi: I would not agree with that for a moment! It seems to me that the essence of scientific work is that we should make assumptions. I entirely agree with you, of course, that the cosmological principle is an assumption and that the perfect cosmological principle is a bigger assumption. But the bigger the assumption we make, the more testable it is likely to be by experiment and observation. It is the purpose of a scientific hypothesis to stick out its neck, that is to be vulnerable. It is because the perfect cosmological principle is so extremely vulnerable that I regard it as a useful principle. It is something that could in practice be 'shot down' by experiment and observation far more easily than the ordinary cosmological principle, and I think you will agree with that.

Bonnor: I agree that the steady-state theory is more vulnerable to observation; but from what has been said so far, it seems that the only reward we get for giving up the conservation of energy, and for accepting the perfect cosmological principle, is a theory which will give observational astronomers the opportunity of disproving it. I must say that this does not seem an adequate return.

Bondi: If this does not seem to you to be an adequate return, then your views on what constitutes science must differ markedly from mine. I certainly regard vulnerability to observation as the chief purpose of any theory. Moreover it is only on the basis of the perfect cosmological principle that we have any grounds for believing our terrestrial physical theories to be applicable to the universe at large. You make the assumption that the laws of general relativity (whose main support are observations of the present motions of the solar system) should be equally valid in an utterly different state of the universe. This assumption seems to me to be extremely arbitrary and unlikely to be correct. If the perfect cosmological principle turned out to be false, then cosmology would be a far more difficult subject than you seem to imagine. One would have to contemplate changes in local physics conditioned by changes in the universe and reacting back on it in an exceedingly complicated way.

Bonnor: I certainly believe that the field equations of general relativity are valid for all states of the universe. What we do in relativistic cosmology is to take laws which have been established for local gravitation, and apply them to the gravitational behaviour of the
universe as a whole. This has led to no conflict with observation, and is in any case well-established scientific practice. We are, after all, continually extrapolating laws of nature: for example, when we consider the interior of the sun we are contemplating something which we have no direct knowledge of, and we have to use the laws of physics and assume that they are valid in conditions very different from those in which they have been directly tested. We do not usually set up a “principle” to justify us in extrapolating, and I do not feel any need for one in cosmology.

Bondi: To come to another point, I entirely agree with you that general relativity is an excellent theory for the description of local phenomena, like motions in the solar system. But do you find it really fruitful in its extrapolation to the universe as a whole?

Bonnor: I am glad you have asked me that because I think that in the original talk which you gave, and also in Lyttleton’s talk, it was implied that relativistic cosmology has not been particularly fruitful. I do not agree with this at all. Indeed, I think it is fair to say that general relativity predicted the expansion of the universe before anybody had thought of looking for it observationally. This was a tremendous achievement. I think it is also true to say that throughout the 1920s and the 1930s the fact that general relativity suggested certain different models of the universe was a great impetus to astronomers in causing them to make fresh observations to find out which form the universe actually takes; for example, there was—and still is—the staggering possibility that it might be finite. It is hardly necessary to remind you that ten years ago it was thought that there was a contradiction between general relativity and observation, because the start of the expansion appeared according to some of the principal general relativity models to have taken place after the formation of our galaxy. I think that this contradiction was one of the things which caused astronomers to look again at Hubble’s Law, and eventually to find the reformulation of it that now fits quite well with the relativistic theory.

Bondi: Another point on which I would like to take you up is this distinction between expanding and other phases of our universe. One of the points that I regard as particularly important is that it is because the universe is expanding that the sky is dark at night. It is a fact of vital experimental importance that radiation is swallowed up by the universe, resulting in the marked disequilibrium between matter and radiation which is necessary for evolution to occur and for life to exist. I am puzzled by the suggestion that the laws of physics that we have discovered experimentally to hold, within a certain accuracy, in our period of the universe, should be supposed to hold at a time when it was not expanding, when the situation must have been quite unbelievably different from what it is now.

Bonnor: I think what you mean, Bondi, is that in the finite universe which I was talking about there will eventually be a phase of contraction. And you are saying that, when this phase comes about, the universe will be totally different, and perhaps the difference will be such that we could not make observations at this
period. Of course, this may be so, but it seems to me rather an anthropocentric view to say that this cannot happen, because we could not be there to observe it.

**Bondi:** I am much more worried about the past than about the future. If, as some cosmologists suggest, the universe is oscillating, then the present period of expansion follows a previous period of contraction. It is this previous period of contraction that I am worried about, since we might see it happening at large distances. For since light has a finite speed we see distant regions as they were long ago. If the universe was contracting some time ago, it probably was then very bright (radiation is weakened by expansion and enhanced by contraction), and we should still see this light.

**Lyttleton:** Might I say something now about the point you mentioned, Whitrow, that the Doppler explanation of the red-shift is really better founded than any other explanation? I thoroughly agree with this, but there have been claims from time to time that the Doppler shift is not the proper interpretation. For example, there is the suggestion that hundreds of millions of years ago, when the light by which we see distant galaxies was emitted, the laws of physics were not the same as now, and that is why the spectral lines were in a different position.

Now, I cannot see that laws of physics that change with time are really laws of physics at all. This is perhaps an act of scientific faith on my part, but I think that we must always formulate scientific laws in such a way that the time itself does not enter into them explicitly. If it appears to do so, then I think that what we have got to do is to look round for some specific cause of the phenomenon in question and retain timeless laws. I can give an instance of this. Not more than a few decades ago the motions of the inner planets all seemed to be accelerated in longitude, and had that been the case it would have meant that Newtonian dynamics did not accurately apply to the inner planets. At that time, the standard that was used for a clock was the rotating Earth; but if the hypothesis is introduced that the rotation of the Earth is not strictly constant, but is in fact slowing down slightly, then this has the effect of putting the planets in their right places and at the same time suggesting that we look for a cause that would change the rotation of the Earth. Such causes have actually been identified, at any rate up to a point, and this has led to advances from the point of view of the dynamics of the Earth itself. I therefore believe that it is a fundamentally wrong line of attack on this particular problem when people try to explain the red-shift by some device equivalent to introducing the time into the equations of motion.

**Bonnor:** I would like to emphasize again that the laws of nature, as postulated by general relativity, do not change with time. We believe that the field equations of general relativity apply at all times. What changes with time is the state of the universe. Of course, we have plenty of examples where things obviously change with time; for example, the galaxies. In general relativity we go one step further and we speak about the evolution of the universe, and it does not seem to
me that, in this respect, there is any reason why we may not jump from the galaxies to the universe.

Whitrow: We have been discussing the question of the confirmation or refutation of theories by experiment. As regards cosmology, one of the most remarkable features of your theory, Lyttleton, is that it is based on a hypothesis which before long may be confirmed or refuted by actual experiments in the laboratory. Now suppose, for the sake of argument, that it is confirmed within reasonable experimental error. Would this automatically indicate the steady-state theory and disprove theories which do not depend on continuous creation?

Lyttleton: I do not think it will completely establish the steady-state theory to the exclusion of all others. I am not quite clear in my own mind whether one could have a universe homogeneous in space but not in time and driven by electrical repulsion.

Whitrow: Is there any chance of direct verification of this difference in charge between the proton and the electron?

Lyttleton: Yes, and that is why Bondi and I chose to put the theory forward in terms of a charge difference between the proton and the electron. Alternatively it would still be possible to have an excess of charge in the universe, with these precisely equal and opposite, if there were slightly more protons in the universe than electrons, but we chose the other form of the hypothesis precisely because it is on the verge of what could be verified in the laboratory. Nevertheless, I think it is going to be a very difficult experiment. One of the difficulties is that we tend to think all the time in terms of the classical theory, if I may put it that way, according to which these two charges are exactly equal and opposite. Indeed, all the equipment in the laboratories with which one would attempt to do the experiment, including all containers, is immediately suspect because it has all got the charge-excess in it. So one will have to be very careful.

For this reason I think that any satisfactory macroscopic experiment is likely to be very difficult to devise. On the other hand, there have already been experiments with individual particles, that is molecules themselves, in strong electric fields, that have shown that the two charges are probably equal and opposite to one part in $10^{16}$. It will need only an increase in accuracy of about a thousand-fold, or perhaps ten thousand-fold, to reach the accuracy wanted, and so it may be possible before long to perform a crucial experiment.

If, however, charge-excess in the universe is due to the number of protons exceeding the number of electrons, rather than there being equal numbers of protons and electrons and the protons having a slightly greater charge, it will obviously be much more difficult to make a decisive experimental test.

Whitrow: One of the definite observational criteria of the steady-state theory that differentiates it from some, though admittedly not all, theories based on general relativity is its prediction of what the average density of matter in the universe should be. According to the steady-state theory, there is a definite prediction for this which on the basis of our present observational
knowledge of the distribution of matter in the universe would appear to imply that most matter, perhaps considerably more than ninety per cent., must be diffuse material in between the galaxies and clusters, presumably mainly hydrogen. I wonder whether you would like to say anything about this, Lyttleton?

LYTTL ET ON: Curiously enough, this is one of the questions that artificial satellites may help to settle. If we could get a telescope mounted on to a satellite or vehicle moving outside the Earth's atmosphere, then we would no longer be troubled by the intense absorption in the ultra-violet that at present affects all ground observations. In this way it might be possible to ascertain just how much diffuse matter there is in the universe. This is one of the reasons why I am looking forward to the day when we shall have space observatories from which these interesting observations can be made.

11. EXAMPLES OF COLLIDING GALAXIES

(a) The Cygnus source. Although about 300 million light-years distant, this pair of colliding galaxies is one of the most powerful radio sources yet found in the heavens. The extent of the system is actually several times greater than that of the dark objects shown in this negative print.

(b) NGC 4038 and 4039. A pair of galaxies in collision, with evidence of associated streamers of great length. (The photograph is a negative print.) Curiously enough the system emits only weakly in radio wavelengths.

(c) NGC 5426 and 5427. A pair of spiral galaxies probably very nearly in collision. This negative print shows evidence of connecting streamers.

(d) The system NGC 1275 in Perseus. Spectroscopic studies (in ordinary light) suggest that the system consists of two colliding galaxies but now undergoing subsequent separation. The entire system is far more extensive than this negative print shows, parts of it reaching as far as four or five times the diameter of the dark central object. This nebula is a strong radio source.

Some astronomers, notably the Russian Ambarzumian, do not believe that objects like the Cygnus source are pairs of colliding galaxies.

(By courtesy of the Mount Wilson and Palomar Observatories.)
This strange extragalactic object is believed by many astronomers to consist of two galaxies in direct collision. Because the stars in a galaxy are so widely spaced, such a collision would affect only the interstellar gas and dust. These diffuse contents of the two galaxies would meet at several hundred miles a second as a result of the attractions of the two systems. Objects of this kind are usually highly intense sources of radio emission. Unlike the stars, galaxies are sufficiently close in comparison with their sizes for collisions to be reasonably probable especially within clusters, and a considerable proportion of external nebulae can be expected to represent pairs of galaxies in collision. The radio mapping of such systems extends to far greater distances than can be penetrated with present optical telescopes and provides another means of investigating the distribution of galaxies in the universe. (200-inch Hale Reflector. By courtesy of the Mount Wilson and Palomar Observatories.)

**Discussion of the Rival Theories**

BOND: Perhaps I might point out why we require so much matter in between the galaxies. On the basis of the steady-state theory, as the galaxies recede from each other new galaxies must be formed in the spaces between them in order that the average distance between galaxies may be maintained. And it is for this building material that we require a considerable amount of matter between the galaxies.

BONNOR: I would like to raise the question of the age of the universe. This is not a term which I like; I prefer to call it the period of the expansion. It seems to me that one of the defects of relativistic cosmologies has been that they supposed that at a period 8,000 million years ago, the universe had a definite creation or a definite start. In my opinion, this is an unscientific view. Instead, we shall have to try to decide what was happening to the universe before the start of the present phase of expansion.

It does seem, however, that there are certain indications that something surprising and unusual happened to the universe between 5,000 million years ago and 10,000 million years ago. It is not merely that the age of our own galaxy seems to lie between these limits. For example, the famous observational astronomer Walter Baade has argued that there must have been a period of star formation in all galaxies about 6,000 million years ago, and there is certain other evidence too concerning the tendency of clusters of galaxies to diffuse with time which suggests that they may have been in existence for only about the same period. It is clear that the steady-state theory...
would be in very serious difficulties if it were found that all the galaxies were about the same age. I would like to ask Bondi what sort of explanation he has for these observations.

Bondi: This is indeed the type of observation for which I have been calling for many a year. Since Gold and I formulated the steady-state theory some eleven or twelve years ago, we have felt that observation of a time-effect was the most direct way of discovering whether our universe was in a steady state or not. To put it a little differently, if we look out into space, we look back into time. For, owing to its finite velocity, the light that we now receive from the very distant galaxies must have left them a long time ago to reach us now. Therefore, we have some idea of what the universe was like a good long time ago by looking at the most distant galaxies. The times in question are quite substantial, extending up to several thousand million years. If a difference is discovered between galaxies in the remote past and now, the steady-state theory will have to be abandoned. This is one of the points where the theory is most vulnerable. Indeed, in the last twelve years there have been two claims by observers that in fact there was such a time-effect. But in neither case has the original claim been substantiated. In one case it has definitely been withdrawn by the originator; in the other case the whole matter is in doubt, although I am pleased to say that work on it continues.

As for Baade's views, my attitude is this: until we have a clear and consistent theory of the evolution of galaxies, any attempt to ascribe a particular age to any galaxy is sheer guesswork, however distinguished the astronomer from whom it comes. And it seems to me, as the discussions at the recent Solvay Conference showed, that neither Baade nor any of the other observational astronomers—some of whom disagree with him very strongly—have as yet clear views on the evolution of galaxies, and therefore about the interpretation of observations. This is a challenge to the theoretician. The more we know about the evolution of galaxies, the easier it will be to interpret the observations and to say whether all galaxies have the same birthday, or whether they are spaced out in time, as the steady-state theory claims.

Wittrow: You therefore maintain that there is insufficient evidence to support Baade's contention that there was a period of star formation in all elliptical galaxies about 6,000 million years ago.

Bondi: I think it is a very weak inference from a particular picture of star formation which I think is, in any case, dynamically unsound.

Lyttleton: I would like to stress that our present knowledge of the dynamical behaviour of clusters of galaxies is very uncertain. If from time to time individual galaxies were fired out from clusters as the result of dynamical interactions, they would become new galaxies, as it were, in intergalactic space. In this way clusters might seed the surrounding space with galaxies and create conditions in which new clusters might form. I am not saying this is what I believe, because I think that we shall have to know a great deal
more about the structure and evolution of clusters before we can draw the conclusions to which Bonnor referred.

Whitrow: As we are now talking about clusters, there has been some recent work that you might like to comment on concerning the richness of clusters. It is comparatively simple to determine the number of galaxies per cluster and to correlate these numbers with the distances of the clusters and consequently with the times at which the light left them.

Bonnor: I think this is a most interesting modern approach, which I very much hope will be pursued in considerable detail. Actually richness is correlated with brightness, and brightness is then correlated statistically with distance. The question then arises whether there is any significant variation of richness with distance. It has recently been claimed that there is. If this claim is confirmed it will be a disproof of the steady-state theory. At the same time, I think it should be pointed out that this is a very tricky test. Just because distant objects look much fainter than nearer ones, and, if they are of the same intrinsic size, occupy a much smaller part of the photographic plate, it is exceedingly difficult to separate out selection effects from genuine effects. At greater distances, you may happen to see only clusters of a particular type, or count the number of members differently than in the case of nearer clusters. Nevertheless, I regard this as a most fruitful line of advance, and I think it is fair to say that it is this type of observation that has been suggested by the steady-state theory.

Whitrow: We have been speaking about the contribution of visual observations to the problem. Do you think the claim made by radio astronomers that they can provide us with a definite criterion for distinguishing between evolutionary and steady-state theories is well founded?

Bondi: I think there is a very distinct possibility that radio-astronomy can give us great assistance in this direction. The great difficulty in radio astronomy is that the measurement of distances is even more inferential and uncertain than it is in optical astronomy. It is an interesting comment on the scientific situation that the very fact that radio sources were observed to be uniformly distributed around us made everybody agree that they must be distant objects of cosmological interest. Whether or not there is any variation in their density with distance is an observational question on which opinions are very much divided at present. Any systematic variation of density with distance would definitely be evidence against the steady-state theory. But if there is no variation of density with distance, we could not automatically reject evolutionary theories, because we would not know whether the radio-astronomers were seeing far enough to get observations of significance.

Whitrow: Lyttleton, what observational evidence do you think is most likely to decide between the rival theories?

Lytton: I think we should bear in mind that present observations refer only to the galaxies, whereas it may well be that there is as much, if not more, material in the space between the galaxies. We must therefore not
Rival Theories of Cosmology

forget that apart from visible matter there may be much diffuse unseen matter as well. Until we know more about this it is going to be very difficult to decide between rival theories merely by considerations relating to galaxies.

Whitrow: What do you think, Bonnor?

Bonnor: I should think that the steady-state theory is most likely to be disproved by the radio observations on variations with distance. If it should survive a series of reliable observations of this type, it would have to be taken very seriously.

On the other hand, the relativistic theories would be difficult to disprove definitely by this means. The reason is that these theories are not represented by a unique model of the universe, and models exist in which the variation of density with distance, though not quite negligible, is none the less small. Thus, as Bondi has said, even if no variation with distance were observed, this might simply mean that the astronomers were not yet probing far enough into space to notice any significant variation.

However, for those who believe in relativistic cosmology, the most interesting result which is likely to come from these observations is a refinement to Hubble's Law which will give some decision between the various sorts of model. For example, they may indicate whether the universe is finite in size, and whether it will ultimately stop expanding and start to contract.

Whitrow: One of the most remarkable theoretical advances in recent years has been the break-through in connection with the problem of the origin of the elements and of their abundance ratios. Bondi, would you like to say something about the relevance of this to cosmology?

Bondi: I would like to start with a little story. When Eddington first investigated the structure of the stars, he hoped very much to find in their centres the places in which the more complex elements, like iron and carbon and oxygen, were built up from hydrogen and helium, the simplest of all elements. In his pioneer work on stellar structure, he calculated the temperatures of the centres of the stars, but when he told the nuclear physicists of his day, some thirty years ago, what these temperatures were, they said that they were far too cold for the production of heavy elements. Eddington is reported to have retorted that, if the centres of the stars were too cold for the nuclear physicists, he hoped they would go to a much hotter place! Well, since that time, the search for the much hotter place has been going on. Many people have thought that these much hotter places could not be found in the stars, but only in the origin of the universe. For, if there are no natural factories for making heavy elements in the universe at present, then there must have been factories for making them a long time ago. On the steady-state theory, this explanation is quite unacceptable, for if there ever were any factories for making heavy elements, then there must be some now. On this assumption, the Burbidges, Fowler, Cameron, Hoyle, and others attacked the problem a few years ago. They showed that certain fairly common stars could

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generate the heavy elements and then explode and distribute them throughout space to produce the observed abundance ratios of heavy elements. This theory has been so successful that we must regard it as one of the classics of modern physics. It was directly inspired by the steady-state theory.

Whitrow: Whether one believes in the steady-state theory or not, this is a good example of the function of theory in stimulating people to solve particular problems.

Even though we cannot agree on all the questions at issue, I believe that this discussion has helped to spotlight some of the ways in which further progress may be made in the difficult but fascinating subject of the structure and evolution of the universe. In cosmology, as in other branches of science, theories are not necessarily useless because they are eventually discarded. Whatever may be the respective fates of the theories we have discussed today, they are likely to continue for some time to guide us in our empirical researches and, above all, to stimulate us in our attempts to probe some of the most recondite of nature's secrets.

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INDEX

Annihilation of the universe, 8
Artificial satellites, 52
Atomic constants, 90
Atomic structure and gravitation, 31
Baade, W., 53, 54, 55
Background brightness, see Sky brightness
Bondi, H., 1, 54
Burbidge, E. M. and G. R., 59
Cameron, A. G., 59
Charge-excess hypothesis, 24–31, 40, 59; test, 32, 59
Clerk Maxwell, J., 27
Clusters of galaxies, 27, 34, 53, 55, 56
Constants, atomic, 30
Constants of the universe, 30
Continual creation, 10–11, 16, 26, 39, 41–43
Contracting universe, 4, 8, 9, 47, 48
Cosmic rays, 29
Cosmological constant, 3, 4, 27, 30
Cosmological Principle, 2, 33, 38, 44
Cosmological Principle, Perfect, 38, 44, 45
Creation of matter, see Continual creation
Creation of the universe, 1, 5, 6, 8, 35, 36, 53
de Sitter, W., 3
Doppler effect, 2, 34, 48
Eddington, A., 3, 24, 42, 59
Einstein, A., 3, 10, 24, 27, 29, 35, 36
Electric charge-excess, see Charge-excess hypothesis
Electron: electric charge, 24; radius, 31
Elements, origin of, 20, 59
Elliptical galaxies, 55
Energy, conservation of, 11, 17, 41, 42, 45
Evolutionary theories, see Relativistic theories
Finite universe, 46, 58
Fowler, W. A., 59
Friedmann, A., 3
Galaxies (see also Clusters; Velocity-distance relation):
age, 53, 55; age differences, 19, 54, 55; distribution, 2; formation, 16, 28, 40, 41, 53; recession, 2, 10, 14, 22, 26, 34, 39, 47, 58
Galaxy, age of, 7, 34, 53
Gold, T., 1, 54
Gravitation: 22, 49, 41; and atomic structure, 31; general relativity, 8, 30, 45; Newton's theory, 8, 30
Heckmann, O., 9
Hoyle, F., 59
Hubble's Law, 34, 39, 47, 58
Intergalactic matter, 16, 27, 52–54, 57
Ionization, 28, 41
Lemaître, G., 3
 Matter in the universe (see also Intergalactic matter): creation, see Continual creation; density, 4, 7, 9, 14, 17, 26, 51; ionization, 28, 41; rotation, 9
Maxwell, J. Clerk, 27
Milky Way, see Galaxy
Neuhäuser, Extragalactic, see Galaxies
Neutrino, 43
Newton, I., 8, 39, 49
Pauli, W., 43
Physics, laws of: independence of time, 13, 14, 23, 45, 48
Planetary motion, 49
Index

Popper, K. R., 12
Proton: electric charge, 24
Pure numbers, 30
Quantum theory: links with cosmology and relativity, 33

Radio astronomy, 19, 57
Radio sources, distribution of, 57, 58
Recession of the galaxies, 2, 10, 14, 22, 26, 34, 39, 47, 58
Red-shift, 2, 34, 48, 49
Relativistic theories, 1-11, 19, 20, 24, 30, 35, 36, 46, 54, 57-58
Relativity, general theory of, 3, 8, 19, 30, 31, 36, 45, 46, 49; link with quantum theory, 33
Rotation of matter in the universe, 9

Satellites, artificial, 52
Scientific method, 11, 12, 38, 39, 44, 45, 48

Sky brightness, 47, 48
Star formation, 40, 53, 55
Star structure, 59
Steady-state theory, 1, 10-11, 14-21, 36, 38, 39, 41, 44, 51, 54-59; tests, 18, 44, 50, 54, 56, 57, 58

Thermodynamics, Second Law of, 9, 10

Uncertainty principle, 11
Universe (see also Annihilation; Contracting universe; Creation; Expanding universe; Finite universe): age, 53; size, 31, 32

Velocity-distance relation, 14, 26, 29, 34, 39, 47, 58

World-models, see Relativistic theories; Steady-state theory
IN THE AUTUMN of 1959 three talks were given in the Third Programme of the BBC on current theories concerning the form and structure of the physical universe. Despite the recondite nature of the problems at issue, these talks were so lucid and stimulating and aroused such widespread interest that a general discussion between the three speakers was broadcast at the end of the year. This, too, had an enthusiastic reception and it was felt that the whole series ought to be reproduced in a more permanent form.

The present book is a carefully revised version of the original broadcasts, supplemented with a number of beautiful photographs of spiral nebulae and other celestial objects, most of which were taken with the aid of the great 200-in. Hale Telescope on Mount Palomar, in California. No previous specialized knowledge is required in order to appreciate the give and take of argument as here presented. Together, text and pictures provide for the general reader a fascinating introduction to current theories concerning the physical universe.

Of the four authors, Professor Bondi is Professor of Mathematics, King's College, London; Dr Bonnor is Reader in Mathematics at Queen Elizabeth College, London; Dr Lyttleton is a Fellow and Lecturer of St John's College, Cambridge, and Reader in Theoretical Astronomy in the University of Cambridge; and Dr Whitrow is Reader in Applied Mathematics at the Imperial College of Science and Technology, London.
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