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THE DEPTHS OF SPACE

THE LORIMER LECTURE

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BY

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THE DEPTHS OF SPACE

As the power of telescopes increases, that portion of the universe which is accessible to observation continually expands, so that it has been well said that the history of astronomy is a history of receding horizons. The depths of space which we shall be discussing to-night have only recently been thrown open to exploration, and are now perhaps the most interesting territory in which the astronomer can work.

The ancients believed that the earth was the centre of the universe; at a later date, and indeed until well into the present century, the sun was thought to be, if not the centre, at least very near to the centre. The reason for this belief was the fact that the night-sky looks equally brilliant in all directions. But we know now that this appearance of symmetry is illusory. Behind the few stars we can see with our unaided eyes, the telescope discloses a background of faint stars which are invisible to the unaided eye. We must study these before we can discover our true position in the universe. And when these faint stars are studied with the aid of our telescopes, we find that the stars are far from being arranged symmetrically round our sun. They form a structure which is shaped like a flat wheel, with the Milky Way forming the rim. The sun is neither at nor near the centre, but is about one-third of the way along one spoke. All the stars that we can see without a telescope lie inside a sphere having a radius of about 3000 light-years - that is to say, the distance which light travelling at eleven million miles a minute takes 3000 years to cover. Judged by terrestrial standards such a sphere seems inconceivably great - the light by which we see its furthest stars started on its journey before the foundation of Rome, before the siege of Troy, and only reaches us now. Yet this sphere is only one drop in the great ocean of space, and it is uniformly spread with stars simply because it is on so small a scale; it is too minute a fraction of the whole for the structure of the universe to show itself. The great wheel of stars has a diameter of something like 200,000 light-years, its furthest stars being probably about 130,000 light-years away from us; their light started on its journey through space long before man had become civilised. If we compare this wheel to the driving-wheel of an express locomotive, all the stars we can see with the unaided eye lie within a drop of steel one-eighth of an inch in diameter.

Our own sun and planets are held together by the gravitational pulls they exert on one another; in the same way this great wheel of stars is held together by the gravitational attractions of all the stars of which it is composed. The planets revolve around the sun, the outermost moving most slowly, and it is the same in the system of stars; the outer stars are revolving around the group of

stars which constitute the hub of the wheel, the outermost stars moving with the slowest speeds, and so taking longest to perform a complete revolution. So far as is at present known, the sun moves at about 170 miles per second, and yet - so immense is the great wheel - it requires about 220 million years to perform a complete revolution.

These data make it possible to calculate the gravitational pull needed to keep the sun and other stars from flying off into space, and, knowing this, we can estimate how much matter there is in the whole wheel of stars. The method is precisely that by which we estimate the mass of the sun, the earth, or Jupiter. Lindblad has estimated the mass of the whole system to be that of 160,000 million suns. Still more recently Berman, studying the motions of the planetary nebulae, instead of that of the sun, has estimated the mass as that of 230,000 million suns. Some of this mass may be dust or gas or stray matter in general, but a good part of it is probably stars. Thus the total number of stars in the wheel is likely to be greater than a hundred thousand million, and may quite well be double this number - let us say about 100 stars for each inhabitant of the earth's surface.

Plate I

Mt Wilson Observatory
Fig. 1. - A Planetary Nebula (N.G.C. 1501)

Mt Wilson Observatory
Fig. 2. - The "ring" Planetary Nebula (N.G.C. 6720) in Lyra

Kerolyr
Fig. 3. - The Pleiades photographed with a long exposure

Of recent years it has become clear that this system of stars is in no way unique. Space is full of rotating wheels of stars; our own system is only one of many. The other similar systems are the objects we describe as "extra-galactic" nebulae - i.e. nebulae outside the Milky Way.

The word "nebula" is, of course, the Latin for a cloud or mist. The sun, moon and planets are seen in the telescope as clearly defined circles of light, with perfectly sharp edges. Other objects exhibit a fuzzy texture and a misty outline, and these the early astronomers described indiscriminately as "nebulae". As we now know, these vary greatly in their physical structure, but they fall into two main classes, which we shall discuss in turn - the "galactic" nebulae, which lie inside the Milky Way, and the "extra-galactic" nebulae which lie outside it, and are themselves systems of stars similar to our own.

The simplest of the galactic nebulae are the planetary nebulae of which I spoke just now. These are merely rather bright stars surrounded by very extensive atmospheres, which are made to glow by the radiation from the central star.

Typical examples are shown in Figs. 1 and 2 on Plate I. Fig. 1 shows the nebula N.G.C. 1501, while Fig. 2 shows the Ring-nebula in Lyra (N.G.C. 6720); longer exposures would make the ring thicken and finally close up-as it begins to in places already - and we should see that it is really a continuous shell.

The central stars of the planetary nebulae are remarkable as being among the hottest stars known to astronomy - indeed this is probably why they alone have these vast atmospheres round them. Their surface-temperatures range up to about 60,000 degrees Centigrade, or ten times the temperature of the sun. The fire in the fire-box of a locomotive is so hot that its few square feet of surface send out enough energy to run a train, but these stars are so hot that an area of surface the size of a postage-stamp sends out enough energy to run a vast liner of the size of the Queen Mary or Normandie.

The central stars of these nebulae are abnormally small as well as abnormally hot; they belong to the class of very compact stars known as white dwarfs. One of these stars has recently been discovered with only about half the dimensions of the earth. In spite of its small size, it probably contains nearly a million times as much substance as the earth, so that its average density must be about 36 million times that of water. To put it in another way, a cubic foot of water on earth contains 1000 ounces, but the average cubic foot of matter in this star contains about a million tons; a piece the size of a pinhead would break a man's back. This is an extreme case, and the central stars of the planetary nebulae are mostly considerably larger than this, the majority having one-half or one-third of the diameter of the sun. Even the nearest of these nebulae are many thousands of light-years distant, so that they appear as quite faint objects in the telescope.

Leaving these planetary nebulae, we come to a second class of nebulae - the irregular galactic nebulae. The nebulae of the first class - the planetary nebulae - consist of gas lighted by the radiation of a single central star. The nebulae of the second class are masses of gas lighted up by the radiation of the many stars enmeshed in them.

Fig. 3 on Plate I shows a long-exposure photograph of the well-known constellation of the Pleiades. With a shorter exposure, the stars would have appeared as mere points of light, as we ordinarily see them in the sky. The longer exposure reveals the nebulosity surrounding them, while with still longer exposures we should see the separate nebulosities closing up to form a continuous cloud. We see an instance of this in Plate II, which shows the great nebulae in Orion. Here the exposure has been so long that we hardly see individual stars at all - only the nebulosity surrounding them. Almost the whole constellation of Orion is occupied by such nebulosity.

Plate II

Mt. Wilson Observatory
The central part of the Great Nebula in Orion

Plate III

Mt. Wilson Observatory
The central part of the Great Nebula in Andromeda

We now come to the second and more important kind of nebula. The nebulae we have so far discussed have all lain within the great wheel of stars to which our sun belongs, but the nebulae to which we are now coming lie outside this wheel. Most of them are other wheels of stars, comparable in size with the wheel which we ourselves inhabit.

We shall see in a moment how immensely large and luminous these nebulae are, yet they are so distant that only one can be clearly seen without a telescope; it is known as the Great Nebula in Andromeda (see Plate III). Photography shows that this nebula is far larger than it appears to the unaided eye, or even by direct vision through a telescope; its whole expanse covers something like twenty times as much sky as the full moon. Round the comparatively bright central mass which we see with the unaided eye - rather smaller than the moon in size, fuzzy in appearance and ill-defined in outline - we find an extensive and detailed structure which lies hidden until it is photographed with a very long exposure. This outer structure is found to consist, in large part, of separate points of light, and these are believed to be stars similar to those which form our own system. We believe them to be stars, because many of them do not shine with a steady light, but fluctuate in the same characteristic and quite unmistakable way as a number of the stars of our own system. These particular stars are known as Cepheid variables, and they have a very remarkable property - their candle-power depends almost entirely on the speed with which their output of light varies. Stars which fluctuate rapidly are of low candle-power, while those which fluctuate slowly are of high candle-power. We can, in fact, estimate the candle-power of such a star from the rapidity with which its light changes, and knowing its candle-power, we can then estimate its distance from its apparent faintness. Dr. Hubble of Mount Wilson Observatory finds in this way that the Great Nebula in Andromeda is some 700,000 or 800,000 light-years distant. This is the nearest of all the extra-galactic nebulae except for one - the nebula M. 33 in the constellation Triangulum - which is probably a few per cent. nearer.

We have said that our own galactic system is shaped like a flat wheel, and the same is probably true of the Andromeda nebula. The object shown in Plate III certainly does not show any marked resemblance to a wheel, but this is probably only because we are looking at it from the wrong direction. Fig. 5 on Plate IV shows a nebula which is probably very similar in its structure both to the Great Nebula in Andromeda and to our own galaxy, but is seen "edge-on", so that the wheel shape is at once apparent.

Plate IV

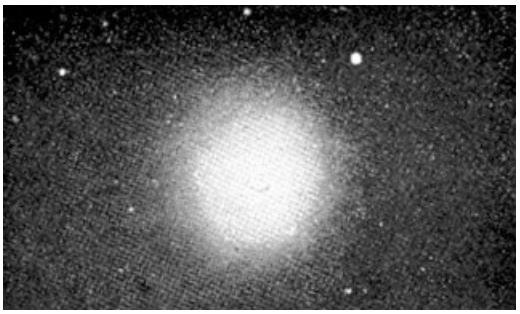


Fig. 1
N.G.C. 3379

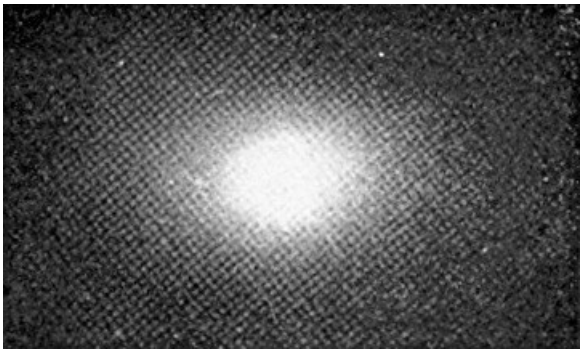


Fig. 2
N.G.C. 4621

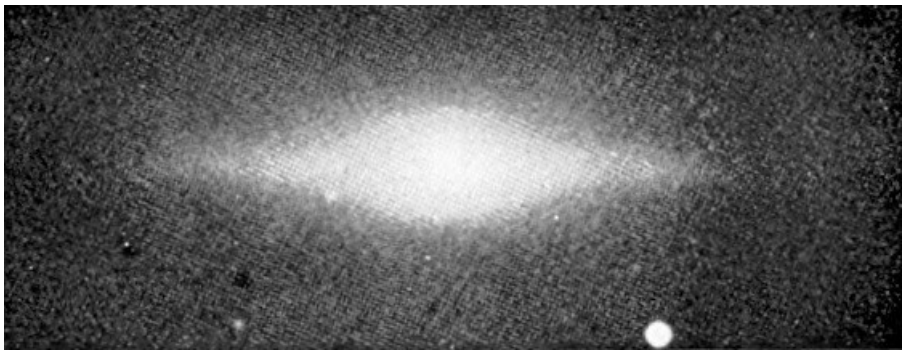


Fig. 3
N.G.C. 3115

Fig. 4
N.G.C. 4594
in Virgo

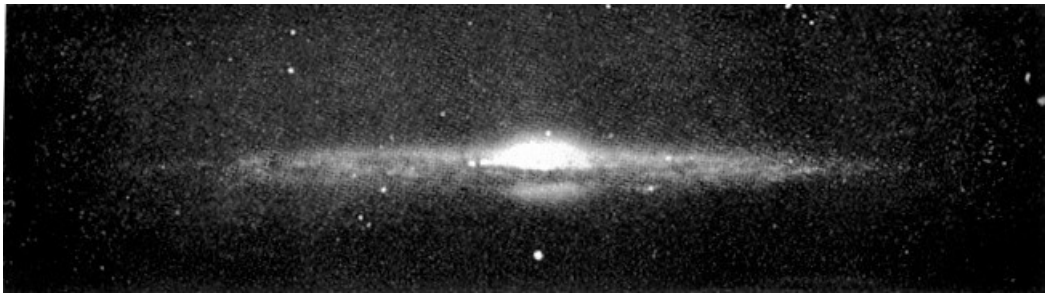


Fig. 5
N.G.C. 4563
in Berenice's
hair

Mt. Wilson Observatory
A sequence of Nebular Configurations

Generally speaking, the various "extra-galactic nebulae" are distinct and detached from one another, so that the universe appears to be a veritable collection of fragments. Our own vast system of stars is one such fragment; the extra-galactic nebulae are the others.

It is natural to wonder how the matter of the universe came to be broken up into such fragments. Most cosmogonies have supposed that the universe originally consisted of a continuous mass of gas, which filled the whole of space. If this is a true picture of the primaeval universe, how did this continuous mass get broken up and scattered?

A mathematical investigation shows that such a mass would not stay spread uniformly throughout space for long. Even if it were in equilibrium, the equilibrium would be unstable, so that any slight irregularity would not smooth itself out and disappear, but would tend to increase. Ultimately the gas would be concentrated round distinct centres of condensation; it would form "drops" of dense gas - much as a cloud of super-cooled steam condenses into drops of water, although the underlying physical causes would be very different. Finally, numerical calculation shows that these "drops" would be on something like the scale of the observed nebulae, and would be at something like the same distances apart.

If we assume that there were currents and eddies in the matter of the original universe, these broken fragments would start their existences in a state of rotation, and as they gradually shrank down to the sizes of the present nebulae, their speeds of rotation would increase, and their shapes change accordingly. The sequence of shapes which they would assume can be calculated, and it is significant that these agree very closely with the shapes of the observed nebulae - indeed the majority of the observed nebulae can be placed at definite points on this theoretical sequence from their appearance and shapes alone.

The five nebulae shown in Plate IV, all seen in the "edge-on" position, represent five milestones in this sequence, and the intervening stages can easily be imagined. The last stage of this sequence is of special interest, because mathematical analysis shows that, by the time this stage was reached, the outermost parts of the nebula - the spokes and rim of the cart-wheel - would again be in a state of unstable equilibrium. Like the matter of the earlier primaeval chaos, it would again tend to condense into distinct "drops" of gas. Again we can calculate the scale on which these drops would be formed, and find that each drop would be comparable to a star. Thus the process we have been studying appears to be that of the birth of the stars, and a succession of nebular photographs, such as that which is shown in Plate IV, may almost be treated as a cinematograph film, exhibiting the gradual metamorphosis of a formless mass of gas into a vast system of stars.

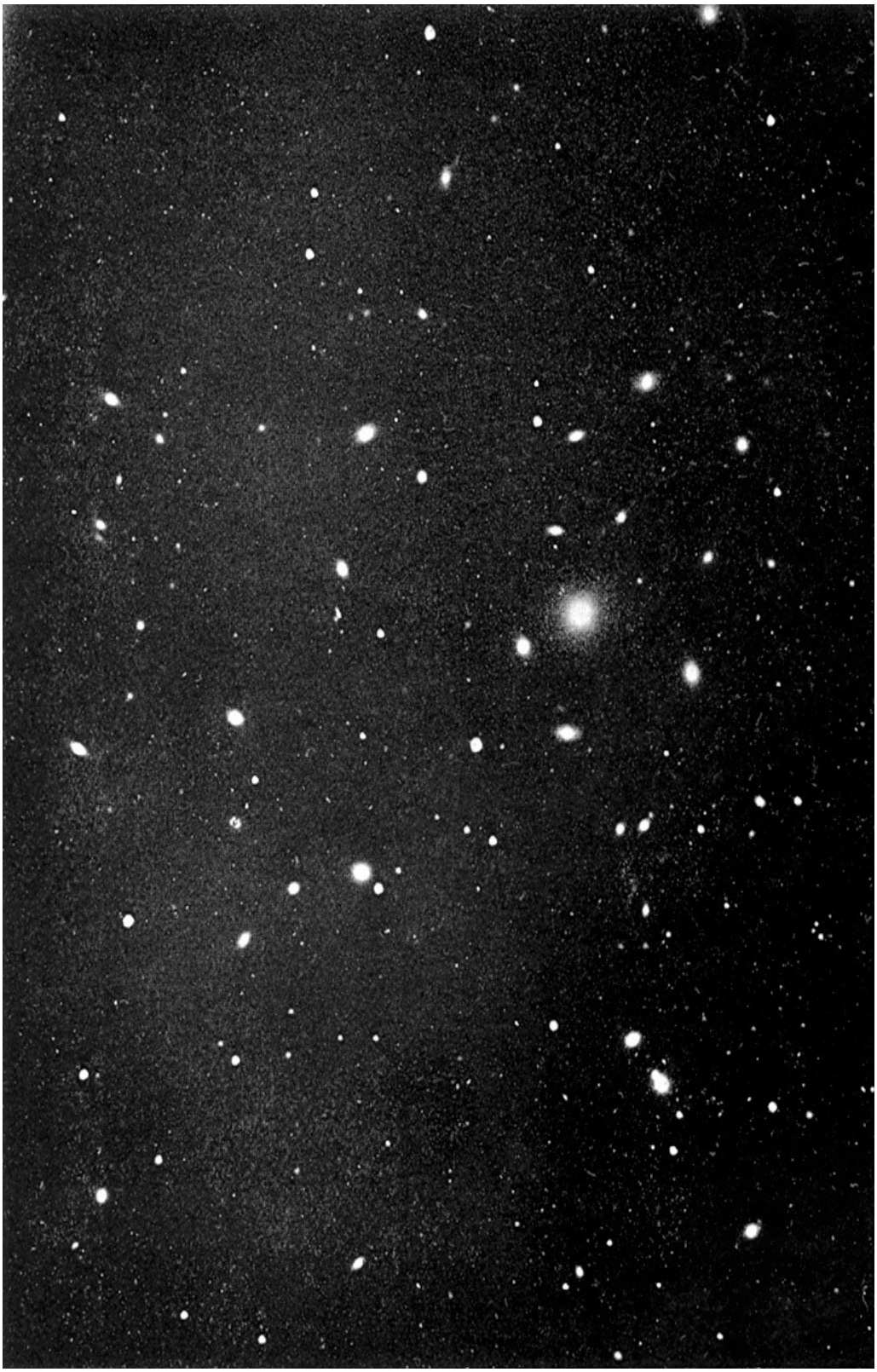
The stars in the sky show great differences of brightness, but the astronomer knows that these differences result in a large degree from differences of distances. One star looks bright because it is near; another looks faint because it is far away. The same is even more true of the nebulae. Two nebulae which are similar in shape and structure often appear to differ widely in size and brightness, but Dr. Hubble of Mount Wilson Observatory has shown that these apparent differences are almost entirely due to a distance-effect. If we could eliminate this distance-effect by placing the nebulae in a row, all at the same distance from us, we should find that nebulae of the same shape all had approximately the same dimensions and luminosity. This being so, the apparent size and faintness of a nebula give a measure of its distance, and it becomes possible to estimate the distances of the nebulae, even the faintest, with fair accuracy.

This is not by any means the only method available. The distances of nebulae have been estimated from the faintness of their brightest stars, from the faintness of their fifth brightest stars and also, as we shall see later, from the speeds of their apparent motions in space. All these different methods lead to concordant results. The faintest nebulae which can be observed photographically in the 100-inch telescope at Mount Wilson prove to be about 500,000,000 light-years distant, so that they are about 4000 times as distant as the furthest stars of the Milky Way.

It is impossible to form any clear mental picture of such vast distances, but a small-scale model may, perhaps, provide some slight help. If we construct a model on the scale of a million light-years to the inch, all the stars we can see with our unaided eyes are contained in a sphere less than a hundredth of an inch in diameter - a mere speck of dust. But the telescopic universe occupies a sphere 80 feet in diameter. In this model our whole galaxy is a small disc, of the size of a pin-head; our sun is a single electron, and the earth is a millionth part of an electron.

When the distances of individual nebulae are estimated in the way just explained, the nebulae are found to be, on the whole, scattered fairly uniformly throughout space; the average distance between neighbours being about 2,000,000 light-years. Here and there marked irregularities occur, and there are certain regions of space in which the nebulae are so closely crowded together that they may properly be described as forming a cluster. Our own galaxy is a member of a sort of cluster; its distance from its two nearest neighbours, some 7 or 8 hundred thousand light-years, falling far below the normal distance of 2 million light-years. But far denser clusters are found out in space. Plate V shows part only of a great cluster of about 1000 nebulae in Coma Berenicis, in which the average distance apart can at most be a few hundred thousand light-years. The photograph shows only 85 members of the cluster, but if each of these contains 100,000 million stars, we are looking at 8½ million million stars - say 4000 stars for each inhabitant of the earth. The great distance of the cluster - about 45 million light-years - explains why 8½ million million suns make such a poor showing.

Plate V



Mt. Wilson Observatory

Part of a cluster in Coma Berenicis, at a distance of about 45 million light-years. The cluster consists of about 1000 nebulae, each containing perhaps 100,000 million stars.

There is a still more compact cluster of about 400 members in Corona Borealis, the whole cluster covering a smaller area of the sky than does the full moon. The distance of the cluster is about 130 million light-years, and the average distance between adjacent nebulae is less than 100,000 light-years.

Now we come to a most remarkable phenomenon. As compared with the light of our own galaxy, the light received from these distant galaxies is found to be abnormally red, and the more distant the galaxy, the redder the light. If we pass the light through a spectroscope, we can still recognise the characteristic light emitted by atoms such as we know on earth - calcium in particular - but it is redder than the corresponding light with which we are familiar on earth. According to the wave-theory of light, red light consists of long waves, violet light of short waves. On this interpretation, then, the waves of light which reach us from the nebulae must be abnormally long. The most obvious way of explaining this is by supposing that the waves are "drawn-out" because the nebulae are receding from us.

For the moment, we shall assume that this is the true explanation of the reddening of the light. For instance, a faint nebula in the constellation of the Great Bear emits calcium light with a wave-length a seventh part longer than that of ordinary terrestrial calcium light; where eight waves ought normally to reach us, only seven arrive. We conclude that the nebula is receding at a seventh part of the speed of light - about 25,000 miles a second, or nearly two million times the speed of an express train.

When the light from the nearer nebulae is treated in the same way, we find that these are receding less rapidly; indeed some of the nearest are found to be actually approaching us. We must, however, remember that the rotation of our wheel of stars carries the sun on through space at about 170 miles a second, and when this motion has been allowed for, all the nebulae, near and distant, are found to be receding from the centre of the galaxy, the most remote receding with the highest speeds. Detailed studies by Hubble and Humason have shown that the nebulae are receding with speeds which are roughly proportional to their distances.

The proportionality is not quite exact. The nebulae of a cluster are all at about the same distance from us, but are not found all to be moving at the same speed. This shows that the nebulae are moving about inside the cluster. When we average the speeds of all the nebulae, we obtain the speed of motion of the cluster as a whole, and this is found to be almost exactly proportional to the distance of the cluster - about 100 miles a second for every million light-years of distance. Indeed the proportionality is so exact that the distances of remote clusters may be estimated with fair accuracy from their velocities alone.

We can estimate the total mass of a cluster from the speeds of its constituent nebulae, just as we estimate the mass of the earth from the speed of the moon's motion. For we must suppose that a cluster of nebulae - like the simpler earth-moon system - is held together by the mutual gravitational attraction of its members. If so, the speed with which these members move inside the cluster tells us how large a gravitational field is needed to keep them from flying off into space, and from this we can calculate the average mass of a nebula. Sinclair Smith, from a study of internal motions in the Virgo cluster, found the average mass of the nebulae in this cluster to be about 200,000 million suns. A simpler problem arises when the "cluster" consists of only two nebulae revolving about one another like the two components of a binary star; many such double nebulae are found in the sky, a typical example being shown in Plate VI. Holmberg of Lund has studied a number of double nebulae, and finds that the average mass of a single nebula is about 100,000 million suns. These values agree well with estimates made by other methods. Thus Lindblad, calculating the masses of four nebulae from their spectroscopic rotations, again finds an average value of 100,000 million suns. The values also agree well with estimates of the mass of our own galaxy, thus providing further evidence that the nebulae are of the same nature and size as our own galaxy.

Plate VI

Mt. Wilson Observatory
The Double Nebula N.G.C. 4567, 4568

The motions of the clusters as a whole demand an explanation of a quite different kind. We can imagine the matter of the primaeval chaos breaking up into the distinct condensations which afterwards constitute the nebulae, and it is easy to imagine these condensations falling into clusters and groups with internal motion, but it is far less easy to see why the clusters should scatter from one another in space.

The first glimmering of an explanation came from the theory of relativity. Einstein explained gravitational phenomena by supposing space to be curved, and added the assumption that space had an inherent curvature so that it curved back into itself, and the total volume of space was finite - just as the total area of the earth's surface is finite. It was soon shown that a space of this kind could not stand permanently in stable equilibrium. It would start at once either to expand or to contract; if the former, then every point in it would move away from every other point with a speed proportional to the distance apart of the two points. It is

only necessary to think of the nebulae as objects embedded in space, like grapes in a jelly, and the observed recessions of the nebulae are immediately explained by the expansion of space. The motions of the nebulae reveal the currents in space, just as the motions of particles of dust reveal the currents in air.

If this were the true explanation, it ought to be possible, in principle at least, to determine the whole size of space. Dr. Hubble and his collaborators at Mount Wilson recently discussed this problem, with extremely interesting and rather unexpected results.

If all the nebulae were standing still in space, it would be easy to construct a sort of map of the positions of the various nebulae in the sky, the distance of each nebula being of course estimated simply from its faintness; in such a map the nebulae would be found to be fairly uniformly scattered through space. But if the nebulae are receding from us at the speeds suggested by their spectra, this simple map needs correction in two respects. Part of the light sent out by a receding nebula goes to building a bridge of light, of ever-increasing length, between the nebula and the earth. The result is that the nebula sends out more light towards the earth than is received on earth; the nebula appears unduly faint, and this causes us to over-estimate its distance. When allowance has been made for this, the map is still out of date, since every nebula will have changed its position since it emitted the light by which we see it. Observation cannot tell us the present distance of a nebula; the most it can tell us is that, for instance, 240 million years ago a nebula was at a distance of 240 million light-years. If it has moved away from us throughout all this 240 million years at the speed indicated by its spectrum, its present distance from us will be about 270 million light-years. When we bring our map up to date by allowing for such motions, we find that the distribution of the nebulae has changed; it is no longer approximately uniform; the number of nebulae within any assigned distance x of the earth is now found to increase less rapidly than x^3, which is precisely what is to be expected, if space is curved in the way predicted by the theory of relativity. A slight curving of space would of course show itself in a slight divergence from the x^3 law, while a marked curving of space would cause a marked divergence. If, then, the observed divergence is taken to indicate a curvature of space, the amount of this divergence provides evidence as to the extent to which space is curved, and so makes it possible to estimate the total volume of space. The result is startling. Dr. Hubble found that space cannot extend very far beyond the sphere of 500 million light-years or so in radius, which is open to exploration with existing telescopes.

The calculation does not end here. The theory of relativity tells us that the curvature of space is associated with the presence of matter - marked curvature with matter of high density, and slight curvature with matter of low density. If the observed divergence from the x^3 law results purely and simply from the curvature of space, Dr. Hubble estimates that the matter in space must have an average density "appreciably higher" than 10^{-26} grammes per cubic cm.

On the other hand, he remarks that "there is no observational evidence for supposing the density to be greater than 10^{-28}". Indeed from the figures already given, it follows that if the matter of the nebulae were spread out uniformly through space, the average density would be only about a quarter of 10^{-28}, or 1/400-th of the required density of 10^{-26}.

Thus, although Dr. Hubble is unwilling to form any definite opinion at the moment, his observational evidence seems to suggest that the explanation in terms of a curved space is self-contradictory. We cannot, of course, rule out the possibility that our part of space really may be a region of maximum nebular density, and it is just conceivable that for every gramme of matter in a nebula there are 399 grammes outside. But these alternatives, if not impossible, seem highly improbable. If we disallow them, it is simplest to fall back on the arrangement just mentioned - the nebulae are at rest in space, and are distributed uniformly or nearly so in a space which need not be curved at all. But if we adopt this simple view of nebular distribution then the red shifts of the nebulae must be attributed to "some hitherto unrecognised principle whose implications are unknown".

So far, we have been following Dr. Hubble's line of thought, and have merely stated his tentative conclusions. These have not won universal acceptance. Indeed they have been criticised on at least three grounds. Eddington was the first to criticise them, on the ground that the observational material is not substantial enough to support the superstructure of conclusions which Hubble has attempted to build upon it. It is not possible to deduce the exact distance of a nebula, either from observations of its faintness or in any other way; the most we can say is that the distance probably lies within certain not very close limits. In whatever way we estimate the distances of a number of nebulae, there is probably an appreciable error in the estimated distance of each nebula; these errors may average out in the long run, but on the other hand they may not; it is all a matter of probabilities. Eddington has shown that there is quite an appreciable chance that all Hubble's results may be vitiated simply by the errors not averaging out. According to Eddington, we cannot draw any sure - or even fairly sure - conclusions from the observations.

Dr. Shapley, the Director of Harvard Observatory, is of the same opinion. He and his colleagues have found that the distribution of nebulae is far from being the same in all parts of the sky. Dividing the sky into two hemispheres they find that Hubble's treatment of the observations would indicate that one half of the universe is expanding, while the other half is not. The obvious inference is that Hubble's treatment leads to no sure conclusions - the question remains an open one.

McVittie has challenged Hubble on even more fundamental grounds. When we say that the distance from here to the observatory is 40 chains we mean that 40 surveyor's chains, placed end to end in a straight line, would just reach from here to the observatory. But we cannot measure the distance of the nebulae in the same way. If space is curved there are no straight lines, and whether it is curved or not, there are no surveyor's chains suitable for the job of measuring nebular distances. McVittie in brief charges Hubble with using five different ways of measuring distance, and assuming that they must all lead to equivalent results. If they really are equivalent, Hubble's conclusions are justified - which is only another way of saying that Hubble has made no mistake in his mathematics. On the other hand, the great divergence of the density in Hubble's final universe from that deduced directly from observation suggests the need of caution. McVittie shows that a divergence of this kind might well arise from even a small difference in the various meanings attached to distance by Hubble. He accordingly makes a new attack on the

mathematical problem, making use of only one measure of distance, and choosing this in such a way as to make the divergence in the densities disappear from the outset. With this measure of distance, he finds that space must be of the kind which the mathematician describes as "hyperbolic." Such a space extends to infinity, and as x is made larger, the volume of space enclosed in a sphere of radius x increases more rapidly than x^3.

It is not a case at present for deciding between the curved spherical space of Hubble and the hyperbolic space of McVittie, for a third alternative must be considered - the red shift may have some cause other than the nebular motion. Let us begin by considering a simple example of such a possible cause.

We usually assume that the atoms of the same chemical substance - e.g. calcium - are not only "standard articles" of the same size and structure at the present moment, but also that they have been the same as now from the beginning of time. Observation can, of course, provide no justification for the assumption; it leaves us equally free to assume, as a working hypothesis, that the atoms begin by being large, that they are continually getting smaller, and that they will end up - and the material universe with them - by being of no size at all. After all, this is no more artificial, as a working hypothesis, than that the whole of space is expanding and will end up by being of infinite size.

How are we to test such a hypothesis? What we want to know is what atoms were like some millions of years ago, and astronomy gives us the chance of looking at atoms as they were millions of years ago. There is, for instance, a nebula in Ursa Major at a distance of 250 millions of light-years from us, and its spectrum shows us, and analyses for us, the light emitted by the atoms of 250 million years ago. If these atoms were larger than the atoms of to-day, the light they emitted would be of greater wave-length, so that on comparing its spectrum with that emitted by the smaller atoms of to-day, all the lines would be seen shifted to the red. The amount of shift would be proportional to the age of the light, and so to the distance of the nebula emitting the light-which is precisely what is observed in nebular spectra.

This is only one example, which has been worked out in detail by Sambursky, of the possibility of explaining the red shift in a simple way by introducing new principles. It represents only one of a vast series of possibilities and I may conclude by trying to indicate the general nature of these possibilities.

A well-known and long-standing series of difficulties in astronomy is centred in the problem of the time-scale. If the universe is really expanding at the rate suggested by the shifts of the spectral lines, the expansion is so rapid that the age of the universe can hardly be more than a few thousands of millions of years; the same is true on the alternative hypothesis that the atoms are shrinking. This agrees with accepted estimates of the age of the earth, the radio active contents of rocks showing that the earth cannot be much more than 2000 millions of years old. Yet the intrinsic evidence of the masses and constitution of the stars, as well as of their motion, seems to show that the stars must be millions of millions of years old.

Some years ago, de Sitter advanced the startling suggestion that we are concerned here with two different ways of measuring time. We are certainly concerned with two kinds of clocks - what may be called astronomical clocks (the day, the year) and also with physical or atomic clocks (half-periods of radium, uranium, etc.), and maybe they do not keep the same sort of time; one may gain on the other. The half-period of radium may be 2000 years now, but may have been 2,000,000 years when the earth was thrown out of the sun - there is absolutely no observational evidence against such a hypothesis.

Some years later, Milne introduced a working hypothesis which he described as the "cosmological principle". He supposed, in brief, that the universe looked the same when viewed from all galaxies, provided the observer noticed no points of detail smaller than whole galaxies, and treated even these in a statistical manner. This hypothesis, somewhat surprisingly, was found to imply the existence of the two separate time-scales, atomic and astronomical, which de Sitter had proposed some years earlier.

It also led to the conception that the so-called universal constants of nature, such as the gravitational constant, Planck's constant and the total mass of the universe, may not retain the same values through all time, but may undergo a slow secular change as the universe ages. In brief, the so-called constants may prove not to be constants at all. That they appear to be constants may only be because so small a fragment of the universe - especially in time - is open to our observation.

Milne's is not the only revolutionary theory of the kind; others have been propounded by Dirac and Arnot. The details hardly matter for our purpose, but I will try to sketch one of them to illustrate their general nature; I choose Dirac's because it is the simplest to explain.

Out of the so-called constants of nature we can form a number of other constants having the same physical dimensions as time - such for instance are e^2/Mc^3, h/mc^2, where M,m are the masses of the proton and electron respectively. The values of these quantities are fixed by nature herself, and are presumably the same throughout the universe; they may be described as natural units of time, or "time-atoms". The values of the two just written down are found to be 5×10^{-27} secs. And 8×10^{-21} secs. These are the two extremes, the other natural time-units having intermediate values. On multiplying these by the velocity of light, we obtain quantities such as e^2/Mc^2, and h/mc, which have the same physical dimensions as a length, and may be regarded as "length-atoms".

The recessions of the nebulae provide evidence of yet another time which seems to be the same throughout the universe, namely 6×10^{16} secs. The nebulae move as if they had all started from the same point; if their motion had all been performed with their present speeds, it would have taken 6×10^{16} secs. In terms of the two "time-atoms" just introduced, this has the values

1.2×10^{43} and 7.5×10^{36} respectively.

These numbers are both of the same general order of magnitude, say 10^{39}, and Dirac comments on the frequency with which large numbers of precisely this order of magnitude turn up as constants in cosmological calculations. For instance, the ratio of the electrical and gravitational attraction between an electron and a proton is 2.3×10^{39}. Dirac suggests that this agreement is too marked to be a mere coincidence; it is more likely to be the outcome of some deep-seated law of nature. If so, the agreement must persist throughout the whole life of the universe. But the 10^{39} of which we spoke first is not a constant; It is a continually increasing quantity, being the number of "time-atoms" in the age of the world. This being so, Dirac supposes that all the other quantities of the order of 10^{39} increase pari passu. For instance, when the universe is twice as old as now, the ratio of electric to gravitational force will have twice its present value. Dirac supposes that this is secured by a secular decrease in the value of the gravitation constant, which must thus be supposed to vary inversely as the age of the universe. (On Milne's theory, by contrast, the gravitation constant varies directly as the age of the universe, while Arnot's theory makes it vary inversely as the fourth power of this age.)

Dirac argues that the number of particles in the universe cannot be finite, since if it were it would increase pari passu with the other large numbers, and this is contrary to the law of conservation of mass. This leads him to suppose that space is infinite and contains an infinite number of particles. The average space per particle, as measured by the number of cubic "length-atoms" to each electron or proton, is again found, from the observational evidence I have described, to be a large number of the order of 10^{39}, so that Dirac concludes that this also must increase pari passu with the age of the universe. The average distance between particles accordingly increases, and in this way Dirac accounts for the observed recessions of the nebulae.

Milne's theory commences by taking this recession as an observed fact, and showing that it is in accord with his cosmological principle.

Arnot's theory is based on the hypothesis that the measure of a distance must be the same, whichever of the two time-scales of Milne is used; from this and the principle of conservation of energy he deduces that the number of particles in the universe continually increases, being proportional to the square of the age of the universe, and so of the order of 10^{78}. The radius of the universe is the product of the age of the universe in time-atoms and the velocity of light, but as, on his theory, the velocity of light decreases as rapidly as the age of the universe increases, the product, which is the radius of the universe, stays ftxed at the 10^{39} length-units which is its present value. In more usual language, this radius is the 2000 million light-years - the distance which light would have travelled if it had moved with its present velocity from the beginning of time. The continual decrease in the velocity of light explains the red shift of the nebulae, without our having to suppose that these recede in space.

As you will see by now there is an absolute feast of hypotheses to choose between. You may pin your faith to anyone you please, but you must not be certain about any. Personally, I feel very disinclined even to pin my faith to any; it seems to me that it is still very open to question whether space is finite or infinite, whether it is curved or flat, whether the so-called constants of nature change in value or stand still - if indeed any of these questions have any meaning. I know that in saying this I lay myself open to the charge that, having led you into a maze, I do not even try to show you the way out. In my defence let me quote to you your own R. L. Stevenson: "Little do ye know your own blessedness, for to travel hopefully is a better thing than to arrive." Those scientists who work at these problems can still enjoy the explorer's thrill as they ever venture into new territory.