25 September 1964, Volume 145, Number 3639 SCIENCE

Explorations with the Hale Telescope

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In the April 1928 number of *Harper's Magazine* there appeared an article by George E. Hale entitled "The possibilities of large telescopes." This article came to the attention of Wickliffe Rose of the International Education Board, and this board, in cooperation with the General Education Board, provided the funds for the construction of the Hale 200-inch telescope on Palomar Mountain.

In his article Hale wrote, "Other reasons that combine to assure the success of a large telescope are the remarkable opportunities for new discoveries revealed by recent astronomical progress and the equally remarkable means of interpreting them afforded by recent advances in physics. These new possibilities are so numerous that I must confine myself to three general examples, bearing upon the structure of the universe, the evolution of stars, and the constitution of matter."

It is now nearly a decade and a half since the Hale telescope began regular observations. We may therefore appropriately ask to what extent the opportunities for discoveries in the fields enumerated by Hale have been realized by the 200-inch telescope and its supporting instruments.

The author retired on 30 June 1964 from the directorship of the Mount Wilson and Palomar Observatories, operated by the Carnegie Institution of Washington, Washington, D.C., and California Institute of Technology, Pasadena. This article is adapted from an address delivered 15 May 1964 at the Carnegie Institution of Washington.

Structure of the Universe

Consider first the structure of the universe. When Hale wrote in 1928, Hubble had just succeeded in resolving the stars in the Andromeda galaxy with the 100-inch telescope on Mount Wilson. By identifying among these stars a number of cepheid variables and by comparing their apparent brightness with the absolute brightness, as determined from examples in our Milky Way, he arrived at a distance for Andromeda of a little less than 1 million light-years. Similar comparisons, in which, finally, the brightest galaxies in a cluster of galaxies were used as a distance indicator, led Hubble to an estimate of 500 million light-years as the maximum distance observable with the 100-inch.

All these observations were at the extreme limit of the capabilities of the 100-inch, and it was realized that all the measurements were subject to large uncertainties. One of the high-priority programs planned for the Hale telescope was a thorough reexamination of all the steps in determining the distance of Andromeda and more distant objects. First, a recalibration of the whole scale of stellar magnitudes was undertaken, by means of the new and more precise photoelectric techniques. In the hands first of Stebbins and Whitford and later of Baum, these remeasurements showed that the older photographically determined magnitudes were more and more in error as fainter magnitudes were reached until, in the range from the 20th to the 23rd magnitude, which had been used in the Andromeda studies, the error approached a full magnitude.

Next, a reevaluation of the absolute magnitudes of nearby cepheids as a function of period was undertaken by Baade at Palomar, by Thackeray and Wesselink at Pretoria, and by Mineur, Blaauw, and H. R. Morgan. All these groups arrived independently at the conclusion that the classical cepheids are about 1.5 magnitudes brighter than had been supposed.

Finally, Baade carried out a very extensive investigation of the apparent magnitudes of the cepheid variables in Andromeda. To establish light curves of these variables it was necessary to obtain, with the 200-inch, well over 100 photographs of each of the four fields under study, shown in Fig. 1. Areas I, II, and III were photographed first, but a preliminary study of the variables gave erratic magnitudes, indicating that many of the cepheids were embedded in dust clouds that absorbed part of their light. Field IV, far out from the nucleus of Andromeda, was then photographed. Here the variables are much fewer but are free of obscuration. More than 300 cepheids and numerous other variables were located by Baade on the plates of the four fields. Henrietta Swope then measured the magnitude of each of the cepheids or other variables in fields I, II, and IV, on each of the 100 or more plates on which the star was located, and drew a light curve in each of two colors. Figure 2 shows a sample of curves for four variables in field IV; for each variable the top curve is for blue light, the center is for light of wavelengths in the visual region, and the bottom curve represents the difference. Unfortunately Baade did not live to see the completion of these measurements. Swope's final analysis, which has just been completed, when considered in combination with the new magnitude scale and the new values for the luminosity of the cepheids, leads to a distance for Andromeda of 2.2 million

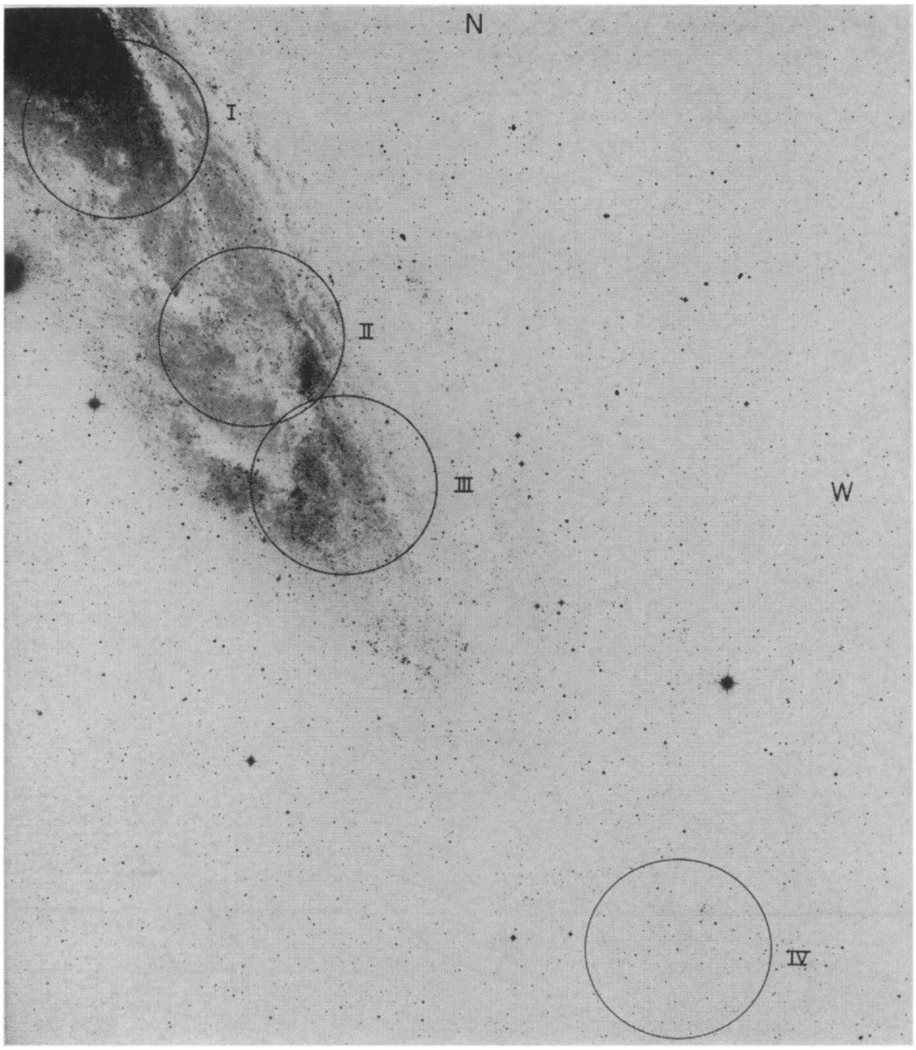


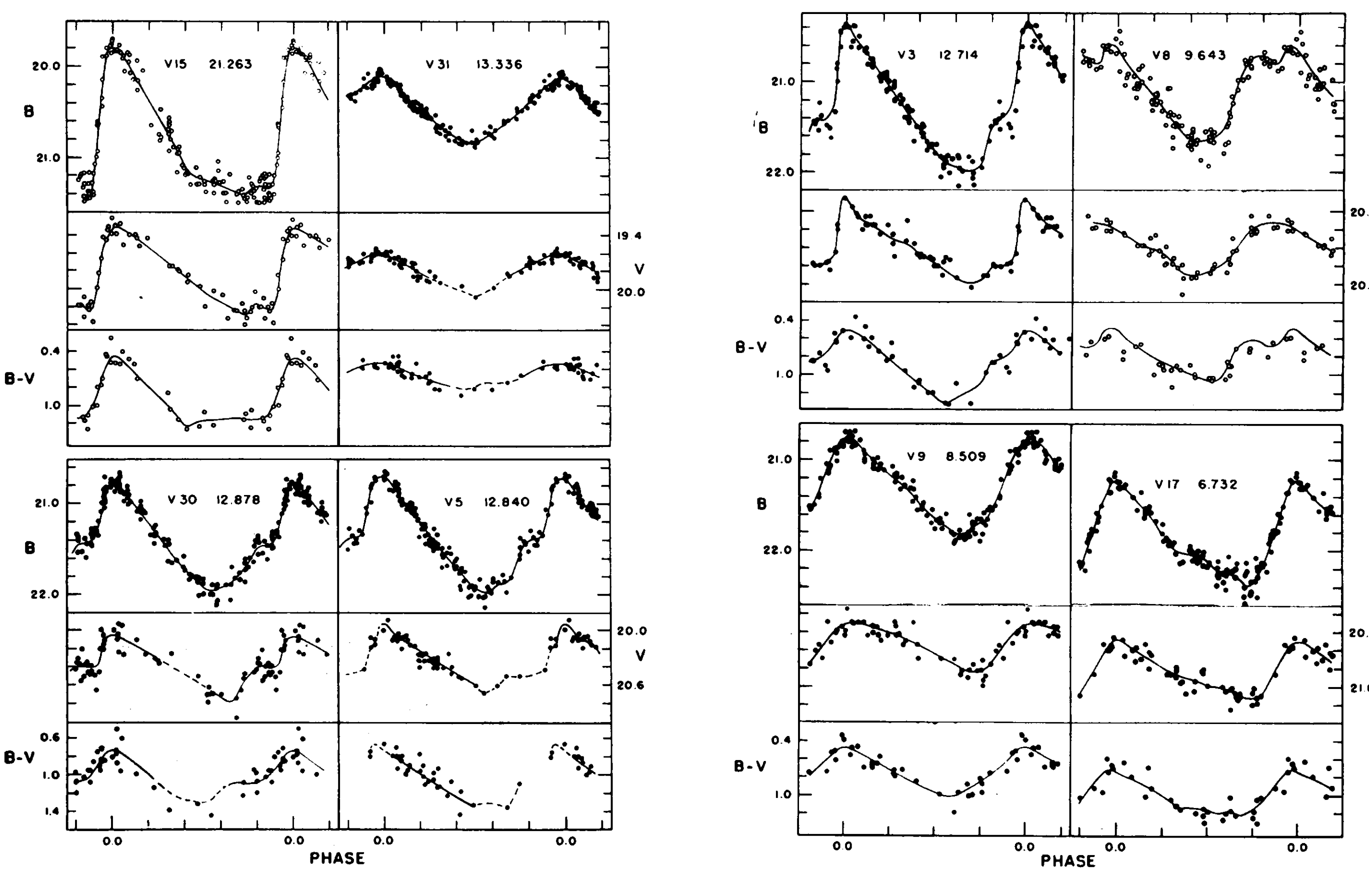
Fig. 1. (left) Fields in the Andromeda galaxy investigated by Baade (negative print). Fig. 2 (below). Sample of light curves of cepheid variables observed in field IV. *B* shows variation of magnitude photographed in blue light; *V* shows variation as photographed in green-yellow light.

light-years, or three times Hubble's value.

This new value also means that Andromeda has a diameter 3 times, a luminosity 9 times, and a mass 3 times the earlier estimates. Hubble's original values indicated that Andromeda and other large galaxies were all appreciably smaller than our Milky Way and led one well-known astronomer to remark in the 1920's, "if we call them islands, the Galaxy is a continent." Swope's latest value for the distance indicates that Andromeda is both larger and more massive than the Milky Way.

The extension of these and related methods to the study of more distant galaxies is still in progress, and final values for distances and related constants are not yet available. Preliminary estimates by Sandage and others, however, indicate that Hubble's values for the distances of the farthest galaxies he observed must be increased by an even greater factor, of perhaps 4 to 7.

Following Hubble's identification of the galaxies as distant stellar systems,



Hubble and Humason investigated the spectra of these objects. This led to the discovery that all their spectra are shifted toward the red end of the spectrum by an amount that is approximately proportional to the distance as shown in Fig. 3. Interpreted as a velocity of recession, the red shift led to the concept of the expanding universe, which has been fundamental to all cosmological theories since that time. In the original study with the 100-inch, Humason observed galaxies with red shifts of up to 13 percent of the wavelength. With the completion of the 200-inch telescope he was able to observe galaxies with shifts of more than 20 percent.

Radio Sources and Galaxies

In the meantime a new and unexpected approach to many of these problems developed from the discovery that, in addition to light, short-wave radio waves are coming from outside the atmosphere. Much of the radiation comes from huge clouds of gas in the spiral arms of our Galaxy and has proved a very powerful tool in outlining the position of the arms. More detailed study revealed a large number of small localized sources. As radio techniques improved it was possible to locate the sources with sufficient accuracy to identify them with optically observed objects. Minkowski and Baade in the mid and late 1950's were especially successful in making identifications on plates made with 48-inch Schmidt and the 200-inch Hale telescopes. A number of the sources were found to be objects in the Milky Way, several being remnants of supernova explosions, including those recorded in A.D. 1054, 1572, and 1604 (see Fig. 4).

A number of additional radio sources were identified with galaxies. All the radio galaxies close enough for detailed study (for example, NGC 5128) show many peculiarities (see Fig. 5). Other galaxies, such as M87, show jets of matter being ejected (see Fig. 6). In general the light of the jets is strongly polarized, indicating that much of the light comes from very-high-speed charged particles (electrons or protons) being accelerated in a magnetic field, the so-called synchrotron radiation. Spectroscopic studies show strong emission lines of abnormal strength. Furthermore, the lines are wide and often have complicated structures indicating large relative motions of a thousand or more kilometers per second between various parts of the galaxy. Because of the dual character of several of the galaxies and the high relative velocities of their parts, several of these objects were originally interpreted as galaxies in collision.

Four years ago Minkowski reported on the identification of one such radio source, 3C295, with the brightest member of a very faint cluster of galaxies. Like the spectra of most radio sources, its spectrum was characterized by strong emission. The red shift was the largest that had been observed—46 percent of the wavelength (see Fig. 7). This red shift was confirmed by Baum from the shift of the maximum of the continuous radiation of two of the normal galaxies in the same cluster. These observations placed the cluster at the greatest distance of any object then known.

Less than 2 years ago Matthews (from California Institute of Technology Radio Observatory) and Sandage identified three of the radio sources with stellar objects, although one or two showed faint wisps of nebulosity extending out from them. Spectrograms taken with the 200-inch showed emission lines, which, however, did not agree in position with any known lines. Finally, a detailed study of the spectra by Schmidt, in combination with infrared scanner observations by Oke, gave a convincing identification of the lines in the object 3C273 with well-known nebular lines shifted toward the red by 16 percent from their normal positions. Following this clue, Greenstein and Matthews were able to interpret their spectra of 3C48 in a similar way, finding a shift toward the red of 37 percent. A theoretical discussion by Greenstein and Schmidt has shown

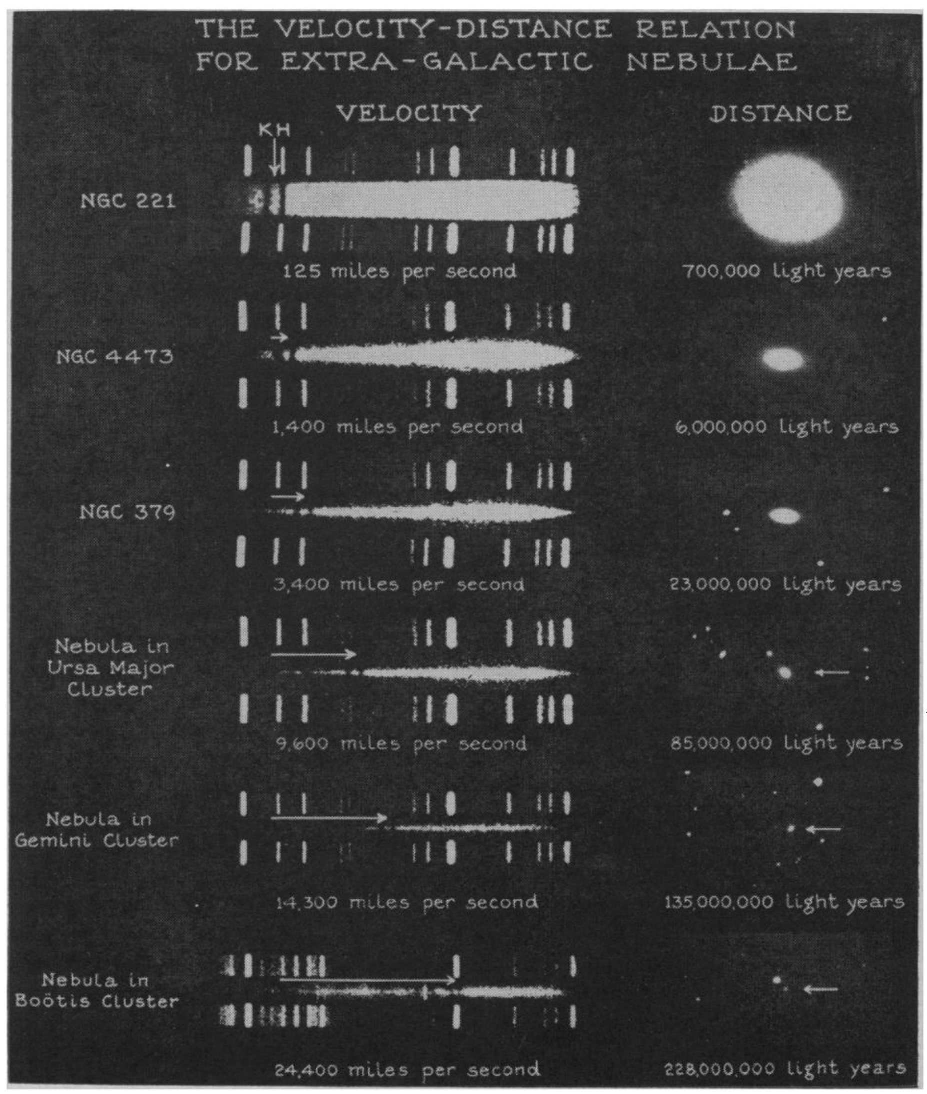


Fig. 3. Velocity-distance relation for galaxies. At right are direct photographs of galaxies arranged in order of distances from the earth; at left are spectra of these galaxies. The arrows on the spectra indicate shift of the H and K lines. [Photographed with the 100-inch telescope]

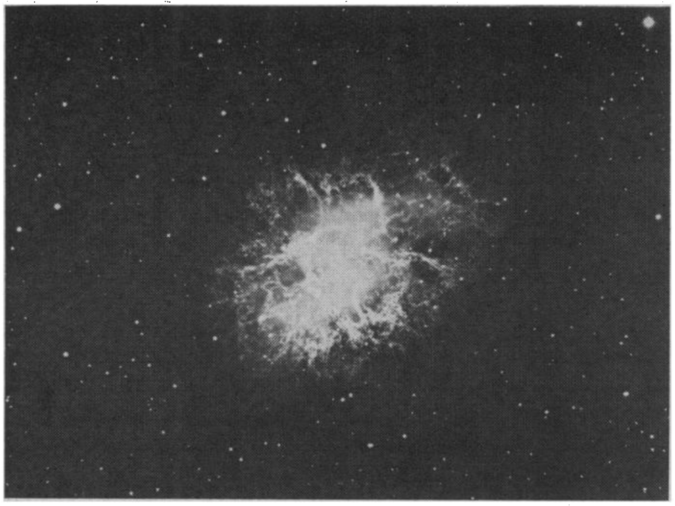
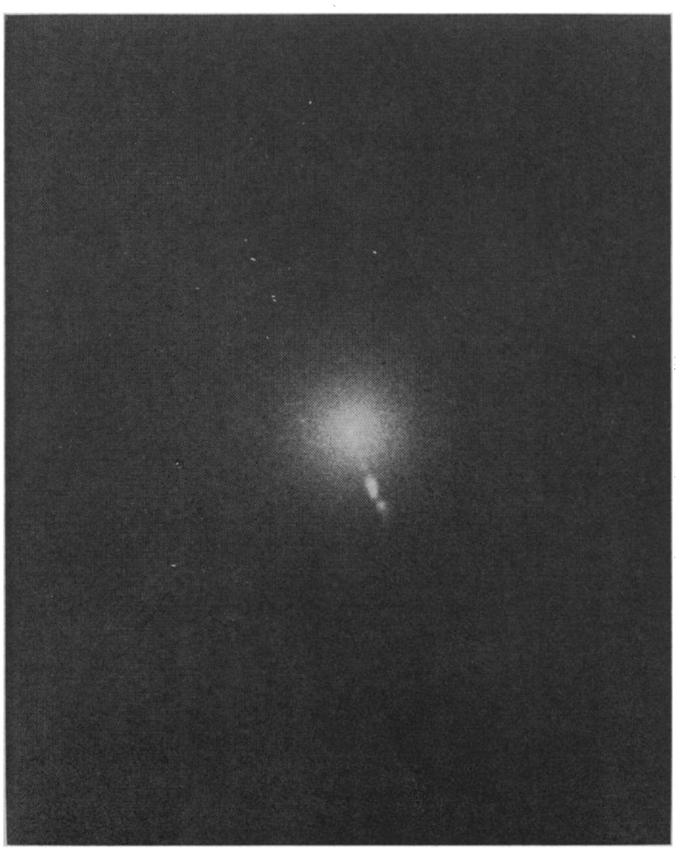


Fig. 4 (left). Remains of the supernova of A.D. 1054 (the Crab Nebula) photographed in red light with the 200-inch telescope. Fig. 5 (right). The peculiar galaxy NGC 5128, which is also a radio source, as photographed with the 200-inch telescope.

that the red shift can be interpreted best as a velocity of recession similar to that characteristic of all distant galaxies. Interpretation on the basis of the usual Hubble relationships between distance and red shift places these objects at such a distance that their absolute brightness is nearly 100 times that of any normal galaxy such as Andromeda.

At about the same time the very detailed study of these radio galaxies made with the California Institute of Technology radio interferometer in Owens Valley showed that the radio sources associated with these objects are often double, the two lobes being placed symmetrically on opposite sides of the optical object and at distances of a few tens or hundreds of thousands of light-years from it, as shown in Fig. 8.

Sandage, in collaboration with Lynds of the Kitt Peak Observatory, then investigated M 82, one of the nearby radio galaxies. They found from spectroscopic observations that the streamers moving out from the nucleus on both sides of the galaxy had at each point a velocity proportional to the distance from the nucleus (see Fig.



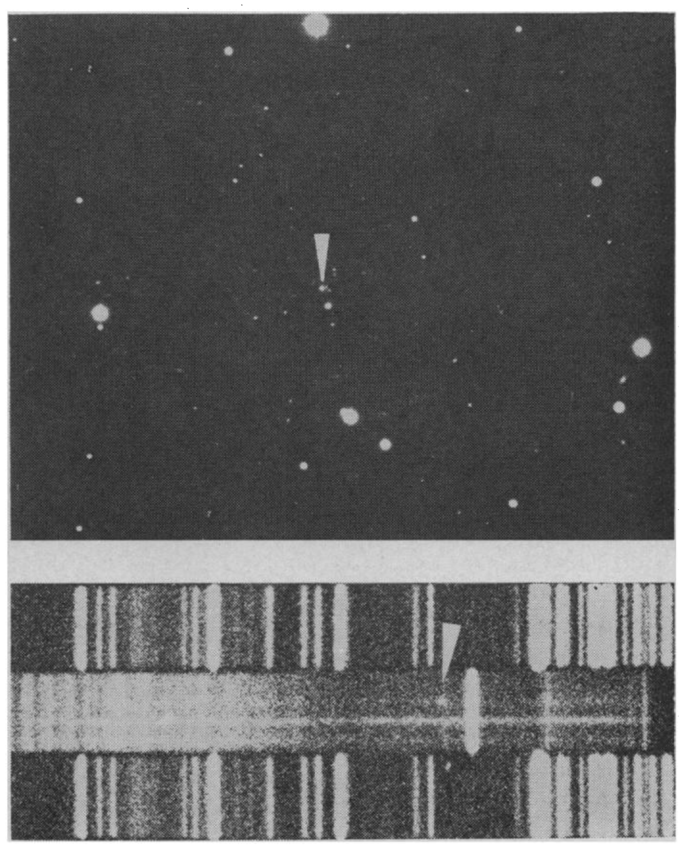


Fig. 6 (left). Galaxy M 87, showing jet of matter, as photographed with the 100-inch telescope. Fig. 7 (right). Radio source 3C295. (Top) Direct photograph; the arrow indicates the radio galaxy. (Bottom) Spectrum; the arrow points to the ultraviolet line (3728 Å), shifted toward the red into the green. [Photographed with the 200-inch telescope]

9). This, of course, indicates that all parts of the material left the nucleus at the same time, about a million and a half years ago.

All these observations point to some enormous release of energy which can occur in the nucleus of a galaxy and which can cause the galaxy to emit energy in amounts as large as 100 times the normal radiation from all the stars of a large galaxy such as Andromeda. At the same time, great numbers of charged particles of very high energy are ejected normal to the plane of the galaxy, giving rise to the pair of radio sources, and large quantities of matter are thrown off, producing the effects studied by Sandage and Lynds. Obviously an entirely new mechanism of tremendous power has been discovered. Present indications are that a substantial fraction of the several thousands of known radio sources are galaxies undergoing an explosion of this type. This is therefore not a rare phenomenon, particularly when we consider that the lifetime of the explosion, perhaps a few million years, is very short in comparison with the life of a galaxy. Although it is too early to propose any definite theory about the exact mechanisms involved, obviously these events must play a very major role in the evolution of many galaxies.

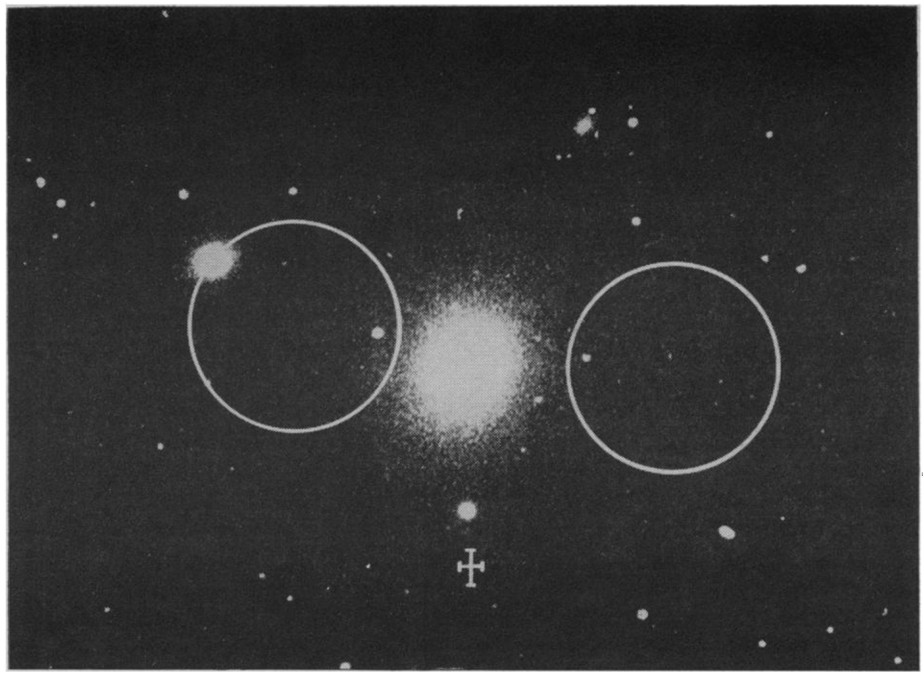


Fig. 8. Relationship between radio sources and galaxy. The double circles show the location of the radio sources with relation to the galaxy between them.

Implications for Cosmology

The objects are also of great importance for the study of cosmology. Since they are up to 100 times as bright as any normal galaxy they can be observed at a much greater distance. Furthermore, owing to their intense activity, these sources emit a large amount of radiation in the far-ultraviolet, especially in the form of emission lines. At great distances the radiation is red shifted up into the easily observable range. Thus is eliminated the difficulty that has set a limit on observations of normal galaxies—namely, that the radiations, which are chiefly in the visual region, are shifted at these great distances far into the infrared, out of the range of sensitive receivers.

For example, during the past few months Matthews and Schmidt have observed a red shift of 54.5 percent in the spectrum of the radio galaxy 3C147 (see Fig. 10). This makes 3C147 the most distant object thus far located. Indeed, its distance is so large a fraction of the radius of the universe that corrections which depend on the cosmological model of the universe adopted are large and uncertain. These uncertainties, in combination with the uncertainties that remain in the distance scale, make it impractical to quote a definite distance in light-years. It is abundantly clear, however, that we are observing with the 200-inch at distances greater by a whole order of magnitude than Hubble's 1940 values for the limit reached with the 100-inch. Thus, owing to the much greater penetration in space of the 200-inch and the several-fold increase in the distance scale, we now discuss these distances in billions of light-years, whereas Hubble listed his most distant objects in hundreds of millions of light-years.

Of far greater significance than the increase in distance is the fact that, in extending the observations to a large fraction of the radius of the universe, we have reached the region where it should be possible to differentiate observationally among the various cosmological models.

The second and third of Hale's examples of problems for the 200-inch were the evolution of stars and the constitution of matter. The two programs have developed together, and the advances in one field have provided the keys to the problems of the other.

Stellar Evolution

On the observation side, the first major step in the investigation of stellar evolution was taken by Baade in his observations of the Andromeda galaxy from Mount Wilson during World War II. Thanks to the blackout in Los Angeles, the skies above Mount Wilson were dark, and Baade was able to make a long series of photographs of the galaxy in light of different colors. He noted that in the spiral arms the brightest stars are blue, and that they are accompanied by extended luminous clouds of gas. In the nuclear region, however, the gas clouds are missing and the brightest stars are red.

Baade correctly guessed that the bright blue giants in the spiral arms have recently condensed from the gas clouds and hence are very young stars, and that the red giants in the nuclear regions are old stars. He designated the young stars as population I, since they have characteristics similar to those of the stars in the neighborhood of the sun, which is located in one of the spiral arms of the Milky Way. He called the old stars population II.

At the time Hale wrote his article the mechanism of the production of the enormous energy radiated by the stars was not known, and, of necessity, theories about the evolutionary development of a star were the crudest speculations. By the late 1930's, how-

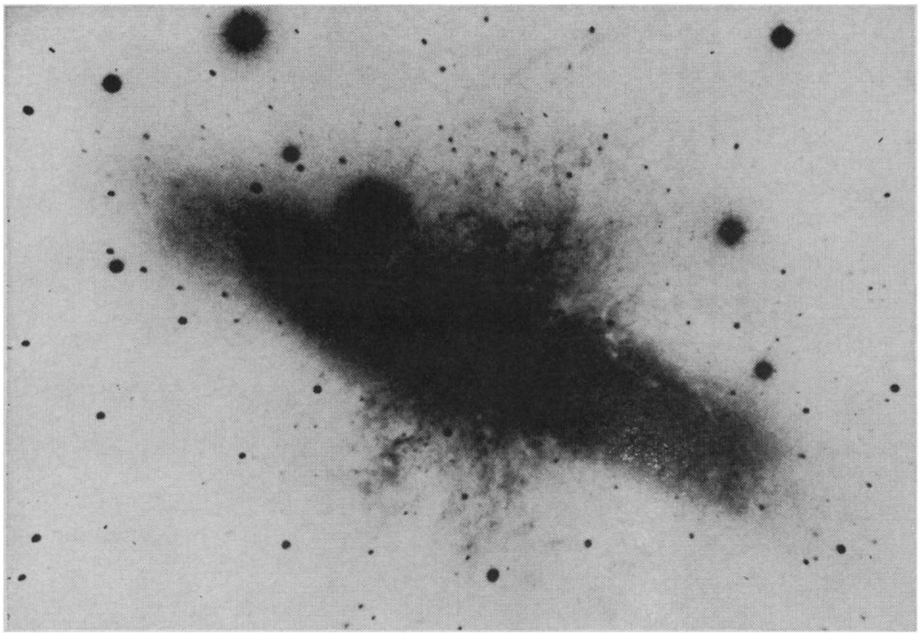


Fig. 9. Radio source M 82 with filaments streaming out from the nucleus, as photographed with the 200-inch telescope (negative print).

ever, advances in nuclear physics had made it clear that the primary source of the energy is the transformation of hydrogen into helium in the hot core of the star. On this basis theories of stellar structure were developed which showed that, if a large mass of gas, chiefly hydrogen, condenses into stars of various masses, certain relationships must hold between the luminosity, the surface temperature, and the mass. The relationships are shown in the curve at left in Fig. 11, where the luminosity is plotted against the surface temperature, as indicated by the color. The point on the curve where a given star is located is fixed by its mass, the luminosity being proportional to about the third power of the mass.

Until the hydrogen fuel in the stellar core drops to a certain critical value the stars continue to have the properties shown by this curve, which is known as the main sequence. Since the rate of radiation goes up much more rapidly than the mass of available fuel, the very bright massive stars use up their hydrogen much sooner than the smaller stars do. The theory of stellar interiors predicts that when the fuel is exhausted the surface of the star will cool off but the star, at the same time, will expand so much that its brightness will increase. In other words, in the diagram (Fig. 11) the star moves off the main sequence up and to the right. The star remains in the expanded red stage for a relatively short period, then its luminosity drops and its surface temperature rises; it often passes through a stage of rapid fluctuation in brightness, with a period of a day or less. Finally the star ends up as an exceedingly dense white dwarf in the region to the left of the main sequence.

An old group of stars would therefore have the distribution shown at the right in Fig. 11. Here the brightest stars are red, corresponding to Baade's population II. Furthermore, as the group of stars grows still older the point of break-off from the main sequence moves down lower on the diagram. If, therefore, the magnitudes and colors of a homogeneous group of stars are measured and plotted on such a diagram, the position of the break-off point indicates the interval since the original condensation of the stars occurred, and thus the age of the group. The development of precise photoelectric photometry shortly after the war made this type of measurement feasible.

To establish a precise curve it is necessary to measure the magnitude in two or more colors for each of a few hundred stars in the group or cluster of stars under investigation. During the past 15 years several scores of globular and galactic clusters and other groups of stars have been observed in detail by Sandage, Baum, Arp, Eggen, and others. A comprehensive pattern of the ages of various parts of our Galaxy and of several nearby galaxies has been developed. Ages from a million years for the youngest galactic clusters up to 12 billion years for the oldest globular clusters have been found. Figure 12 is a composite graph of a number of the observed curves. The ages are in satisfactory agreement with the age of the universe as estimated from cosmological investigations. The

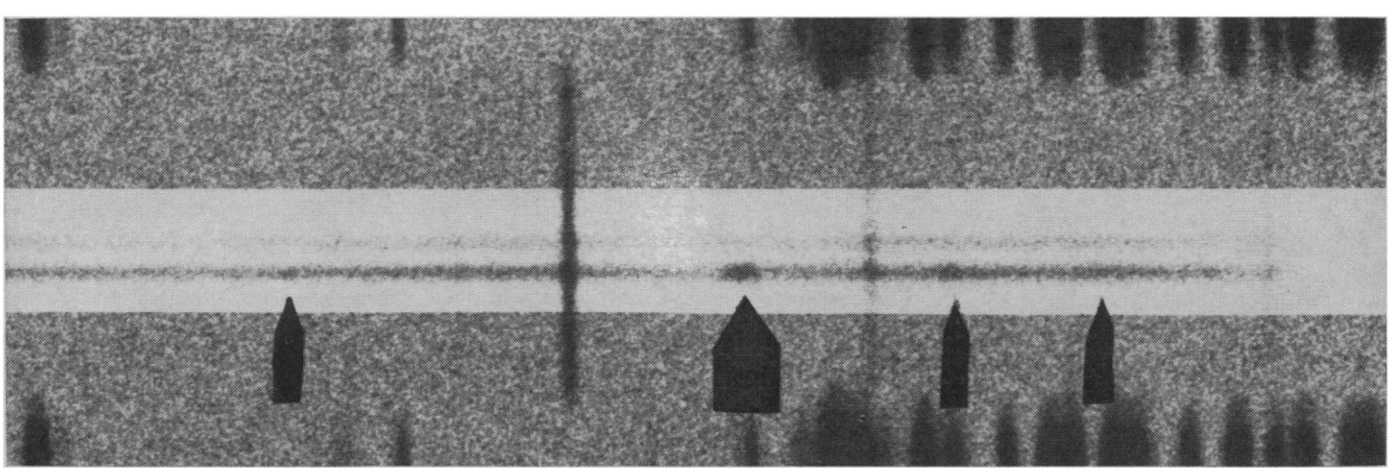


Fig. 10. Spectrum of the radio galaxy 3C147, showing the largest red shift thus far observed. The broad arrow points to a line in the ultraviolet at 3728 angstroms, and the narrow arrows point to other lines, all shifted toward the red by an amount equal to 54.5 percent of the wavelength. [Photographed with the 200-inch telescope]

age of 5 billion years for the sun and solar system, as calculated by other procedures, fits this pattern satisfactorily.

A very effective joint attack on the problems of elucidating the detailed mechanisms by which the stellar evolution occurs, especially in its later stages, and the simultaneous changes that occur in the chemical composition of the star as it grows older, has been made through very close cooperation between the nuclear physicists at the California Institute of Technology and the Observatory staff. Shortly after the war William Fowler of the Institute physics department became interested in the nuclear transformations that may occur under the conditions of temperature and pressure that exist in stellar cores. The experiments and theoretical studies of Fowler and his collaborators have provided much of the physical basis for the theories of stellar evolution. In a parallel large project supported by the Air Force Office of Scientific Research, Greenstein and his collaborators have used the very fast and efficient spectrographs of the 100-inch and 200-inch telescopes to make detailed quantitative chemical analyses of large numbers of stars of different ages and evolutionary histories. From the studies the following picture of the evolutionary history of a star has been developed.

The gas clouds from which the star condenses are made up chiefly of hydrogen. As the mass of hydrogen condenses into the star its core is heated to a temperature of the order of 10^7 degrees Kelvin. At this temperature hydrogen is slowly transformed into helium by one or both of two possible mechanisms. Each kilogram of hydrogen transformed into helium produces an amount of energy equivalent to the combustion of about 20,000 metric tons of the best coal. While this transformation of hydrogen continues the star remains stable, with properties corresponding to those of stars on the main sequence. When the hydrogen fuel in the core approaches exhaustion, the star moves off the main sequence and the core heats to about 100 million degrees. At these temperatures the helium atoms, which are now the chief constituent of the core, can react to form carbon, nitrogen, oxygen, and neon. These reactions also liberate a number of neutrons which can combine with the atoms present to form the heavier elements, such as iron. As the reactions continue, the core tem-

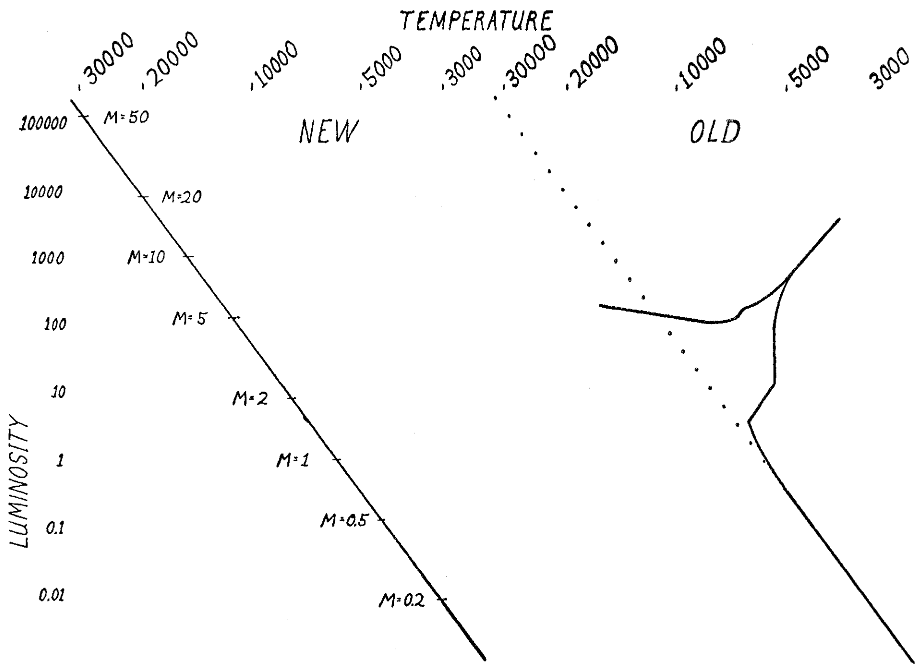


Fig. 11. Curve at left (the main sequence) shows relationship between luminosity, surface temperature, and mass of stars while they are burning hydrogen. Curve at right shows the relationships after the more luminous stars have exhausted their hydrogen fuel.

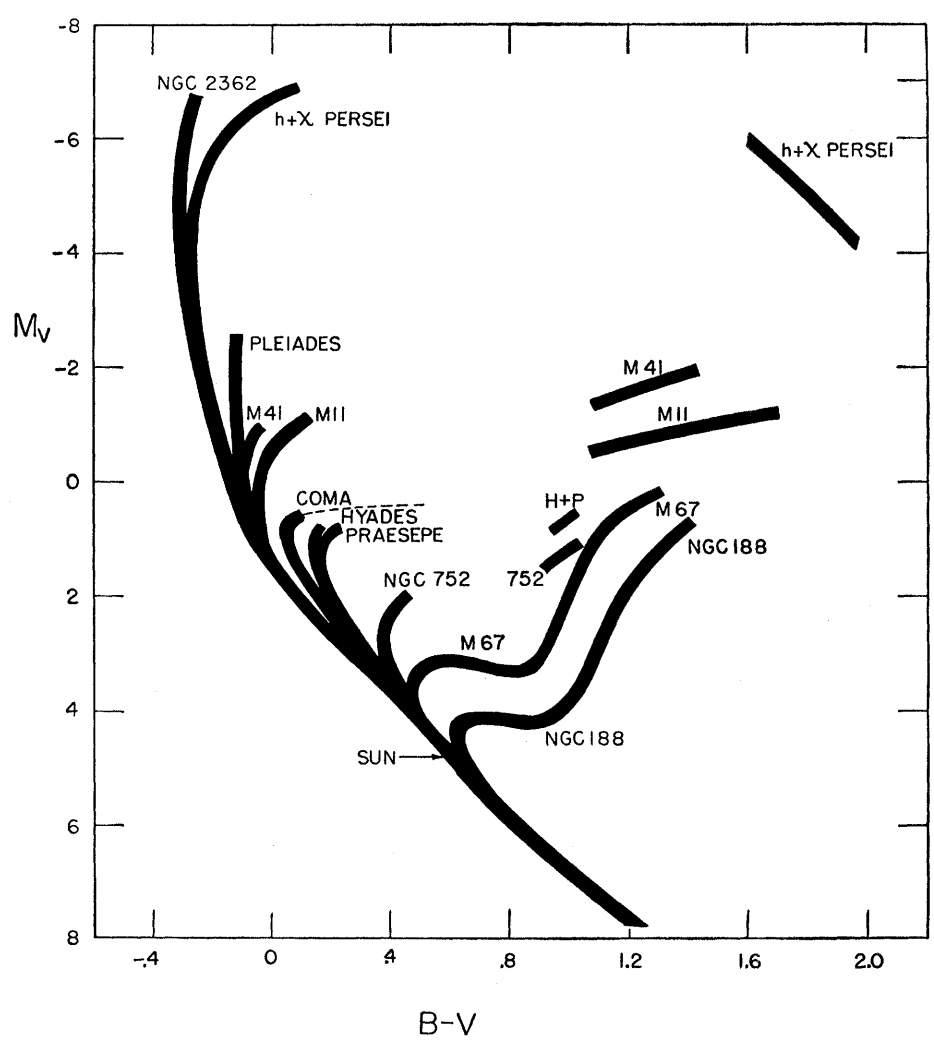


Fig. 12. Composite graph of observed curves for a number of star clusters, showing the relationship between luminosity and surface temperature as indicated by color.

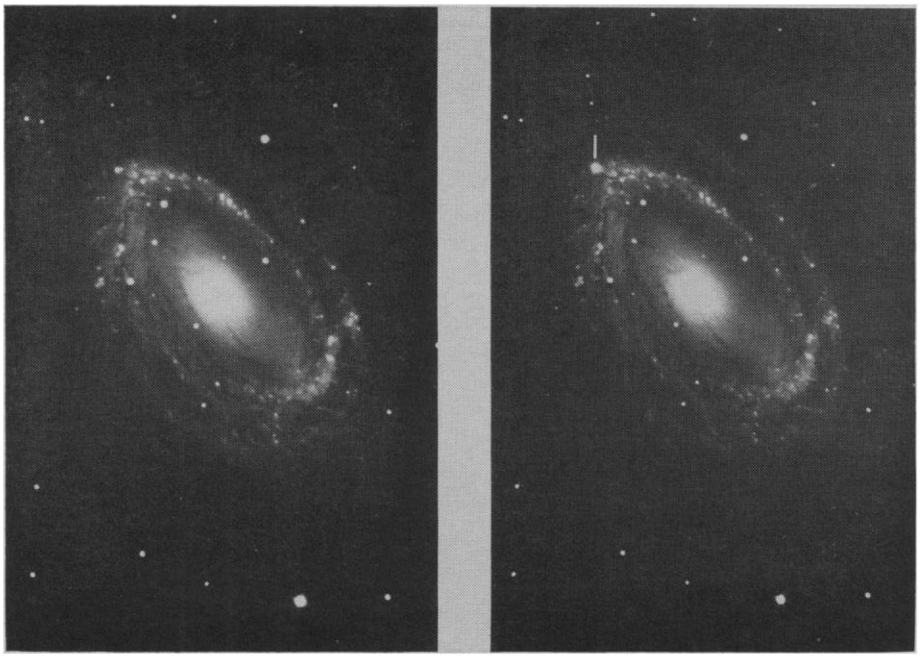


Fig. 13. (Left) Photograph of the NGC 4725 galaxy before the appearance of the supernova; (right) the same galaxy after appearance of the supernova.

perature may eventually increase to a few billion degrees. In the more massive stars the reactions, because of the star's gravitational instability, may eventually proceed explosively, being completed in a matter of hours or even seconds. This is presumably the cause of supernovae, in which, for the period of a few weeks after the explosion, the star emits as much light as all the billions of normal stars in a whole galaxy (see Fig. 13). During the explosion a substantial fraction of the mass of the star is thrown off into space with a velocity of thousands of kilometers per second. In stars of smaller mass these reactions normally proceed more slowly, taking millions of years to reach completion. Even in these smaller stars, as Deutsch has shown, some of the material of the star is slowly blown off into space.

Stellar Composition

The spectroscopic observations show that all stars contain a small amount of the heavier elements, like calcium and iron. Since the heavy elements cannot be formed in the star until long after it has moved off the main sequence, these elements must have been present as an impurity in the hydrogen clouds that condensed into the star. Recent quantitative measurements do show, however, that the heavy metals are much more abundant, often by a factor of 100 or more, in young or moderate-age stars, like the sun, than they are in very old stars, such as those in certain globular clusters that condensed very soon after the formation of the galaxy. Presumably part of the material that condensed into the younger stars had already passed through one or more earlier generations of stars, during which the metals were formed, and was then blown off into space to mix with the uncondensed hydrogen.

In addition to these gross variations in the ratio of all heavy elements to hydrogen, many anomalies in the abundances of individual elements such as lithium, beryllium, carbon, nitrogen, and phosphorus have been observed and measured in a number of peculiar stars. The mechanisms that might have produced such anomalous abundances have been investigated in great detail by Fowler's group.

The supernovae explosions have been another subject of extensive study. In one project, under the supervision of Zwicky, a monthly patrol for discovery of the outbursts has been maintained. Several score supernovae have been found, and their light curves and spectra have been followed by various observers.

Other Investigations

As was predicted by Hale in 1928, these have been the three major fields of research with the 200-inch telescope. Investigations have also been made in numerous more specialized fields; limitations of space permit mention of only two or three.

One of Hale's most important discoveries in astronomy was the finding of localized magnetic fields in sunspots—the first time magnetic fields had been observed outside the earth. In the late 1940's Horace Babcock initiated a search for magnetic fields in other stars. Large and often variable magnetic fields that evidently covered a substantial fraction of the stars' surface were discovered. More than a third of the several hundred stars that have now been examined show evidence of such fields. In one, a magnetic field of more than 34,000 gauss was measured.

Finally, closer to home, a number of important observations have been made of bodies in the solar system. During the Mariner II flyby of Venus in December 1962, Murray made infrared observations with the 200-inch paralleling those obtained from Mariner II. The results secured with the telescope were much more extensive than those obtained from the spacecraft and on one night showed a point of very intense storm activity in the atmosphere of Venus. A year ago Münch, with the assistance of Spinrad and Kaplan of the Jet Propulsion Laboratory, used the 100-inch to make the first positive observation and measurement of the water vapor in the atmosphere of Mars. At the same time these workers observed faint bands of carbon dioxide in the near-infrared. From the strength of these lines relative to stronger lines in the far-infrared, observed earlier by Kuiper, they were able to determine that the total pressure of Mars' present atmosphere is between 1/5 and 1/2 that of earlier estimates. This observation has made necessary a major modification of plans to parachute equipment to the Martian surface.

Summary

The 200-inch telescope has performed much as Hale had hoped and predicted. Most of the programs he listed have made large advances. A very few have run into unforeseen difficulties. On the other hand, important breakthroughs have occurred along lines of which Hale had no inkling. If Hale were with us today I believe he would be content with the results of the great adventure he started.