THE R. A. F. PENROSE, JR., MEMORIAL LECTURE

EXPLORATIONS IN SPACE

THE COSMOLOGICAL PROGRAM FOR THE PALOMAR TELESCOPES

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THE ultimate problems of astronomy concern the structure and behaviour of the universe. From our home on the earth we look out into space, and strive to imagine the sort of world into which we are born. The urge is older than history.

From time immemorial men studied the heavens with their unaided eyes, and on the cosmic scale the explorations were confined to a microscopic spot in the universe. Finally, about three and a half centuries ago, the telescope was invented. With the growth and development of these giant eyes a new era was opened. Explorations in space swept outward in great waves. Today, we observe a region so vast that it may well be a fair sample of the universe itself. And we are engaged in the attempt to infer the nature of the universe from what we can see in the sample.

The possibility of this venture emerged within our own generation, when about twenty-five years ago the 100-inch telescope on Mount Wilson suddenly opened to exploration the realm of the nebulae. An essential clue was found, that nebulae are stellar systems like our own system of the Milky Way, and this clue was rapidly exploited to the utmost limit of the telescope. The observable region of space was suddenly enlarged a million, million fold, and for the first time was so vast that it might possibly represent a fair sample of the universe.

With the 100-inch a reconnaissance was carried out which furnished a rough sketch of the observable region, a framework within which precise, detailed investigations could be planned with a proper understanding of their relation to the general pattern. The detailed work was attempted, of course—a survey following the reconnaissance—but the 100-inch, although by far the greatest telescope in operation, was too small for the purpose. Two general characteristics of the observable region as a whole were found, one that the region is approximately homogeneous, and the other, the strange law of red-shifts, that light reaching us from the nebulae has lost energy approximately in proportion to the distance it has travelled.

These features served to guide cosmological speculations, but they could not be made precise enough to establish a single theory beyond controversy. Precise results were obtained which seemed to be significant, but they were subject to the possibility of hidden systematic errors and at the time there were no ways of testing the possibilities. Consequently the results beyond the two approximate characteristics must be regarded as suggestive and not definitive. The nature of the universe was still unknown.

THE TELESCOPES

The question stirred the imagination profoundly. It seemed not impossible that with a larger telescope we might solve the mystery of the universe. And now, as you know, such a telescope is already in operation on Mount Palomar—two telescopes in fact, the 200-inch and the 48-inch, each the greatest of their (quite different) types. I will not discuss them other than to say that both telescopes surpass our most extravagant hopes. Mechanically and optically they approach perfection at least as closely as any telescopes in operation. Consequently their great light-gathering powers can be used to their full capacities.

These powers are enormous. The 200-inch Hale reflector, for instance, gathers as much light as a million eyes; one could see a candle at 10,000 miles, and photograph the candle at three times that distance. It penetrates into space about twice as far as the 100-inch (the next largest in operation) and will explore a sample of the universe about eight times the volume previously accessible. The enormous penetrating power is attained at the price of a small field of view—only a fraction of the moon can be recorded on a single photograph. Thus the 200-inch probes the universe with immensely long but very narrow beams.

The 48-inch schmidt reflector is the complement of the 200-inch. It penetrates to a lesser although still impressive distance, but records a very large area of the sky, comparable with the area of the Big Dipper, on a single photograph. *This complete coverage to great depths, with the* immense penetration of the 200-inch probe, together make a powerful combination for explorations in space. The two telescopes represent, in their own fields, the combination of low-power and high-power objectives so necessary for successful investigations with a microscope.

Evidently we have the tools. Their very perfection challenges us to use them to the best advantage. A cosmological program has been formulated, and it is this program I will discuss tonight. The program was twenty years in the making because it was developed with the telescopes. And during that time the 100-inch was used constantly to prepare the way. Now the work with the 200-inch is in progress. Isolated results are already accumulating, although it will be some time before there are enough to permit a critical review of cosmological theories.

*Tonight, I can only present briefly the concep*tion of the observable region as derived with the 100-inch, indicate some of the major uncertainties and how they are now being investigated, and finally, mention the plans for exploring the vast regions of space that are now accessible.

THE PRELIMINARY RECONNAISSANCE

THE DISTRIBUTION OF NEBULAE

The sun, as you know, is merely a star. It is one of several thousand million stars which together form our stellar system, a swarm of stars drifting through space. From our place within the system, we look out through the swarm, past the boundaries, into the universe beyond.

Those regions are empty for the most part, but here and there, separated by vast intervals, we now recognize other stellar systems comparable with our own. These lonely, drifting swarms of stars are the true inhabitants of space. They are called "nebulae"—extra-galactic nebulae—because until lately not even the brightest of their stars could be seen individually even in the nearest of the systems, and they appeared as little clouds scattered over the sky.

It was the 100-inch that first detected individual stars in a few of the nearest nebulae, and among them identified several types of stars that are well known in our own system. These stars are called distance-indicators. Because their luminosities, that is, their candle powers, were known, at least roughly, their apparent faintness indicated their distances, and hence the distances of the nebulae in which they lay. This was the essential clue, and with it the mystery of the nebulae was quickly solved. They are huge stellar systems, and appear small and faint only because they are vastly remote.

Moreover, they all appear to lie within a limited range of *total luminosity*. They average about 100 million suns, and while some are giants and some are dwarfs, relatively few fall outside the range from one-tenth to ten times the average. For statistical purposes we can consider them as equally luminous and then estimate their distances from their apparent faintness. On this assumption, preliminary explorations were pushed out through the observable region to the very limit of the telescope.

The faintest nebulae that can be detected with the 100-inch are on the average at a distance of the order of 500 million light-years. Within a sphere of this radius about 100 million nebulae are scattered. They occur singly, in pairs, and groups of various sizes up to great clusters and even clouds. However, when very large volumes of space are compared, the tendency to cluster averages out and the distribution on the grand scale is *approximately uniform, very much* the same everywhere and in all directions. This feature could not be predicted; it was the first general characteristic of the observable region to be established empirically.

We would like to describe the density distribution of matter throughout the observable region in accurate numerical terms—grams per cubic centimeter or suns per cubic light-year—but this problem is still recalcitrant. It is possible to estimate the smoothed-out, average number of nebulae per unit volume of space, but the average masses of nebulae are uncertain by a factor between ten and one hundred. Consequently the smoothed-out density of matter in space, so essential for cosmological theory, can now be expressed only as a very general order of magnitude (order of 10^{-30} g/cc).

THE LAW OF RED-SHIFTS

Only one other general characteristic of the observable region has been found in addition to the approximate homogeneity. It is the much discussed law of red-shifts. Light reaching us from the nebulae has lost energy in proportion to the distance it has travelled. The loss of energy is observed as red-shifts in the spectra of the nebulae. Since the nebulae are stellar systems, their spectra resemble those of stars. Dark lines due to calcium, hydrogen, iron, and other elements in the atmospheres of the stars are identified with confidence. In the nearer nebulae these lines appear close to their normal positions (observed in the laboratory or in the sun). In general, however, accurate measures disclose slight displacements, either to the red or to the violet side of the exact positions. Such small displacements are familiar features in the spectra of stars, and are known to be caused by rapid motion in the line of sight. Violet-shifts mean motion towards us, and shifts to the red mean motion away from us (motion of recession).

Rapid recession draws out each light-wave so that when it reaches us it is longer than normal. Since the wave-lengths determine position in the spectra (they increase steadily from violet to red), the general lengthening of all the waves results in a displacement of the entire spectra towards the red, that is to say, in a red-shift. Rapid approach shortens all wave-lengths, and introduces a violet-shift. Moreover, the fraction by which each wave is lengthened or shortened indicates the speed of recession or approach; it is the same fraction of the speed of light. For instance, a change of a tenth of one per cent means a speed of 186 miles/sec, and so on. In this way the nebulae are found to be drifting about in space, presumably at random, at average speeds of the order of 100 to 200 miles per second.

But superposed on the microscopic shifts representing these individual random motions, is a systematic shift to the red which increases directly with the distance of the nebula observed. If these systematic red-shifts are velocity-shifts (as the small shifts in the nearby nebulae are known to be) then we must conclude that the nebulae are receding from us in all directions at speeds which increase directly with their momentary distances. For every million light-years of distance the speed of recession would increase about 100 miles/sec. With the 100-inch Humason has followed this relation out to about 250 million light-years, where the red-shifts correspond to a velocity of 25,000 miles/sec. (or nearly $\frac{1}{7}$ the velocity of light). This interpretation of the observations has been accepted by many as visible evidence of a rapidly expanding universe.

The observations establish only that red-shifts increase with increasing faintness of the nebulae observed. When faintness is expressed in terms of distance (as may be done with confidence), we find that red-shifts increase directly with distance, and that the relation is approximately linear. This relation is known as the law of red-shifts.

The interpretation of red-shifts as velocity-shifts is less satisfactory. The red-shifts clearly mean loss of energy; there is a very fundamental law of physics which states that

$$\text{energy} \times \text{wave-length} = \text{constant}.$$

Thus, increased wave-lengths mean loss of energy by the individual light quanta, and the observations indicate that light from the nebulae has lost energy in proportion to the distance it has travelled to reach us. There remains the problem of where the loss occurs—in the nebulae, or during the immensely long journeys through space. In the former case it is almost certainly due to recession—to expansion of the universe; in the latter case it might be due to some reaction with matter in space but, if so, the exact mechanism is unknown.

COSMOLOGICAL THEORY

Much of modern cosmology is based upon the assumption that the universe will look very much the same from whatever position it is inspected. In other words, there is no center and no boundary; if the universe appears to be expanding around us, it will appear to be expanding around all other observers, no matter where they are placed. Attempts have been made to find what types of universes are permitted by this so-called Cosmological Principle, together with the principle of general relativity and the general laws of nature. The observed homogeneity of the observable region encouraged and simplified the task. It was found that such universes would be unstable, and in general would be either expanding or contracting. Theory did not predict either the direction or the rate of the change, and at this point the theorists turned to the observed law of red-shifts. The law was interpreted as evidence that the universe is expanding, and expanding rapidly. Thus emerged the various models of homogeneous, expanding universes of general relativity.

It was clear that the theories could be tested critically and weeded out, if we possessed accurate, reliable data on the distribution of matter in space (which indicates the curvature of space), and on the precise form of the law of red-shifts (which indicates the nature of the expansion). Furthermore, such data might permit us to determine directly whether or not red-shifts are velocity-shifts, and thus to test the fundamental assumptions of the cosmologists.

These were the problems to which answers were sought with the 100-inch, and for which the 100-inch proved inadequate. Answers were found, and they may be significant, but they involved uncertainties near the limit of the telescope which could not be evaluated at the time. Therefore the answers are regarded as suggestive rather than definitive. Nevertheless, the results have encouraged reexamination of the theories on more general assumptions. Non-homogeneous universes are under consideration, and a bold hypothesis of the continuous creation of matter has been introduced to save some of the suggested phenomena.

THE PROGRAM FOR PALOMAR

The cosmological program for the Palomar telescopes has been formulated to get new answers to the observational problems, free from systematic errors and with the accidental errors sufficiently small to be unimportant. Specifically, the problems are first, to find the mean density of matter in space, and the rate of increase of red-shifts, in our immediate vicinity—say within 50 million light-years of our own system—and second, to determine whether or not there are any appreciable systematic changes with distance or direction in either of the two data. Hopes for success in the venture are found in the new order of accuracy attained with post-war techniques, and the far greater range over which the techniques can be applied with the 200-inch.

Any systematic departures from homogeneity in the distribution of nebulae, or from linearity in the law of red-shifts, would be of first importance in distinguishing between theories. Absence of such departures would probably mean that the observable region is too small to serve as a fair sample of the universe, and that cosmological theory must still be regarded as speculative.

THE COSMIC DISTANCE-SCALE

Thus the special problem for the 200-inch has been described as a search for second-order effects of great distances. Such effects are predicted by all of the current theories but the pioneer work suggests that if they are found they will be small, at any rate until vast distances are reached. Under the circumstances they may easily be masked by, or confused with, small errors in the distances. Consequently, the first step in the new program is an accurate redetermination of the cosmic distance-scale.

The current scale is a good first approximation. However, several sources of possible uncertainties are known to exist, and with resources now available they can be removed. For instance, the scale of apparent magnitudes (which measures apparent faintness) was established by photography, and the method is inherently difficult when large magnitude intervals must be bridged. The magnitude-scale is now being reconstructed with the aid of extremely sensitive photoelectric cells of new types developed during the war. We can trust the new magnitude-scale down to stars or nebulae several million times fainter than the faintest stars seen with the naked eye. With these very faint standards well determined, the scale can be readily extended by photography over the narrow interval to the extreme limit of the 200-inch. Thus one source of uncertainty will be removed from the distance-scale.

Another example is furnished by Cepheid variables. The pioneer explorations of the observable region were based on these giant, easily recognized stars whose luminosities had been derived (by Hertzsprung and later by Shapley) from all the scanty data then available. When Cepheids were first found in nearby nebulae these luminosities were used to derive distances and to calibrate other distance-indicators. But now we find that something is wrong somewhere. The luminosities assigned to the Cepheids led us to expect that globular clusters in M 31 would be readily resolved with the 200-inch, and that their brightest stars, as well as comparable stars in the main body of the nebula, could be studied individually with ease. It was found, however, that the stars in question were fainter than expected by a considerable fraction of a magnitude, and that they could be recorded and studied only with difficulty. The discrepancy is important because M 31 has been explored on the basis of Cepheids while our own system has been explored, in a sense, on the basis of globular clusters. There are other inconsistencies but there is no need to discuss them. They can all be removed or explained satisfactorily by a redetermination of the distance-scale using new methods that are free from any criticisms.

THE DISTANCE OF MESSIER 31

The new program calls for a concentrated attack on the distance of a single nebula, selected by a compromise between nearness and abundance of distance-indicators included among its stars. The selected nebula is inevitably M 31; there is no competition. This giant spiral, less than a million light-years away, contains all kinds of stars in large numbers. If its distance can be established with confidence it will furnish luminosities of many types of giant stars, and all types of supergiants. Among them the most important distance-indicators are Cepheids (with luminosities of the order of a few hundred to a few thousand suns, depending on their periods) and normal novae (which reach maxima of the order of 100,000 suns). Cepheids can be studied with the 200-inch out to 3 or 4 million light-years, and novae to perhaps 10 million light-years. Several dozen Cepheids are known in the spiral, and novae outbursts occur at the rate of 20 to 30 each year.[1]

Our own stellar system is very similar to M 31. Both contain the two different types of stellar populations first distinguished by Baade.[2] The spiral arms, with their blue supergiants and other distinctive features, are embedded in a substratum of Type II stars in which supergiants are exceedingly rare or absent. Globular clusters with their pure Type II populations are scattered through both nebulae in considerable numbers. The very brightest stars of this population can just be reached in M 31 with the 200-inch, both in the globular clusters and in the main body of the nebula itself.

The similarity of the two stellar systems has suggested a new attack on the problem of the distance of M 31, using globular clusters in our own system as an intermediate step. These clusters are compact masses of many thousands of stars ranging from an abrupt upper limit of luminosity downward in rapidly increasing numbers to the limit of telescopes. A few of the clusters are within 40,000 light-years of the earth, and in them stars like the sun or even fainter can be studied in detail with the largest telescopes.

Because the sun is immersed in the Type II substratum of the galactic system, the stars in our immediate vicinity, say within 50 light-years of the earth, are (almost all of them) the kind of stars found in globular clusters. These neighbors are the stars whose distances are known accurately from direct triangulation, and consequently whose luminosities are best determined. The number is so small that only a few giants are included; most neighbors are dwarfs comparable with or fainter than the sun. Among these latter stars a curiously precise relation has been found between luminosity and color. It is a part of the general Hertzsprung-Russell diagram but a part in which the detailed pattern is especially well determined. The same pattern should exist in globular clusters, and the bright end of the pattern has already been detected. When the diagram for a cluster has been extended to stars as faint as the sun, it can be accurately superposed on ~~the diagram for our neighboring stars. The~~ distance of the cluster is then derived from the apparent faintness of stars of known luminosities.

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[1] Normal novae should not be confused with supernovae. The latter outbursts are the most gigantic explosions known in the universe. They sometimes reach maxima of the order of 100,000,000 suns or as bright as an average stellar system. They occur at the rate of about one per stellar system per three or four centuries. None has been seen in our own system since telescopes came into use but a few can be identified in the pretelescopic annals, and in two of these cases, in A.D. 1054 and 1572, the novae were visible in broad daylight. In 1885, an outburst occurred in M 31 and reached almost to naked eye visibility.

Some thirty or more supernovae have been found on photographs of nebulae, at distances ranging out to about 50 million light-years. Although they could be detected out to far greater limits, they are too rare, and vary too ~~much among themselves to serve as good distance-indi-~~cators, at least for individual nebulae.

[2] The recognition of two distinct types of stellar populations, announced and fully documented by Baade during the last war, is the most important contribution of the past decade and more to our knowledge of the inhabitants of the universe. It brings order out of apparent confusion in the interpretation of nebular contents, guides the formulation of research programs and suggests inviting lines of speculation on evolution.

Type I populations are found in late type spirals and, in the purest form, in irregular nebulae such as the Large Magellanic Cloud. Because of the dominance of blue super-giants in the populations the integrated light of the systems is bluer than average, and some of the individual stars can be recorded out to great distances. Type II populations, in their pure forms, are found in globular clusters, elliptical nebulae, early spirals, and certain kinds of irregular and dwarf nebulae. Because of the absence of blue supergiants the integrated colors of these nebulae are deep yellow or red, and resolution is restricted to systems less than a million light-years away.

Mixtures of the two types are found in intermediate spirals, such as M 31, where the nuclear regions are pure type II, and as mentioned above, the outer arms, with their type I populations are embedded in a faint substratum of type II stars.

These distances determine accurately the luminosities of the brightest stars in the clusters, and among them are distance-indicators that can be recognized with the 200-inch, in M 31. Thus the distance of M 31, with its Cepheids and novae, is being derived in terms of the dwarf stars in the vicinity of the sun.

The detailed formulation of this phase of the program, as well as the general supervision of the necessary investigations, is largely the work of Baade. It represents a natural extension of his long and fruitful study of M 31 as a stellar system. Accurate luminosities and dimensions will increase greatly the significance of comparisons with the galactic system. The spiral M 31 we see in its entirety but from a great distance. Our own system we know intimately within a limited region but we find it difficult to "see the forest because of the trees." From the study of the two systems together, especially because of their similarity, there is emerging a complete picture of a stellar system that can be accepted with some confidence.

Shapley, in his classical study of globular clusters, used Cepheids to measure distances of the clusters; today, as we invade the next decimal place, we are reversing the process, and using globular clusters to measure the Cepheids.

CEPHEID VARIABLES AS DISTANCE-INDICATORS

Cepheids are now being used to derive distances of a few spirals, each the largest of a pair or group, and all beyond the reach of the 100-inch. This program is well advanced, and accurate distances of a dozen normal nebulae, together with a scattering of dwarf nebulae, will be available shortly, in units of the distance of M 31. These results will furnish tests of the assumption that the stellar populations in M 31 are in no way peculiar, but may be used as representative of stellar systems in general.

NOVAE AS DISTANCE-INDICATORS

In one of these nebulae, M 81 in Ursa Major, novae outbursts are being recorded at the rate of more than one a month. The accumulating data furnish an independent value of the relative luminosity of Cepheids and novae for comparison with that found in M 31. Moreover, M 81 is a giant intermediate type spiral, similar to M 31 and our own system, and with the same mixture of the two stellar populations. Since novae are frequent in all three spirals (in contrast to the Large Magellanic Cloud and later spirals such as M 33 and M 101), we associate the high frequency with this particular type of nebulae. In technical terms, high frequency of normal novae is associated with stellar populations of Type II, but whether of Type II stars in general, or those in intermediate spirals in particular, remains to be determined.

A nova outburst has been described in these words—"a star becomes unstable and blows its cover off." We do not know why the explosions occur but we watch a star suddenly flare out to a maximum luminosity of the order of 100,000 suns, and within hours start to fade, ever more slowly, until months or years later it may reach its pristine level. The average rate of fading is known, so that although the maximum itself may not be observed, it can be estimated if the nova is found within a week or two after maximum.[3] Thus novae are good distance-indicators. The average apparent faintness at maxima measures the relative distances of nebulae in which the novae appear, and with the passage of time and accumulation of data the precision of the measures can be steadily improved.

DISTANCES OF THE VIRGO CLUSTER AND URSA MAJOR CLOUD OF NEBULAE FROM NOVAE

Because novae at maxima are the brightest stars in nebulae, they can be observed out to great distances—at least to ten million light-

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[3] For the informed students, it may be emphasized that the precise maxima, the flash phenomena, are not very useful as distance-indicators. They are rarely observed, and the rates of fading vary widely and rapidly during the first few days. However, the records of many novae observed in M 31 indicate that the dispersion around mean luminosities at, say, 10 or 15 days after maximum is small enough to permit the derivation of the relative distances of nebulae, and the reliability of the results increases steadily with the accumulation of data. The procedure in the study of M 31 consisted in using only those novae whose maxima were observed or which were first seen following an unobserved interval of less than 30 or 40 days, and assuming that maxima occurred, on the average, at the midpoint of the unobserved intervals.

The dispersion from 71 novae, including both the real scatter in luminosities at 14 days after maxima and effects of errors in times of maxima, was about 0.5 mag., hence the probable error of the mean result was about 0.05 mag. (*Mt. Wilson Contr.*, No. 376; *Astrophys. Jour.* 64:103, 1929). A reexamination of the problem using more novae, a reduced interval, and improved magnitudes is under way, and should still further reduce the scatter around mean values derived in the earlier study. A critical test of the method is furnished by the relative distances of M 31 and M 81 as derived from the novae, because in these nebulae the results can be checked by Cepheids.

years with the 200-inch. Now within this limit are the Virgo Cluster and the Large Ursa Major Cloud, each organization containing several hundred nebulae of all types. Distances are currently estimated as of the order of 8 and 6 million light-years respectively. Cepheids cannot be reached at these distances, but novae should be observable in the giant, intermediate spirals belonging to both groups, and perhaps in earlier type nebulae as well.

THE "AVERAGE" NEBULA AS A STATISTICAL DISTANCE-INDICATOR

A search for novae was initiated last winter, using a selected list of likely members in each group, but the weather was persistently bad, and progress during this first season is not impressive. Success, however, is only a matter of time and with it we shall have reliable distances and hence luminosities, of perhaps a thousand nebulae—a sample collection for the study of nebulae themselves. It will then be possible to redetermine the average luminosity of nebulae together with the dispersion about the average. These quantities permit statistical estimates of distances from apparent faintness of the nebulae themselves, out to the extreme limit of the telescope. The distribution of nebulae in space is then derived from counts to successive limits of apparent faintness which furnish the numbers of nebulae in spheres or shells of successively greater radii.

BRIGHTEST STARS IN NEBULAE

Two other distance-indicators can be calibrated from nebulae in the Virgo Cluster and Ursa Major Cloud; they are brightest stars in nebulae and brightest nebulae in clusters. There is an upper limit to the luminosities which permanent (that is, stable) stars can ever attain; this limit is approached in all giant, late type spirals for which information is available. The limit is known to be of the order of 60,000 suns. The many late spirals in the cluster and the cloud will furnish an accurate mean value of the upper limit for nebulae of a given total luminosity together with the dispersion about the mean, and also the variation of the limits with the total luminosities of the nebulae. Brightest stars can then be used to indicate the distances of all late spirals in which even a few stars can be seen. Because of the dispersion about the mean value, individual distances will be somewhat uncertain, but results for groups of nebulae containing several late spirals should be quite reliable. The criterion can be used with the 200-inch out to distances of the order of nearly ten million light-years.

BRIGHTEST NEBULAE IN CLUSTERS

The brightest nebulae in clusters are analogous to the brightest stars in stellar systems. There seems to be an upper limit to the luminosities of nebulae, and the limit is approached in all the great clusters of nebulae for which information is available. The limit is well represented by M 31—of the order of 2,500 million suns.[4] A dozen nebulae seem to be comparable with M 31 but not a single one is known to be brighter.

The great clusters are so similar that the apparent faintness of their 1st, 3rd, 5th, 10th, or any other serial nebulae might be used to indicate their relative distances. Currently, the 5th brightest, of the order of 700 million suns, is used because the 1st or 3rd might be confused with foreground nebulae, seen by projection on the cluster, and fainter nebulae are more difficult to measure.

The criterion of brightest nebulae is of fundamental importance because it permits us to assign very great distances to individual objects with confidence. It is for this reason that clusters are used for investigations concerning effects of great distances. For instance, the law of red-shifts was formulated almost entirely from clusters. Once formulated however, it serves as an excellent criterion of distance for all nebulae whose spectra can be recorded, and it has the virtue that the percentage uncertainty actually decreases as the distance increases.

EFFECTS OF RED-SHIFTS ON THE DISTANCE-SCALE

The last step in the problem of the distance-scale concerns effects of red-shifts on apparent faintness. The combination of atmosphere, telescope, and photographic plate (or other receiver) acts as a window restricting the light which reaches the observer, to a limited range of colors. The results are readily understood if we imagine the light of a nebula spread out as a spectrum,

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[4] M 31, of course, is not in a cluster of nebulae. It is, however, a member of the "Local Group," a loose group of some 16 nebulae, including the galactic system, which is more or less isolated in the general field of nebulae. Until recently, our knowledge of Cepheids and normal novae was restricted to the Local Group. One of the notable achievements of the 200-inch has been to break away from the group and to invade the general field.

and examined through a fixed aperture. Because intensities vary widely through the spectrum, the measures of the amount of light received will depend upon the location of the window in the array of colors.

Now as nebulae are observed at successively greater distances, the spectra march past the fixed window according to the law of red-shifts. Consequently, the measures of apparent faintness made through the window refer to different regions of the spectra, and corrections must be applied in order to reduce the measures to a standard region. Only then can distance be inferred accurately from apparent faintness.

Corrections are derived from the intensity distributions along the spectra of nebulae. They are difficult to determine, and are still imperfectly known. A general investigation of the problem is scheduled for the near future, but meanwhile it is possible to apply corrections with some confidence under certain special conditions. Fortunately, the region of nebular spectra from blue-green to red is the best known, and it is here that the differences in intensities (the corrections for red-shifts) are the least. Much of the uncertainty can be avoided by measuring apparent faintness of nebulae in the red through a red filter. For distant nebulae, these measures represent the intensities normally found in the orange, yellow or green (depending on the distance) but displaced by the red-shifts to the particular region observed. Differences of intensity in the various colors are small, and are fairly well known, therefore errors in corrections for the differences are very small indeed. The method is practical because red-sensitive photographic emulsions have been highly developed during recent years, and with the help of photoelectric cells over much of the range, the measures can be pushed out to the very frontiers of the observable region. As a compromise, until accurate red magnitudes are available, yellow (or photovisual) magnitudes are being used.

ASSUMPTIONS UNDERLYING THE DISTANCE-SCALE

Estimations of distance from apparent faintness involve two assumptions that have not yet been mentioned. The first assumption is that internebular space is sensibly transparent, that nebulae are not noticeably dimmed by dust or gas scattered between the systems. There is a great deal of dust and gas within our own stellar system (and in the other nebulae) and the resulting obscuration is very troublesome. But in space between the nebulae no clear evidence has yet been found of widespread general obscuration. Until such evidence emerges, the explorations will proceed on the assumption of transparency.

The second assumption concerns the rate of nebular evolution. It is a speculative problem and among the speculators a controversial one. When we look out into space, we look back into time, far back into the history of the universe. We must compare neighboring nebulae as they were only a few million years ago with remote nebulae as they were several hundred million years ago. Since we have no more recent information concerning the distant nebulae, we proceed on the assumption that evolutional changes may be ignored, that total luminosities have not altered materially, during the time the light has travelled to reach us.

Geologists have reasons to suppose that the luminosity of the sun has not changed materially during the last 1,000 million years. Stellar systems may perhaps be equally stable, or they may not. Current theories even now suggest that giant stars, unlike the sun, may change rapidly. The best we can do is to start with the simple assumption of stability and keep alert for trouble in the form of systematic variation with distance which can be interpreted as evolutional changes.

The subject has a necessary place in cosmological studies, and a special program has been drafted for its investigation. Evidently the work must start with the comparative study of clusters of nebulae at successive distances because only in these clusters can large individual distances be assigned to many objects with confidence. Even now, a systematic reddening of early-type nebulae in clusters, observed by Stebbins and Whitford out to about 250 million light-years, is widely discussed as possible evidence of evolutional changes. The suggestion is exciting but it is only one of the possible explanations of the phenomena, and more information will be required before the possibilities can be weeded out.[5] Meanwhile it is recognized that the ques-

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[5] Some of the necessary information should be furnished by one project in the program of evolutional studies, formulated by Minkowski. Although supernovae are not accurate distance-indicators for individual nebulae, they are reliable in statistical investigations. By keeping watch (one or two plates per month) over several remote clusters of nebulae, it should be possible to assemble data on a sufficient number of supernovae to furnish, within 5 to 10 years, a reliable mean distance for the clusters as a group.

tion of the rate of evolution of stellar systems seems to be the most serious of the undetermined factors that might confuse the distance-scale.

The program for the distance-scale may be summarized as (1) the use of globular clusters to establish the distance of M 31 in order to calibrate Cepheids and novae; (2) the use of novae to measure distances of the Virgo Cluster and the Ursa Major Cloud in order to calibrate the nebulae themselves, and (3) the measurement of the intensity distribution over the spectra of nebulae in order to furnish accurate corrections for effects of red-shifts on apparent faintness. The various lines of advance are being followed simultaneously, and progress to date seems to assure the success of the program, subject only to the unknown factor of a possibly rapid rate of evolutional changes in nebulae during the transit time of the light. With this restriction we are confident that the program will provide the proper tools for explorations of the whole of the vast observable region of space.

THE USE OF THE DISTANCE-SCALE

THE LAW OF RED-SHIFTS

In conclusion I shall mention briefly some of the plans and prospects involved in those explorations. The first definite result to be expected is the accurate formulation of the law of red-shifts out to about twice the distance previously attained. Clusters selected from those found on 48-inch schmidt plates furnish excellent observing lists out to perhaps 350 million light-years. Beyond the reach of the 48-inch we must depend upon accidental finds with the 100-inch or 200-inch, and the time required for discovery is unpredictable. Humason has already recorded red-shifts corresponding to velocities ranging up to more than one-fifth the velocity of light (50 per cent greater than the limit reached with the 100-inch), and he believes that readable spectra can be obtained out to distances of the order of 500 million light-years, when suitable clusters are found. With accurate distances available, the data should indicate at once whether the law of red-shifts departs from a strictly linear relation, and, if so, whether the rate of expansion of the universe has been speeding up or slowing down during the immediate past. These data will furnish estimates of the "age of the universe"—the elapsed time since the expansion began. Furthermore, there are fairly good prospects that the same data will furnish a critical test of whether or not the red-shifts really are velocity-shifts, whether or not the universe is expanding at all, at the rate suggested by the red-shifts.

THE DISTRIBUTION OF NEBULAE

The second problem, concerning the homogeneity of the observable region, is much more laborious. We wish to know the distribution of nebulae in space, in other words, the average number of nebulae per unit volume, and to search these data for systematic variations, or trends depending either upon direction or upon distance. Furthermore, we wish to know the masses of nebulae in order to express the data as the density distribution of matter in space (in grams per cc).

The distribution of nebulae over the sky is not included in the Palomar program. Such an investigation is being carried out at Lick Observatory by counting the nebulae on survey plates with the fine 20-inch camera which in time will cover the entire sky observable from that latitude. Dr. Shane has described the immense project at a recent meeting of this Society. The final report will present the distribution of more than a million nebulae to about the 18th magnitude or fainter, in the form of a contour map with lines showing equal numbers per unit area. The data will test the current assumption of large-scale uniformity over the sky (isotropy, or "no favored direction") and will describe the small-scale distribution, or tendency towards clustering, in quantative terms. The results will represent a major, fundamental contribution to cosmology.

Distribution in depth, on the other hand, is a part of the Palomar program. It will be derived from counts of nebulae between successive limits of apparent faintness or, in other words, the numbers of nebulae in successive shells of space. Beyond the reach of the 20-inch at Lick, the numbers of nebulae per unit area increase so rapidly that complete counts over the available sky are out of the question. Instead, a number of sample regions spaced over the sky, each covering 100 square degrees, or about 3 or 4 times the area of the Big Dipper, will be studied on 48-inch schmidt plates. Each region will furnish between 40 and 50 thousand nebulae, to about mag. 19.5, and the counts will be made both on blue and on red photographs, to several

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A comparison of mean luminosities of these nebulae with luminosities of similar neighboring nebulae will indicate whether or not there are systematic changes depending on time which can be attributed to evolution.

different limits of apparent faintness. Then in small sample areas scattered over the counted regions the 200-inch will probe out to its extreme limits, again in both blue and red. By this sampling technique we hope to establish the distribution in depth, in the two colors, out to the very boundaries of the observable region, out perhaps to distances of the order of 1,000 million light-years.

The data, when assembled and analyzed, should indicate whether or not the average number of nebulae per unit volume of space varies *systematically with distance. If such a trend is found,* the interpretation will depend upon the nature of the variation. For instance, a fading out of numbers might mean obscuration by diffuse matter in space, or that the galactic system is located within a super-system of nebulae; either a fading out or increasing numbers might indicate and measure the curvature of space that is involved in most of the cosmological theories.

The isolated areas covered by the sampling surveys do not indicate the small-scale distribution of nebulae (the clustering) but instead furnish the average, smoothed-out values of numbers of nebulae per unit volume of space, known as the large-scale distribution. These data alone measure the homogeneity of the observable region, but their significance will be enormously increased when they can be expressed numerically as the density of matter in space. The transformation, however, involves the masses of nebulae, and these quantities are now rather controversial; the various methods of investigation lead to values differing by factors between 10 and 100. All methods, of course, depend upon velocity, and *velocities at great distances are derived only from* velocity-shifts in spectra. Velocities measure the gravitational fields in which they occur, and consequently the masses of the elements in those fields.

The program includes determination of masses from spectrographic rotations in single nebulae, differential velocities in close pairs, and velocity dispersions in clusters of nebulae, and less immediately, from masses of globular clusters, stepped up to early type nebulae in proportion to relative luminosities. Objections have been raised to each method, but as the work progresses the validity of the objections can be tested by the agreement or nonagreement of the results for the different procedures.

At present the greatest confidence is placed on spectrographic rotations, and the most reliable single mass is that assigned to M 31—of the order of 100,000 million suns. M 31, as previously mentioned, is the largest and most luminous nebula known, and presumably the most massive. Since nebulae are stellar systems, the orders of the masses of similar, fainter spirals *may be derived from their relative luminosities.* A nebula 1/100 as luminous as M 31 may contain 1/100 as many stars, and consequently may be about 1/100 as massive. The procedure may be improved by determining reliable masses for a few examples of each of the standard nebular types and extending the results within each type by relative luminosities. Justification is found in accumulating evidence suggesting a mass-luminosity coefficient which varies systematically through the sequence of classification of nebulae.

Time does not permit further discussion of the problems of masses and the time scale (which bear directly upon the curvature and the expansion of space) nor can we even mention the evolution of stars, stellar systems and the universe itself. For these ultimate problems as well as the more immediate problems of the laws of red-shifts and of nebular distribution, the necessary preliminary is reliable information concerning distances, luminosities, and masses; and first of all, concerning distances. This consideration has determined the emphasis of the discussion.

We know the preliminary objectives can be, *and are being, attained. When they are won and* consolidated, we shall turn to the great problems of the universe with new confidence. Observational results can be stated positively, with limits of uncertainties evaluated accurately. Then theory after theory can be eliminated. The long array of possible worlds can be reduced to a few that are compatible with the existing body of knowledge. And possibly, just possibly, we may be able to identify, in the shortened array, the specific type that must include the universe we inhabit.