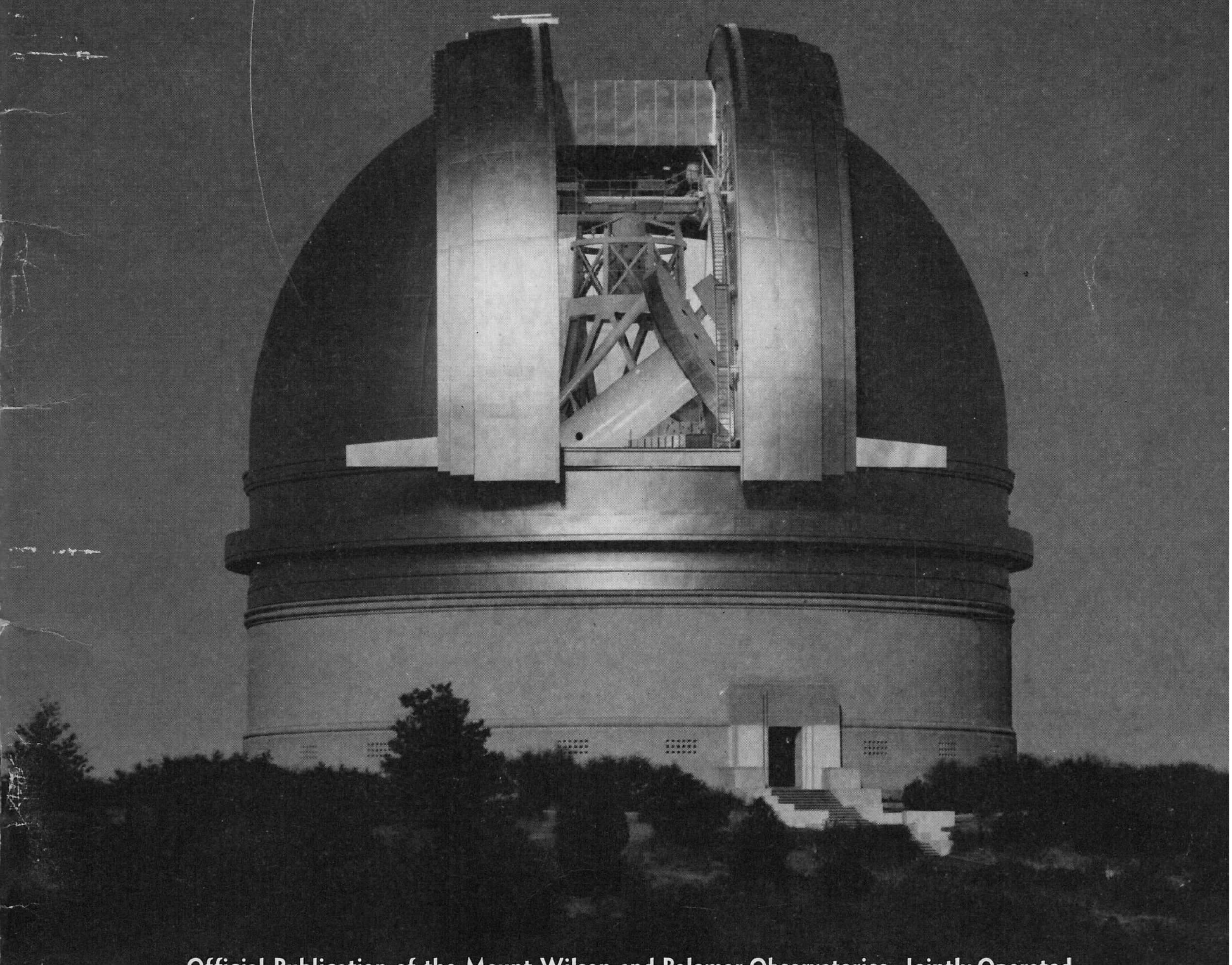
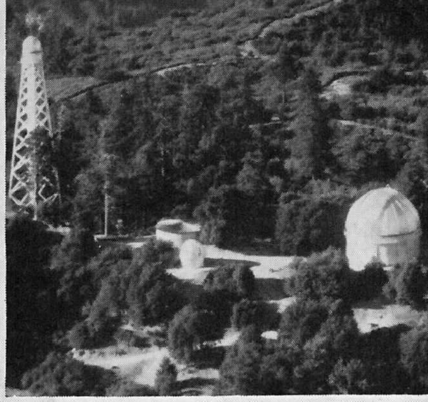
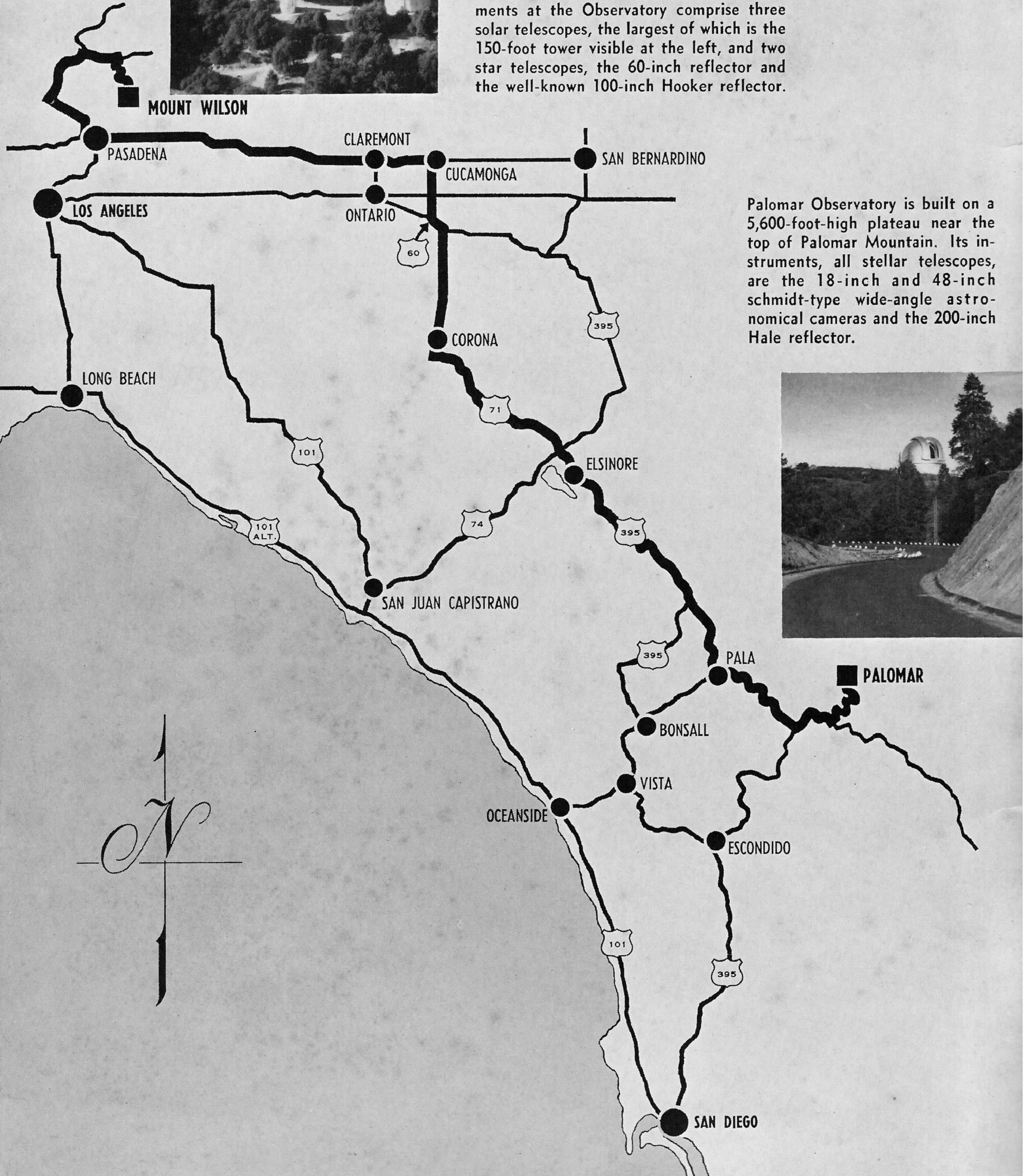
FRONTIERS IN SPACE



Official Publication of the Mount Wilson and Palomar Observatories. Jointly Operated by the Carnegie Institution of Washington and the California Institute of Technology



Mount Wilson Observatory is situated near the summit of a 5,713-foot peak of the San Gabriel range. Astronomical instruments at the Observatory comprise three solar telescopes, the largest of which is the 150-foot tower visible at the left, and two star telescopes, the 60-inch reflector and the well-known 100-inch Hooker reflector.



Palomar Observatory is built on a 5,600-foot-high plateau near the top of Palomar Mountain. Its instruments, all stellar telescopes, are the 18-inch and 48-inch schmidt-type wide-angle astronomical cameras and the 200-inch Hale reflector.

David I. Davis

Mount Wilson and Palomar Observatories

The Mount Wilson and Palomar Observatories are situated on two Southern California mountains: the one, Mount Wilson, about 30 miles by road north of Pasadena; and the other, Palomar Mountain, about 130 miles to the southeast.

The two observatories, together with the administrative and research centers in Pasadena, are operated jointly by the Carnegie Institution of Washington and the California Institute of Technology in a broad, coordinated program of astronomical research. It is because the two observatories take part in this one unified program that both are included in this one book. It would be impossible to talk about the past, present, or future of one without reference to the other.

Both observatories are largely the result of the lifework of one man: the astronomer George Ellery Hale.

Front Cover: The 200-inch Hale Telescope and Dome on Palomar Mountain, by moonlight

Night view from the top of Mount Wilson.

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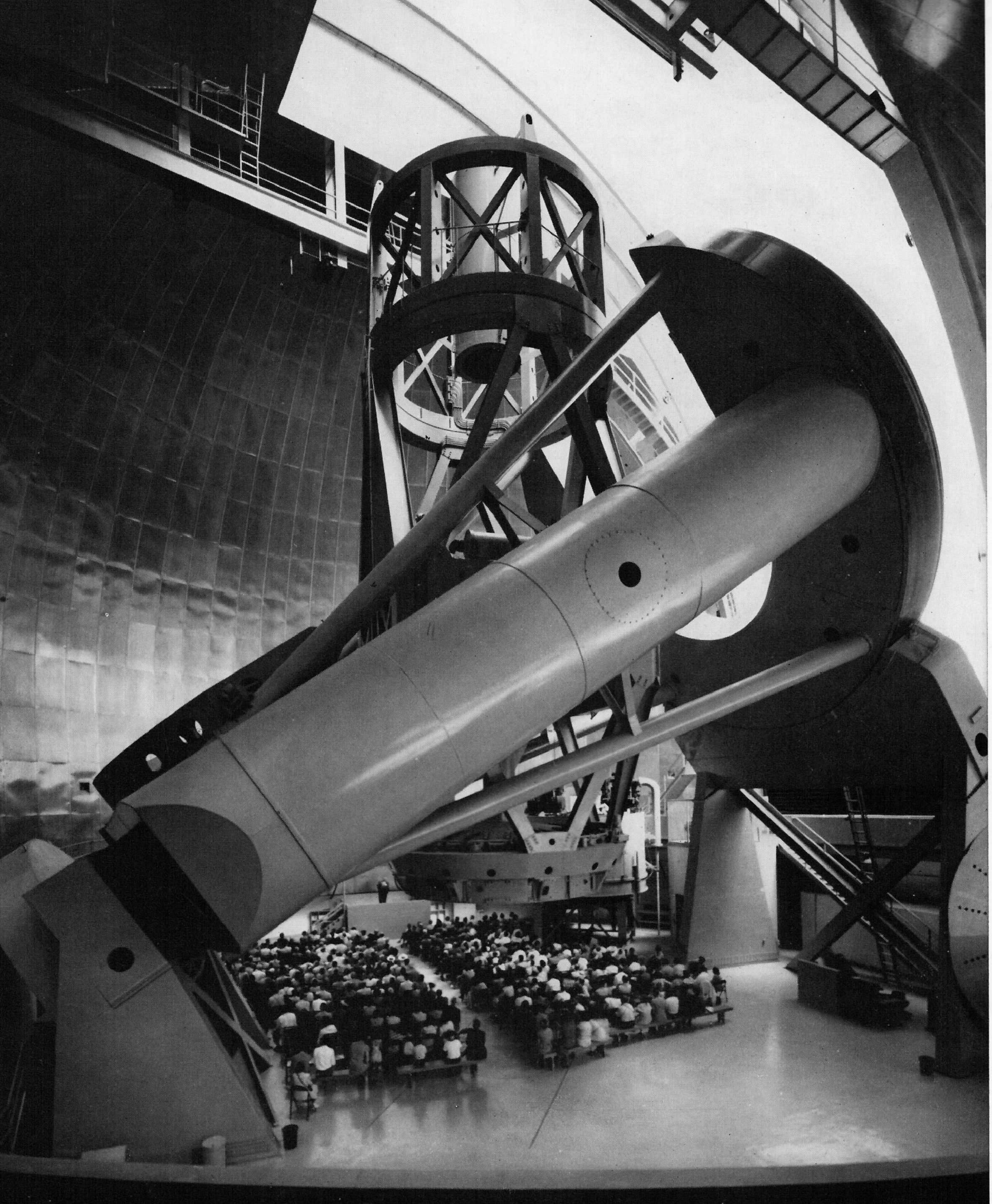
Additional copies of this book can be ordered from the Bookstore, California Institute of Technology, Pasadena, California, 65 cents postpaid.



The 200-inch Hale telescope on Palomar Mountain can photograph celestial bodies clear out to a distant and still-unnamed star-system perhaps a billion light-years — or 6,000,000,000,000,000,000,000 miles — away. In its range lie answers to some of the most basic questions of this age: When and how was our universe born? What is happening to it now? What is its future?

Astronomy and Its Tools

It was a telescope that provided Galileo with observational proof that the earth was not the center of the universe.

It was a telescope that provided the critical tests of Newton's laws of motion, laws that were learned from moons and planets but that have since been applied to every mechanical device from a sewing-machine to a battleship.

It was a telescope that, by detecting a minute effect of the sun on the light from a distant star, offered one of the most decisive experimental proofs that Einstein's theories of relativity were correct.

It was a telescope that revealed the surprising fact that our Milky Way system, which we grandiosely call "ours" because our sun is one of the billion-odd stars that populate it, is not unique. There are millions of systems like the Milky Way scattered through space.

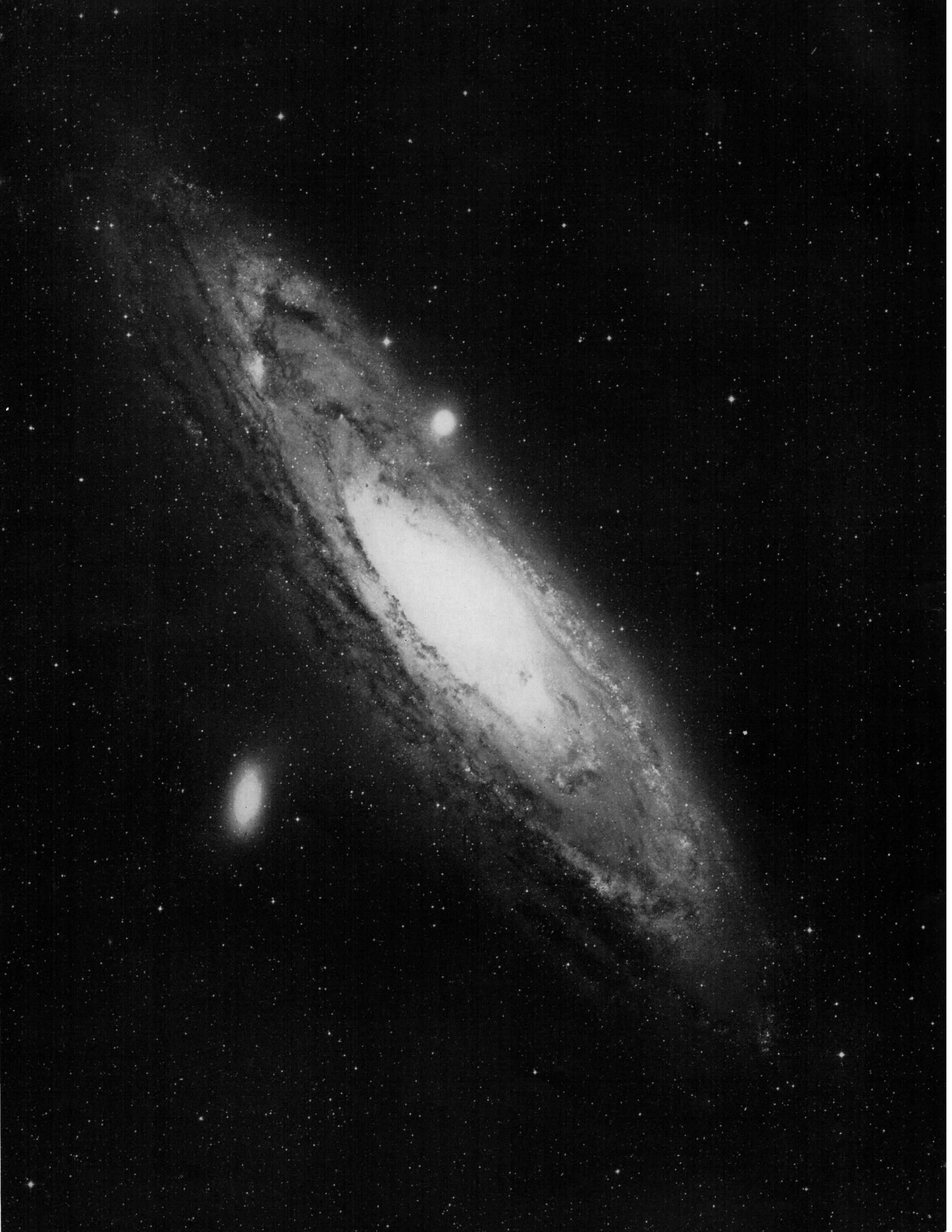
It will be a telescope that will bring us knowledge of these other "island universes," knowledge essential to an understanding of just what this cosmos is.

Telescopes are astronomy's tools. And the bigger a telescope is the more effective it is. Therefore, ever since the days of Galileo, scientists have been building bigger and bigger telescopes, until today they have at their command instruments like the 200-inch Hale and the 48-inch schmidt-type telescopes on Palomar Mountain and the 100-inch Hooker telescope on Mount Wilson.

These great telescopes represent some of the most significant engineering achievements of our time (the 200-inch telescope weighs as much as a freight locomotive and yet is made with all the precision of a fine watch). They can help to answer some of the most fundamental questions of the universe, questions in which every man and woman is interested at least to some degree. Because of these things, giant telescopes such as those of the Mount Wilson and Palomar Observatories have become an integral part of modern American culture.

The Observatories were built, and are now operated, with private funds; and for many technical reasons arising out of the delicate nature of the telescopes themselves they must preserve some privacy. You cannot climb around a big telescope as you can around Pike's Peak. Nevertheless, these Observatories, by their position in the world of science and culture, owe a debt to the public, a debt of explanation: What are they? Why and how were they built? Above all, what are they doing?

This booklet is an attempt to discharge that debt, at least in part, by answering these questions. It offers information about the big telescopes themselves—their histories, accomplishments, capabilities—and a chance to inspect at first hand the photographs that the astronomers who use the telescopes are taking.

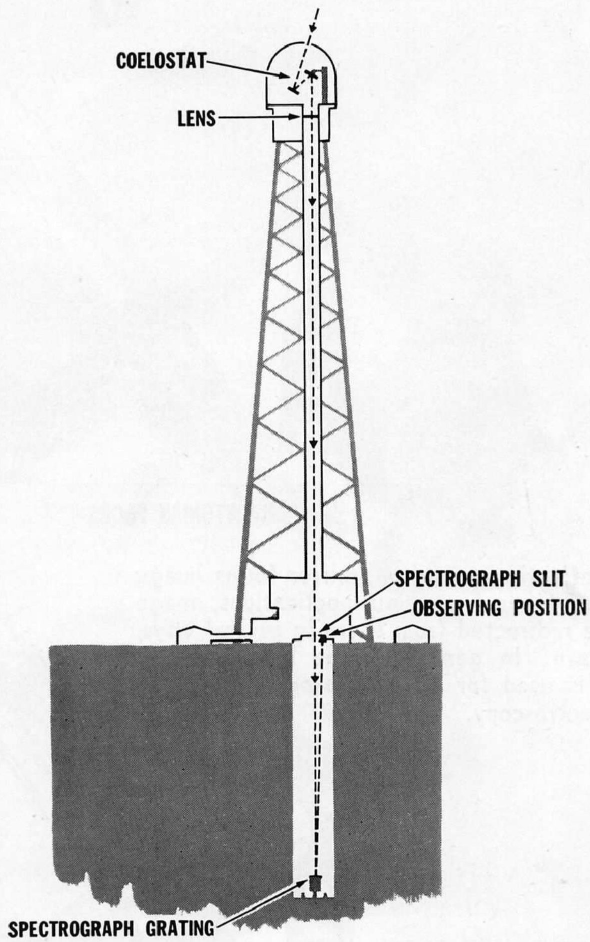


What Is a Telescope?

The place of the Mount Wilson and Palomar Observatories in the astronomical scheme of things stands out most clearly against a backdrop of basic information about telescopes and astronomy in general. So, to start with, consider the telescopes.

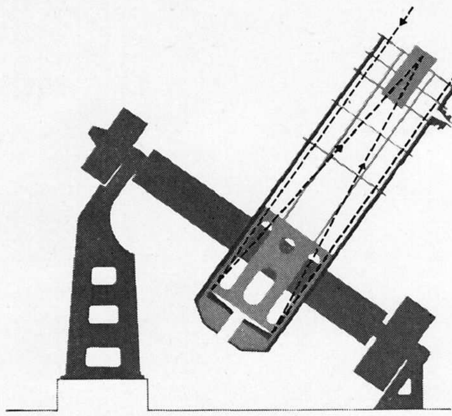
Solar telescopes, as their name indicates, are designed for the study of the sun. The sun offers plenty of light; the problem is simply one of getting a big enough image of the sun. The answer lies in focal length, which is the distance between the lens or mirror that forms the image, and the film, paper, or spectrograph that receives it. The longer the focal length, the bigger the image. That is why the three solar telescopes on Mount Wilson are long, one of them requiring a 170-foot tower with a 75-foot pit beneath it.

The upper end of a solar telescope includes two mirrors which reflect the sun's light to the telescope's lens. The lens then focuses the light in a room at ground level where the image is studied. One of the two mirrors, called the coelostat, turns to follow the sun as the earth rotates.

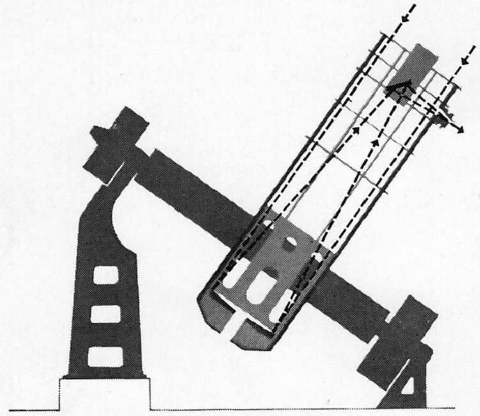


Coelostat mirror follows sun. Lens forms image of sun at observing position. Spectrograph, when used, passes light down to grating which sends its component colors back to observing position.

This spiral nebula in the constellation Andromeda first introduced to man, through the agency of the 100-inch telescope on Mount Wilson, the unimaginable immensity of his universe. Just visible to the naked eye, it contains billions of stars comparable to our sun, and is about as big as our *own* system — the one we call the Milky Way, which includes everything else the unaided human eye can see from the northern hemisphere. The light that made this photograph took about a million years to travel from the Great Nebula in Andromeda to the 48-inch schmidt.

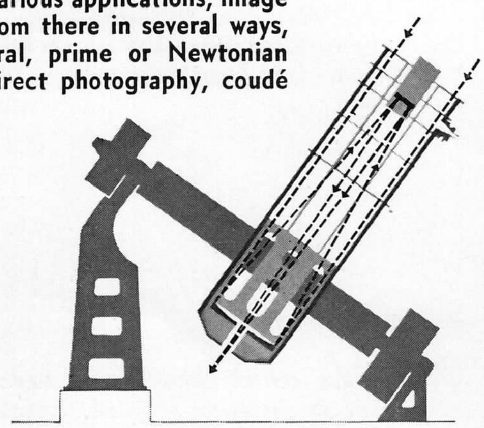


PRIME FOCUS

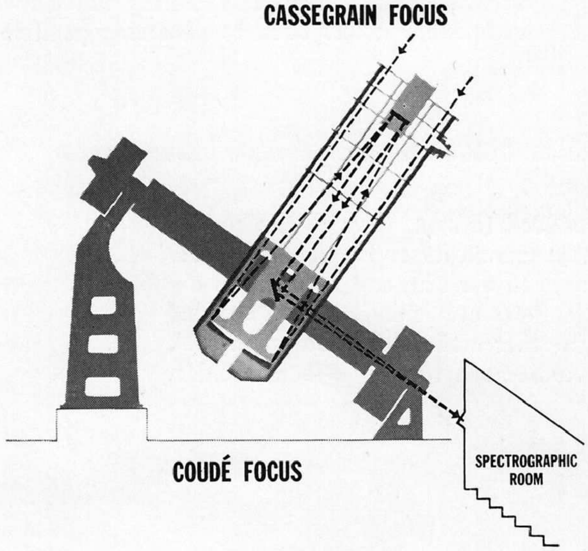


NEWTONIAN FOCUS

In a reflecting telescope, mirror forms image at prime focus. For various applications, image can be redirected from there in several ways, as shown. In general, prime or Newtonian focus is used for direct photography, coudé for spectroscopy.



CASSEGRAIN FOCUS



COUDÉ FOCUS

Early star telescopes, Galileo's, for example, were refracting. Like the lens of a camera, the lens of a refracting telescope bends incoming light to form an image. But no lens can bring to the same focus all of the colors that go to make up a star's light so that the resulting image lives up to the demands of modern science. Also, any lens weakens the light that passes through it. In general, therefore, modern telescopes of high power are of the reflecting, rather than of the refracting, type.

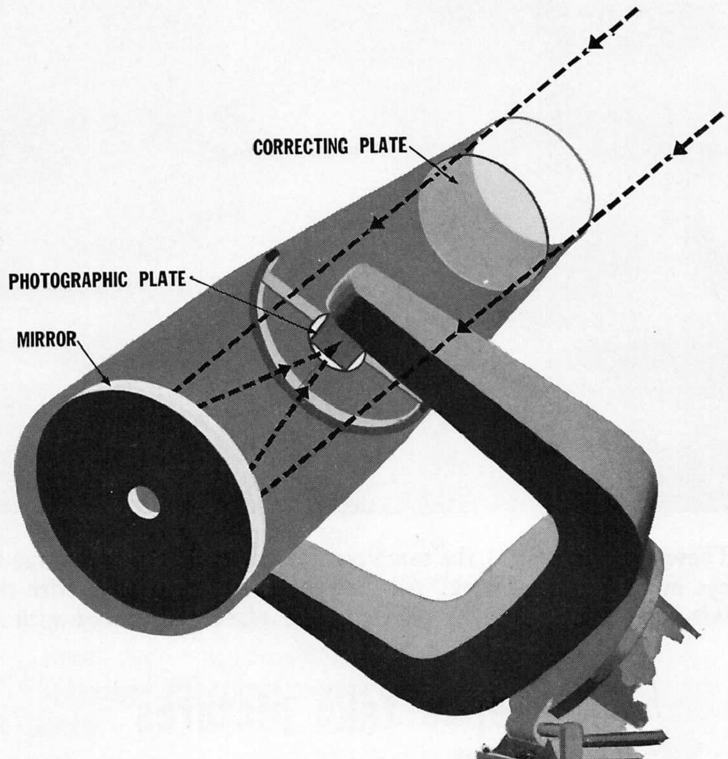
Reflecting telescopes rely on a mirror, instead of a lens, to gather the light and form an image. Mirrors are not only easier to make in large sizes than lenses, they are also able to bring to the same focus all the colors of the spectrum. Furthermore, reflection weakens a star's light less than passage through thick lenses does. The curved front surface of the mirror of a reflecting telescope catches incoming rays of light and reflects them back in the direction from which they came, bringing them to a focus at a point many feet from the mirror, the exact distance depending on the mirror's focal length.

The job of a reflecting telescope is to collect light—light that is often very, very faint—from a distant object in space and concentrate it to such an extent that it can register on a photographic emulsion. The bigger the mirror, the greater the amount of light it can collect. In building a reflecting telescope, therefore, the emphasis is not on increasing the focal length, which would increase the size of the image, but on increasing the diameter of the mirror. Hence, the giant mirror of the 200-inch Hale telescope.

For reasons that lie deep in the fundamental laws that govern the behavior of light, the large reflecting telescopes on Mount Wilson and Palomar have limited angles of view. A big telescope may be unable to photograph more than a part of the moon's surface at one time, for example. In fact, the farther a telescope can "see," the smaller the piece of the celestial sphere it can photograph.

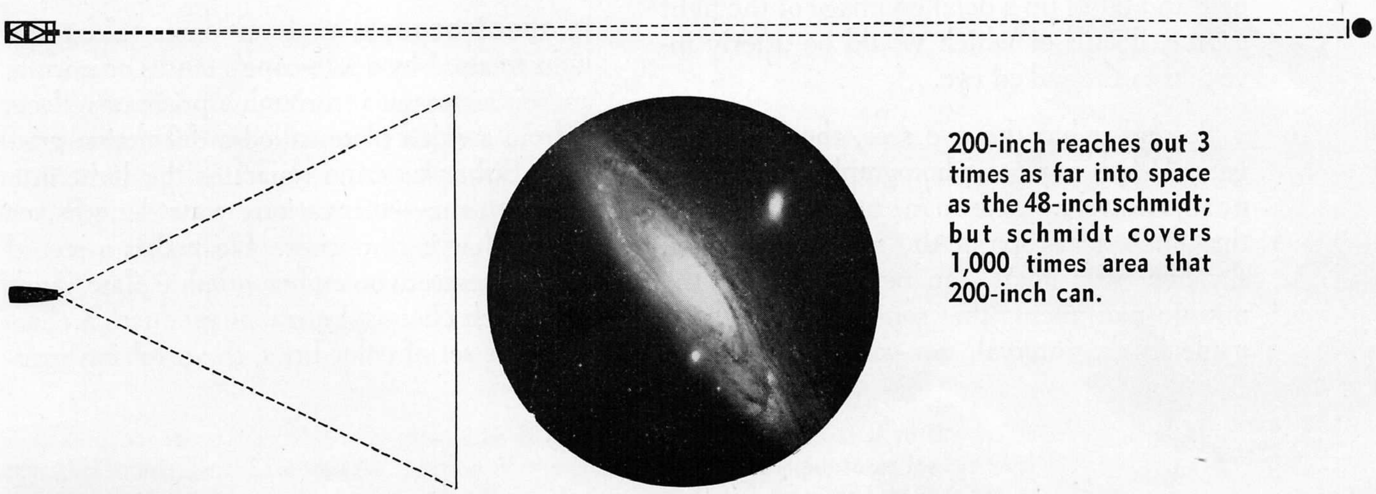
Yet astronomers need, at times, to see more than a pinpoint of space. The question, then, is one of finding some way to "see wide" without sacrificing all ability to "see far." The answer was found, about 1930, by the German astronomer and optician Schmidt.

In a schmidt-type telescope, the incoming light passes through a "correcting plate" before it reaches the mirror. The correcting plate, actually a very thin lens, bends the light rays so that the area of space that appears in sharp focus on the photographic plate is much enlarged. The 48-inch schmidt-type telescope on Palomar Mountain can easily photograph an area equal to that of 200 moons at one time—though, of course, its range into space is only one-third that of the 200-inch.

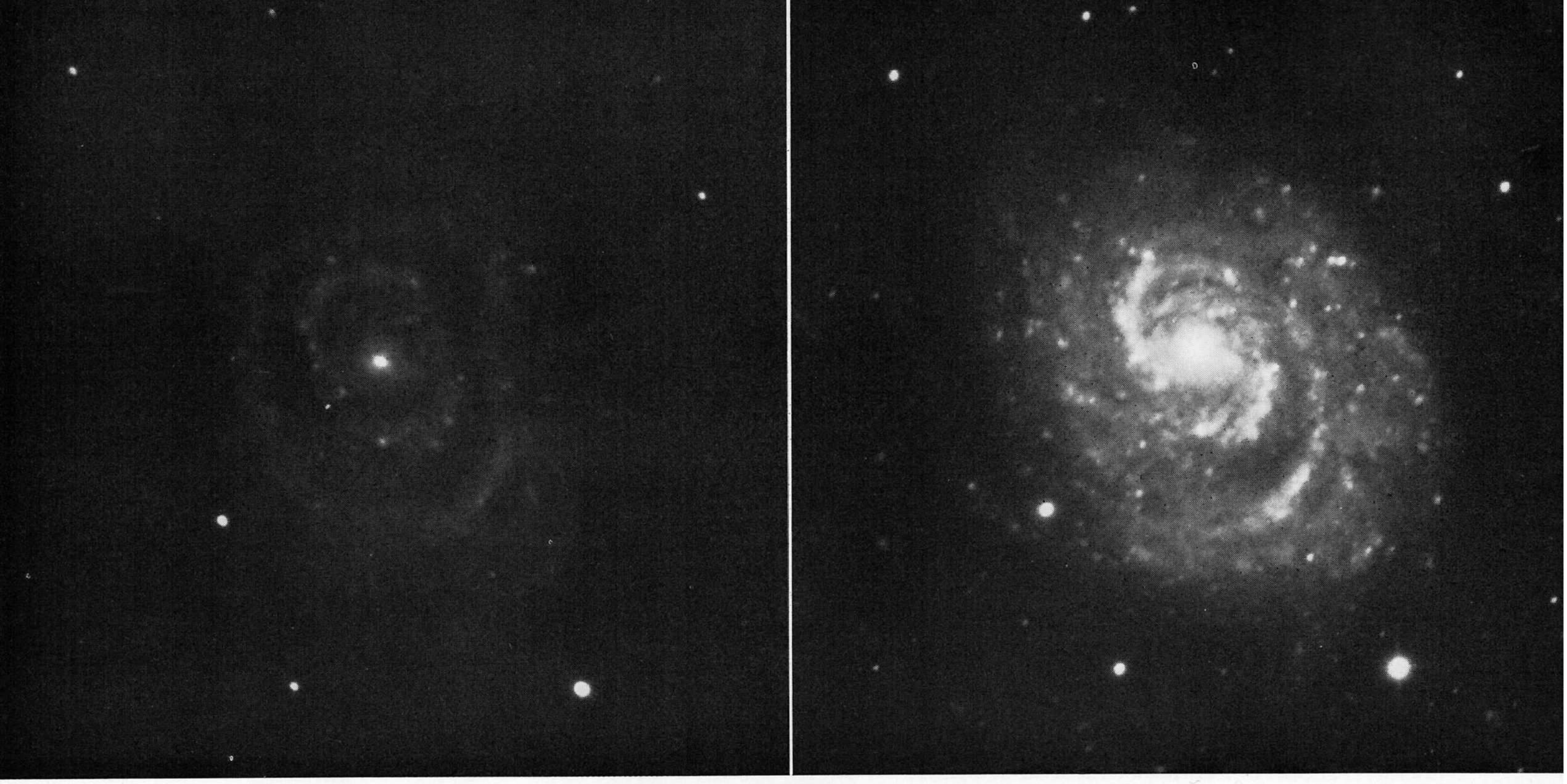


Schmidt-type telescope forms image on photographic plate, has no provision for use by human eye. It is a true camera.

For various reasons, the big schmidt-type telescopes have no provisions whatsoever for use by the human eye. They are invariably used (and often referred to) as cameras.



200-inch reaches out 3 times as far into space as the 48-inch schmidt; but schmidt covers 1,000 times area that 200-inch can.



These two pictures of the same area of sky show the advantage that photography has over the human eye in astronomical work. All that the eye can see, even with the 200-inch telescope, appears in the left-hand photo; what a photographic plate can record with the telescope appears at the right.

Telescopes take pictures

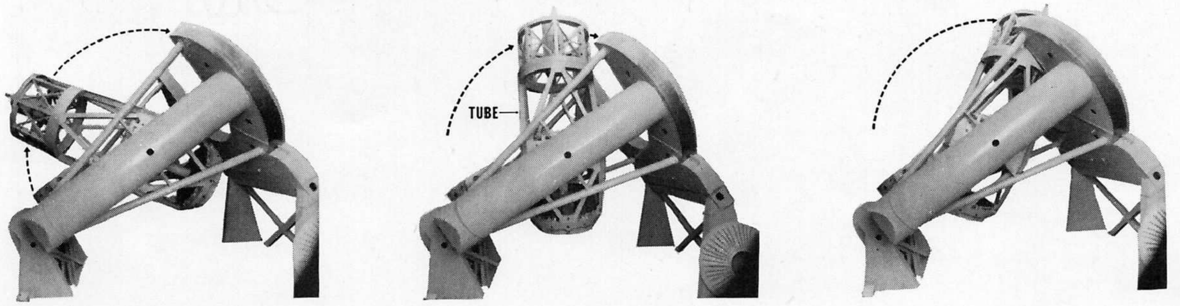
It was just said that schmidt-type telescopes are really cameras. As a matter of fact, every big astronomical telescope is a camera.

In the first place, photographic plates are so much more effective than the human eye that using the eye is a waste of time and telescope. Everything that an eye can see with a telescope, a plate can record in five minutes; from there on (and you can expose a plate for several hours, if you choose) the plate "sees" more. It can accumulate the hour-long effect of light utterly invisible to the human eye, and build up a detailed image of the light source, details of which would be utterly invisible to the naked eye.

Second, what the eye sees, the brain forgets. What a plate photographs, it records permanently. One man, taking two looks through a telescope at the same area of the sky five years apart, can never calculate the minute movements that some stars will have made in the interval, nor can he be sure to notice the appearance of a new bright star—a nova—where none was before. Comparing two photographs made five years apart, either job is simple.

Third, direct photography of objects in the sky is only one part of astronomy. A single direct photograph tells little of a star's composition—what chemical elements predominate in it, how hot they are—or of its motion. A spectrogram, however—the photographic record of a star's spectrum—can reveal composition, motion, and many other details.

In spectroscopy, an astronomer takes the light focused by a telescope's lenses or mirrors and either passes it through a prism or reflects it from a ruled plate called a diffraction grating. Either way, he separates the light into its spectrum—the various wave lengths, or colors, that it comprises. He makes a record of this spectrum on a photographic plate. And, since each chemical element produces a characteristic set of color lines, the resulting spec-



ROTATION OF TUBE

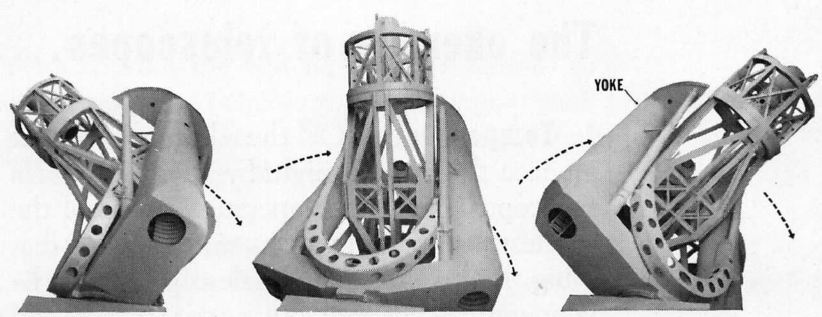
trogram identifies the elements present in the source of the light.

Virtually all that we know about the chemical composition of the stars, including the sun, the spectrograph has taught us. Because temperature affects the lines that an element produces, the spectrograph has also revealed how hot the stars are. And because motion toward or away from the earth also affects the lines—in the same way that motion toward or away from a listener raises or lowers the pitch of a train whistle—the spectrograph has also indicated the speeds at which the stars are moving relative to the observer.

For these reasons, the big astronomical telescopes of today are used not to "look through" but to take photographs; and an important majority of these photographs are not even photographs, in the ordinary sense of the word, but spectrograms made photographically.

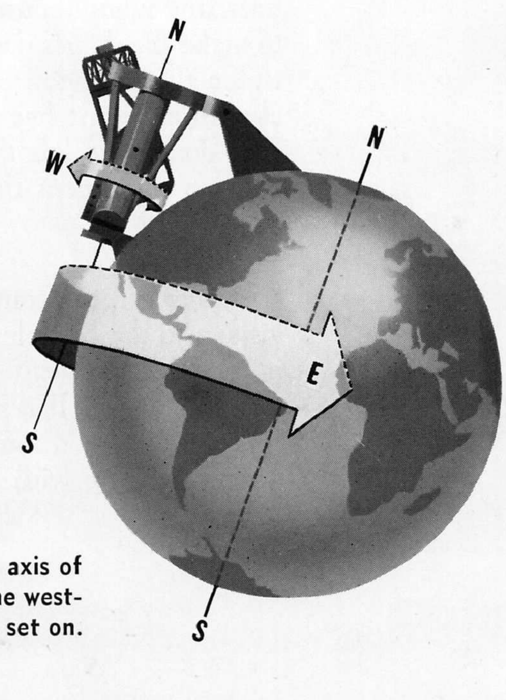
Every telescope must be able to find a star and keep its eye on it. To do this requires both north-and-south and east-and-west motion. The top row of pictures above shows how the north-and-south motion is secured with the 200-inch by tilting the telescope tube in the great yoke in which it is mounted. The lower row of pictures shows how the yoke itself can be rotated to obtain the desired east-and-west motion.

To find the star that he wants to photograph—that is, to "set" the telescope on it—the astronomer uses a combination of the north-and-south tilting of the telescope tube and the east-and-west rotation of the yoke. This is a delicate operation. The job of "setting" the 200-inch has been compared to aiming a rifle at (and hitting) a rolling penny 20 miles away.



ROTATION OF YOKE

But if the telescope remained stationary after "setting," the earth's west-to-east rotation would very soon sweep it past the star it is set on. Hence, if the telescope is to keep its eye on its object—"track" it, as the astronomers say—it must swing east to west at a speed which compensates for the speed of the earth's rotation. This is accomplished by rotating the yoke which holds the telescope tube. Since the axis of the yoke is parallel to the axis of the earth's rotation—as shown by the diagram below—this east-west motion of the yoke ensures accurate "tracking" of the star. This tracking motion of the yoke is controlled by a very precise clock, driving through motors and gears constructed with a degree of accuracy that even a maker of fine watches would admire.



This diagram shows how the telescope yoke is mounted with its axis parallel to the axis of the earth's rotation. East-to-west rotation of the yoke, therefore, compensates for the west-to-east rotation of the earth, and enables the telescope to "track" the star that it is set on.

The enemies of telescopes

1. Temperature. Of the difficulties that menace the smooth night-by-night work of a telescope, changing temperature is one of the greatest. It probably seems unreasonable that a big, bulky affair like a telescope should be temperature-sensitive; but actually a rapid five-degree temperature change can so distort a mirror like the 200-inch that it forms blurred and ill-defined images.

Temperature is a problem primarily because telescopes must work at night, when the stars don't have to compete with the one star—the sun—that is overwhelmingly brilliant on earth. Since telescopes must work at night, they must not be allowed to warm up during the day; if they get warm, then the sudden inrush of cool night air when the dome is opened distorts the mirror so that observation is impossible.

Fortunately, temperature is the one enemy of telescopes that is most subject to human control. To achieve this control, aluminum paint is put on the domes to reflect the sun's heat, and many thousands of dollars are spent to make the domes double-walled with air between the walls to carry off the heat that the aluminum paint has been unable to reflect. The domes are left throughout the day in a position that keeps the sun from shining on their shutters.

It is to achieve control of temperature that visitors to the big telescopes are offered a visitors' gallery instead of the freedom of the observing floor. If a stream of people poured into the dome through constantly opening doors, bringing with them their own bodily heat plus the midday heat of the great outdoors, then all the aluminum paint and double-walled domes would be inadequate; that night, when cold air came in through the opened dome and struck the warmed mirror, the mirror would go out of shape and become useless for hours.

2. Light. A second powerful enemy of telescopes is, paradoxically, light. A telescope trying to capture on a photographic emulsion the image of a star or star-system millions of light-years away can be completely thwarted by the light of the moon, by the light of a nearby city, or by any lights within the dome. Any of these unwanted light-sources can "fog" a plate and make a picture worthless.

About the moon's light, or that of nearby cities (such as plague the telescopes on Mount Wilson) nothing can be done. Fortunately, spectrographic work is less affected by unwanted light than is direct photography, and this fundamental part of the attack on astronomical problems goes on even at times and places at which other work is impossible.

Lights within the dome *can* be controlled, however. By rigid regulation, the inside of a dome is kept pitch-dark when observation is going on. Those who want to visit a telescope at night, to "see it at work," fail to recognize the fact that if they could see it, it would not be working; the light that made it visible would prevent the telescope's operation.

3. Air. The third and perhaps the most important enemy of telescopes is the earth's atmosphere. Everyone knows what air can do to light if he has ever seen "heat waves" distorting the view over a highway on a hot day. Not everyone realizes that the definition on astronomical photographs is also affected in somewhat the same way. There is so much air between a telescope and space that disturbances are inevitable. Even to human eyes, the stars "twinkle."

The only thing that men can do to counteract the adverse effect of the atmosphere on telescopic "seeing" is to move up out of the lower, denser layers of air and toward the stars. So far, the best he has been able to do in this way is to choose mountain-tops—such as those of Palomar Mountain and Mount Wilson—for his observatories.

The result of atmospheric distortion, in the case of starlight, is a minute but constant motion of the apparent image of the star as the air bends its light rays this way and that. An astronomer is kept busy, while a telescope is automatically tracking his star across the sky, making the minute adjustments necessary to keep the star's image in one place on the photographic plate.

The telescope's domain

Three distinct spheres exist in astronomical work, both historically and practically.

1. Solar system. The first sphere is that which embraces our solar system: sun, planets, moons, asteroids. It is a big system. If you reduced the whole thing in scale so that the earth assumed the diameter of a 25-cent piece, the sun (now a nine-foot ball) would be almost 1,000 feet away, and the distance between our sun and the outermost planet, Pluto, would be well over seven miles. The total diameter of the solar system, on this earth-is-a-quarter scale, would then be some 15 miles.

2. Milky Way. The second sphere of astronomy is the stellar system in which our solar system is all but lost. It includes all of the stars that are visible to the naked eye. The concentrated band of stars that gives our system its name is, as almost everyone knows today, a result of the disk-like shape of the system. Looking toward the rim of the disk from earth, which is inside the disk, the observer sees the "Milky Way." In this Milky Way system are not only stars of many types but nebulae—clouds of gas and cosmic dust.

On the scale that reduced the earth to a quarter, the sun's closest neighbor in this system (the star Alpha Centauri) would be over 50,000 miles from the solar system. This figure is too big to be handy, so you will have to change the scale.

This time, reduce the *whole solar system* to the size of a quarter. In it, a keen eye might detect the sun; the earth would be microscopic.

Now, on this scale, Alpha Centauri would be a paltry 300 feet from the solar system. The whole Milky Way would be a disk-shaped collection of stars and gaseous clouds more than 1,300 miles in diameter.

3. The Universe. Now reduce the whole 1,300-mile-wide galaxy to the size of a quarter and you will discover the third sphere of astronomy. For, floating around in space, from 1 foot to 1,000 feet away, will be other quarters — and dimes and half-dollars — each of them a separate nebula, or "island universe," comparable in size to our own Milky Way system. Each contains millions or billions of stars, many of them like our own sun.

Another way of stating distances in the three spheres of astronomy—the astronomer's way—is in light-years, units based on the distance that light, at its speed of 186,000 miles a second, travels in a year. A light-year is six trillion — 6,000,000,000,000 — miles.

Assuming that a man could travel at the speed of light, it would take him less than one-sixtieth of a second to go from Los Angeles to New York. It would also take him:

Sphere 1, the solar system

a) a second and a quarter to reach the moon,

b) 8 minutes to reach the sun,

c) 5½ hours to reach Pluto, the outermost planet,

d) 11 hours to cross the solar system from one edge to the other;

Sphere 2, the Milky Way

e) 4½ years to reach our sun's nearest neighbor among the stars,

f) 100,000 years to go from one edge of our Milky Way to the other;

Sphere 3, the universe

g) 1,000,000 years to get from our system to the next, the Great Nebula in Andromeda,

h) 1,000,000,000 years (or half the estimated age of the earth) to get from earth to the outer limit of the 200-inch telescope.

What our hypothetical traveler would find if he kept on going beyond this point, no one knows.

Each of the slightly elongated blurs below is a star system like our own Milky Way. (The round, sharp objects are stars *in* the Milky Way system.) The appearance of the distant star systems varies for two reasons: first, they lie in different positions as seen from earth; and second, there are numerous types of star-systems — spirals, irregulars, and the like. Most of the systems (nebulae) that appear here are about 120 million light-years away, and each contains millions of stars.

The Story of Mount Wilson

The Mount Wilson Observatory and the Palomar Observatory are both part of one man's dream (the man was George Ellery Hale). Both observatories are now engaged in one unified exploration into space and all that it contains. So, although the story of how the two observatories came about falls naturally into two parts, the whole story should be read as a continuous one.

It begins on Mount Wilson, in 1903.

Mount Wilson is about eight miles, as the crow flies, northeast of Pasadena, or about 30 miles by road. The mountain itself is a peak in the San Gabriel range, with a summit 5,713 feet above sea level. Before 1903, it had little claim to fame. Harvard University foreshadowed its future by establishing an observing station there in 1889; but the station was closed after only two years and moved to the southern hemisphere.

To this scene came Dr. Hale, in the fall of 1903. He was at that time Director of the University of Chicago's Yerkes Observatory at Williams Bay, Wisconsin. He was always on the lookout for likely spots for astronomical observations, however—spots that combined "good seeing" with accessibility—and Mount Wilson interested him.

Mount Wilson had been recommended to Hale by astronomers who had searched not only California, but Arizona and Australia as well, for a likely site. It offered an average of over 300 cloudless days a year; an altitude of over a mile, enough to raise a telescope above the thick and sight-disturbing bottom layer of the atmosphere; and trails that, even if steep, proved that roads were not impossible.

GEORGE ELLERY HALE

Through the winter of 1903-04, Dr. Hale repeatedly climbed one of the two trails to the mountain top and checked the conditions. With a 3½-inch telescope he proved that the reports of the good seeing on Mount Wilson were justified; and he verified the fact that only rarely did clouds drift across to obscure the stars.

In the spring of 1904, acting on Dr. Hale's favorable report on Mount Wilson, the Carnegie Institution of Washington granted the funds necessary to start a new observatory there. Ever since then, the Mount Wilson Observatory has been one branch of the Carnegie Institution, which has financed the construction and operation of all of the Observatory's astronomical facilities.

The mountain-top chosen by Dr. Hale was leased from its owners for 99 years, and work on the Mount Wilson Observatory got under way. The first step agreed upon was the removal of the Snow telescope — a solar telescope named after Helen Snow, who financed its original construction — from the Yerkes Observatory to Mount Wilson.

Pasadena, in 1904, was a small town of 15,000, with rambling dirt roads leading out to ranches and vineyards, since replaced by well-filled residential and shopping districts. Its most exciting project at this time was an elevated boardwalk — never finished — that was intended to give bicyclists a high-speed route into Los Angeles along the path now taken by the Arroyo Seco Parkway.

From this community the Snow telescope was "packed" up the mountain, with the aid of mules and burros, along what is now known as the "Mount Wilson Toll Road"— at that time an eight-mile multiple-switchback affair about two feet wide and with corners so sharp as to limit a burro's load to an absolute maximum of eight feet in length. Any engineer looking at the 200-foot-long building that houses the Snow telescope must feel respect for the men who had to limit themselves to eight-foot girders in its construction.

The next telescope to be set up on the mountain was a 60-foot tower telescope designed, like the Snow, for studying the sun. The first of its type, it had the advantage that the mirrors and lens were far enough above

In the early days of Mount Wilson, horses, mules, and burros provided motive power, and a trip up the mountain took the better part of a day. One burro contributed, besides labor, the cross-hairs that were used in the eyepieces of the earlier astronomical instruments; the hairs were from his tail.

the ground to be away from the disturbing air currents that eddied about the warm surface of the mountaintop.

Like the Snow telescope, the 60-foot tower telescope went up the mountain with the aid of mules. It was finished in 1907.

Long before the 60-foot tower telescope was finished, though, Hale had begun work on the instruments that were to equip Mount Wilson for the study of stars more distant than the sun. In 1904, he had a 60-inch glass disk, a disk that his father had obtained from France some years before, moved from the Yerkes Observatory to the optical shop that had already been built in Pasadena. There the disk was laboriously ground out to serve as a giant mirror for a reflecting telescope that would have, not the sun, but distant stars and nebulae as its objectives.

When it was finished, the mirror was hauled up the mountain over the Toll Road. This time, burros and mules were supplanted by automotive power in the form of a truck. Like everything else connected with the early days of Mount Wilson, however, the engineering of the truck was unorthodox. It was driven by four electric motors, one in each wheel; these motors were driven by a dynamo, which in turn was driven by a gas engine. It steered both front and rear, the better to navigate the switchbacks on the trail; and it had to call on the old familiar mules for help on the steepest grades. The trip up the mountain with the 60-inch mirror took three days.

The 60-inch telescope went into service in 1909. In its first five years, it made more than 4,000 photographs, and, even though in 1910 the 150-foot tower telescope was added to the battery of instruments on Mount Wilson that were devoted to the study of the sun, observations of stars and nebulae began to find an important place in the Observatory's work.

The 60-inch was the most effective telescope then in existence. It could range 300 million light years into space, a good bit farther than any telescope had reached before. On the other hand, the 60-inch wasn't quite powerful enough to give a final answer to many questions. There might be stars beyond its reach; what seemed to it the end of the stars might be simply the limit of its penetrating power.

Getting the answer required a bigger telescope, one that could "look" farther and increase the number of celestial objects that could be analyzed.

At just about the time that the need for a bigger telescope became apparent, a way of obtaining it appeared. John D. Hooker, of Los Angeles, offered to finance the making of a 100-inch mirror.

Hale immediately set to work the same group that had made the 60-inch mirror, the glass-works at Saint Gobain, in France. But the job was not easy. The 100-inch mirror would have to be shaped from a near-perfect disk of glass eight and one-half feet across and more than a foot thick; a disk weighing over four tons, or nearly twice as much as a modern automobile. Naturally, the glass-works had difficulty. They made four disks, one after another, and bubbles formed in every one. Finally, since the job began to seem hopeless, Hale decided to have the best of the four disks (the best happened to be the first one poured) brought to the optical shop in Pasadena. Tests there proved the glass disk to be sounder than its makers had thought, and the Observatory staff decided to try turning it into a telescope mirror.

Six years of careful grinding and polishing proved the decision a sound one. And eventually the huge disk of glass, now concave on one side, followed the 60-inch up the Toll Road to the top of the mountain. The trip was easier this time, for the road, though still a steep, dirt mountain road, had been made wider and safer.

While transportation problems had become simpler, engineering problems had not. Fitting a four-and-a-half-ton piece of glass into a mounting that brought the total moving weight to 100 tons, and then so arranging things that the whole assembly could smoothly follow a star's swing across the sky, was not a simple problem.

In building the 100-inch telescope, the solutions were found in bearings that literally floated the telescope on mercury, so that it could turn as freely as a chip of wood in a mill-pond, and in a worm-gear drive in which the gear was a 17-foot circle of 1,440 precisely machined teeth.

On November 1, 1917, the 100-inch had its first test. The telescope was set on Jupiter. One look—and the astronomers were appalled. Six or seven overlapping images filled the eyepiece. Perhaps heat was to blame for the mirror's distortion: the dome had been open to the sun all day. But the cooling of two or three hours brought only a slight improvement. Gloomily the astronomers went back to the Monastery. But Hale had faith. At 3 A. M. he and a friend returned. They set the telescope on Vega—the image stood out clear and brilliant! The success of the 100-inch was assured.

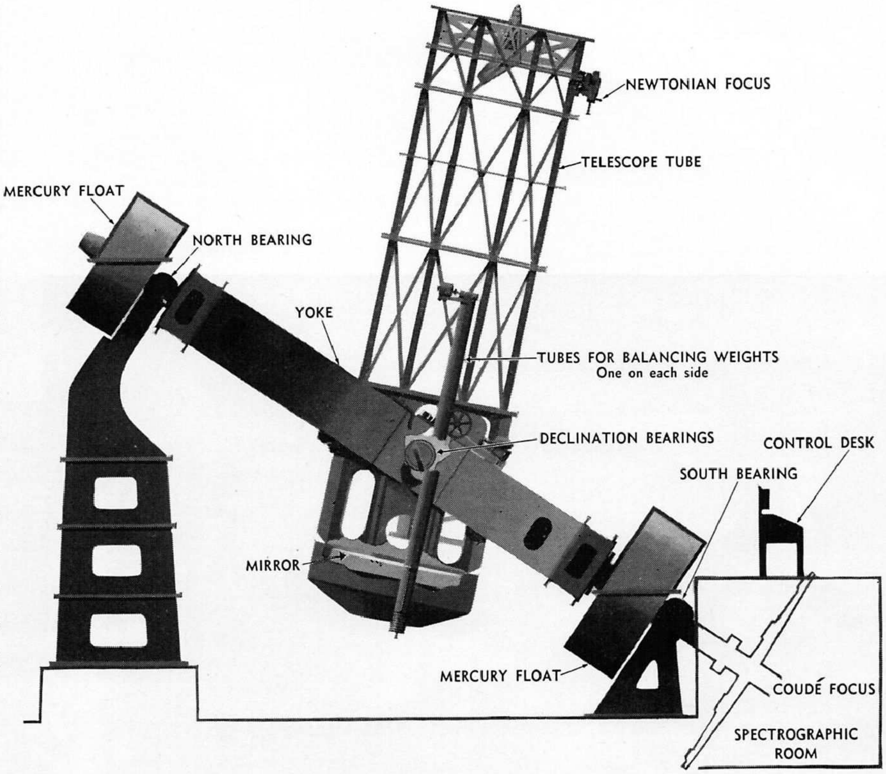
It was a tribute to its designers that the 100-inch behaved according to plan and that it still does after 30-odd years of following pin-pricks of light invisible to the naked eye. Even the electrical controls, which include brass push-buttons that look out of place in this plastic age, and huge business-like but unaesthetic relays that open and close with resounding "clacks," are still intact and working.

This is no point at which to expatiate on the accomplishments of the 100-inch Hooker telescope. But for 30 years it remained the most powerful telescope in the world, a kingpin of astronomical research. In those 30 years, it revolutionized our concepts of space and the universe.

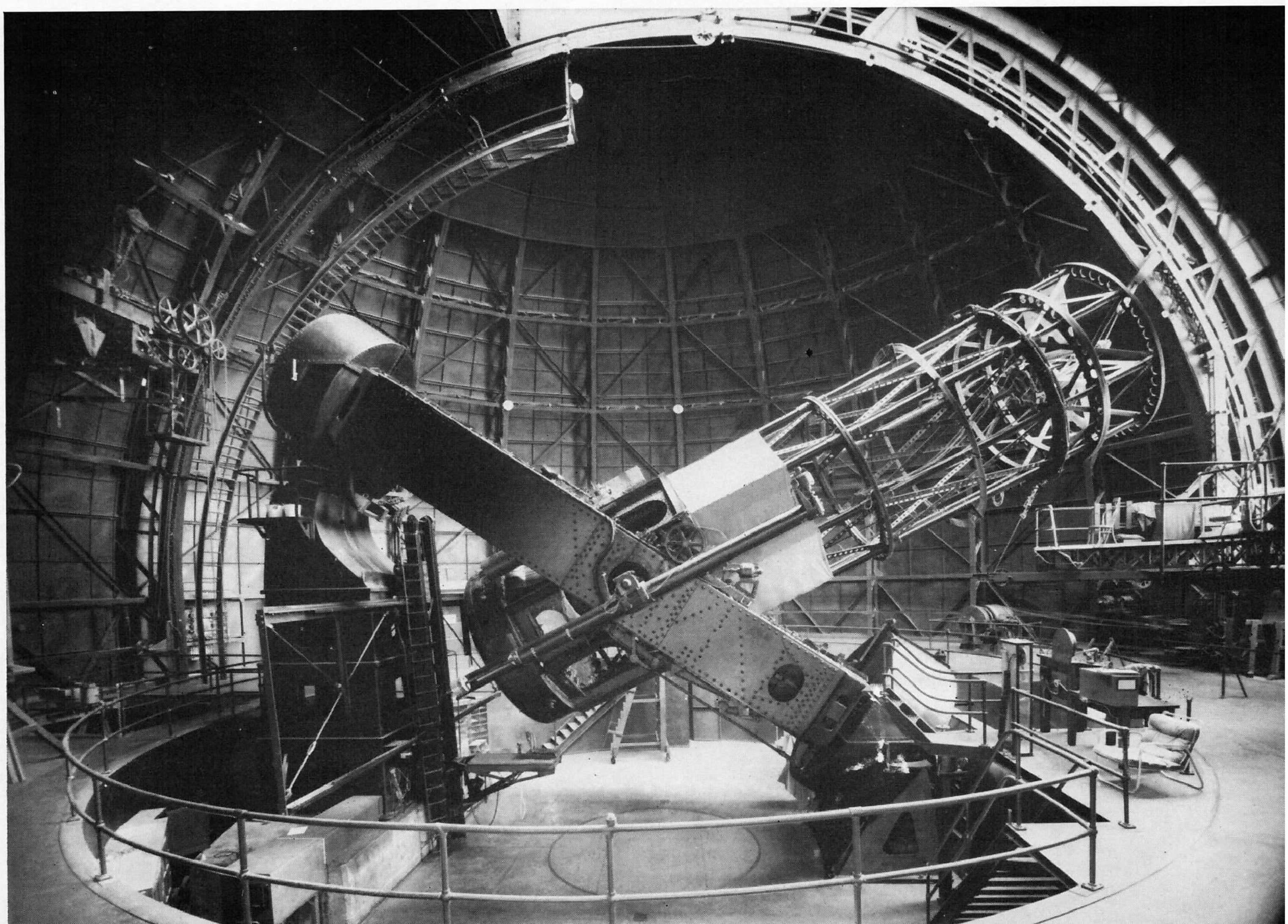
First, it gave a final answer to the question as to whether certain faint objects with a spiral structure that appeared in earlier astronomical photographs were in the Milky Way system or outside of it. The 100-inch proved (1) that the closest of these objects, the Great Nebula in Andromeda, was far, far beyond the edge of the Milky Way; (2) that it alone contained billions of stars; and (3) that far out in space there were millions of other such nebulae.

Second, the 100-inch proved through spectroscopic work that most of these distant nebulæ were moving away from us at thousands of miles a second. Indications of this high-speed motion had been found by astronomers at other observatories, but it remained for the 100-inch to establish this recessive motion as a general property of all of the more distant of these nebulae. The discovery of this motion, and of the fact that velocities became greater with increasing distance, led to the idea of a universe that was not only already immense beyond any previous imaginings but that was constantly expanding.

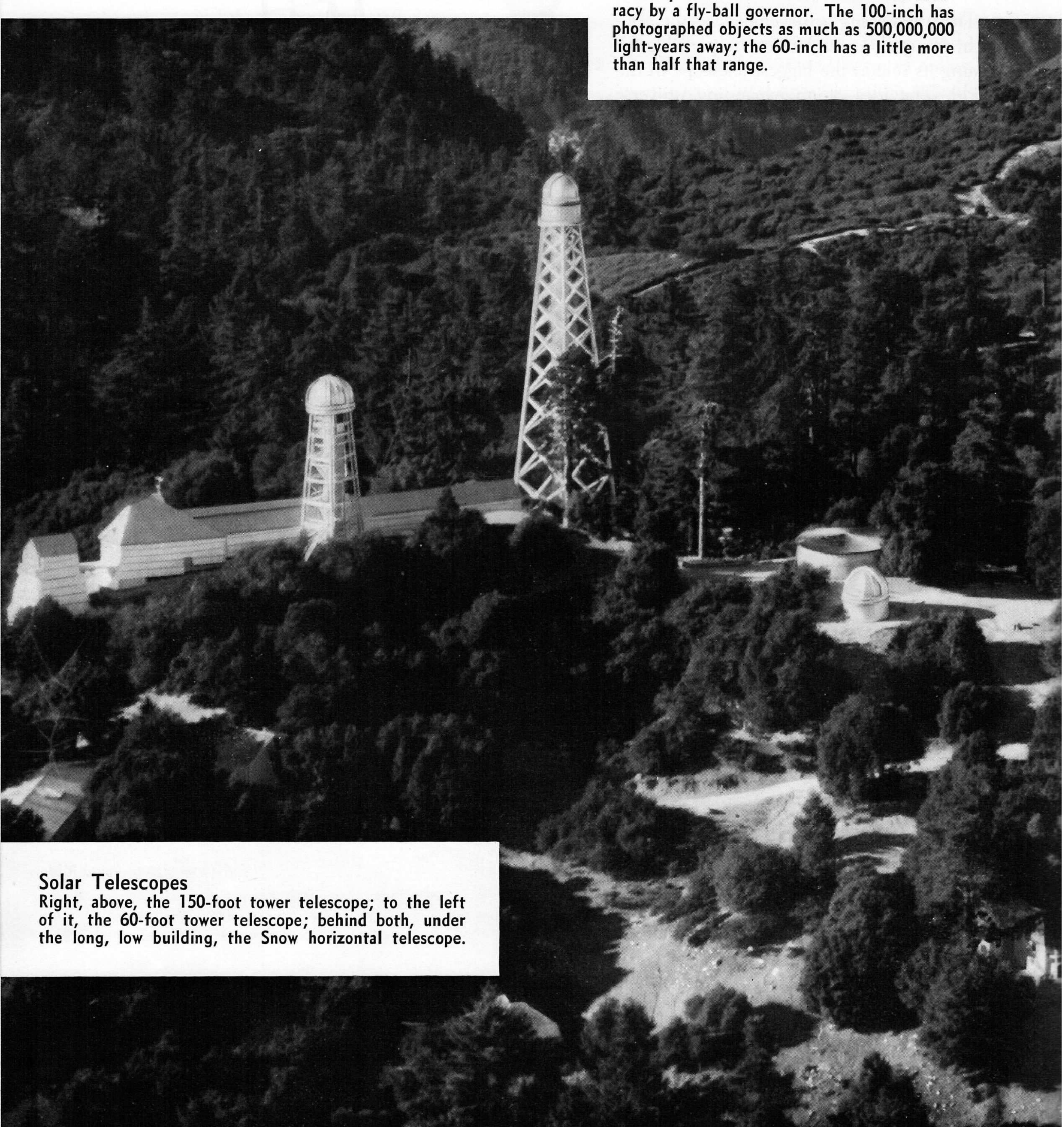
These crowning achievements of the 100-inch, ironically enough, were responsible for ending its role as the biggest telescope in the world. The idea of an expanding universe suggested the need for a telescope effective enough to explore the phenomenon at distances beyond the range of the 100-inch, and the discovery that star-systems like our own stretched off to unimaginable distances in all directions demanded a still bigger and more powerful telescope to explore them. So work on the 200-inch began.



Schematic diagram and photograph of the 100-inch Hooker telescope.

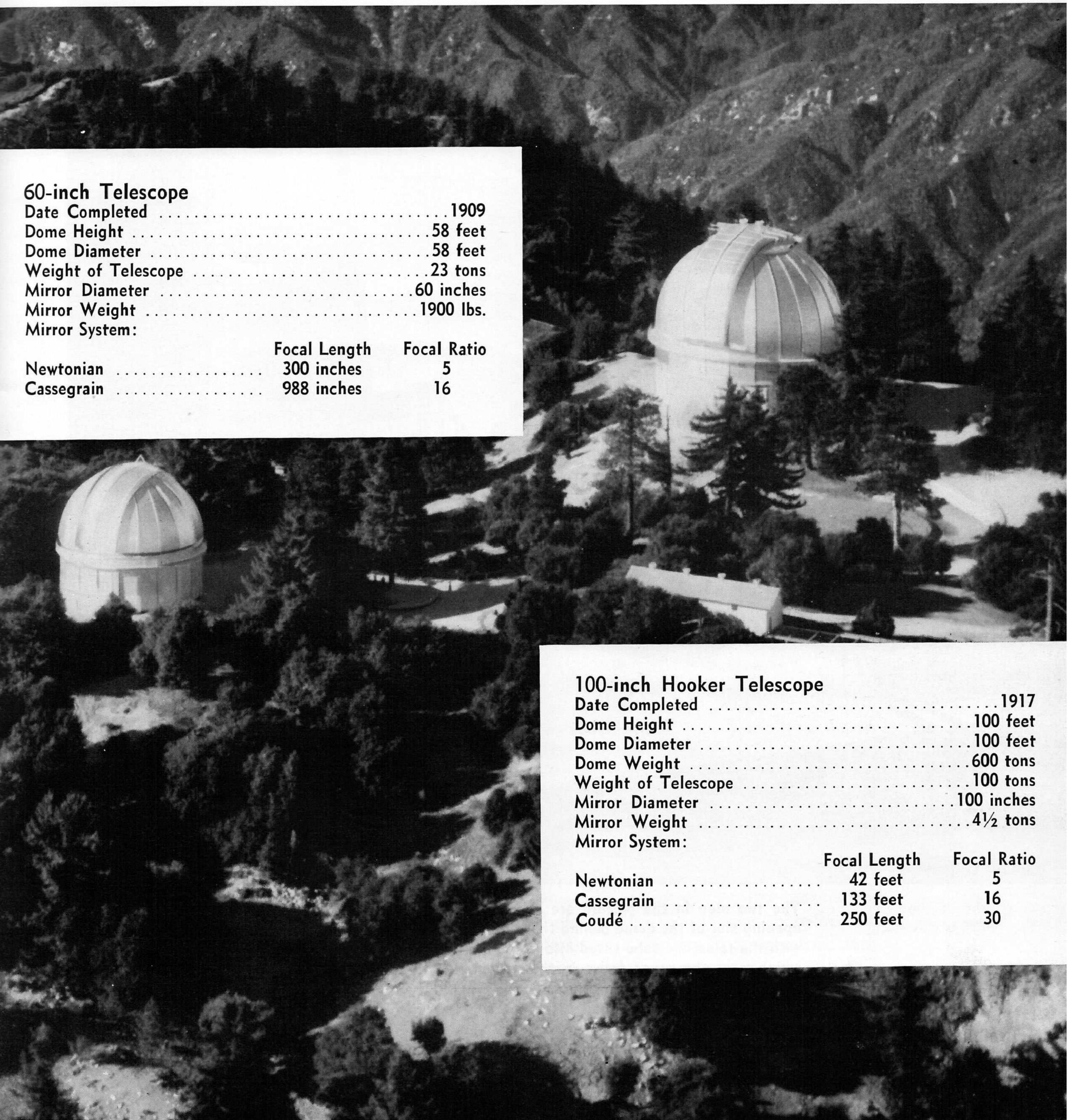


Each of the two reflecting telescopes on Mount Wilson has mercury-flotation bearings; the 60-inch is supported by one, and the 100-inch by two, hollow drums floating in mercury-filled tanks. This mounting has remarkably low friction. Each of the two telescopes is driven, when it is tracking a star from east to west across the sky, by a weight-driven clock whose speed is controlled with extreme accuracy by a fly-ball governor. The 100-inch has photographed objects as much as 500,000,000 light-years away; the 60-inch has a little more than half that range.



Solar Telescopes

Right, above, the 150-foot tower telescope; to the left of it, the 60-foot tower telescope; behind both, under the long, low building, the Snow horizontal telescope.



60-inch Telescope

Date Completed	1909
Dome Height	58 feet
Dome Diameter	58 feet
Weight of Telescope	23 tons
Mirror Diameter	60 inches
Mirror Weight	1900 lbs.

Mirror System:

	Focal Length	Focal Ratio
Newtonian	300 inches	5
Cassegrain	988 inches	16

100-inch Hooker Telescope

Date Completed	1917
Dome Height	100 feet
Dome Diameter	100 feet
Dome Weight	600 tons
Weight of Telescope	100 tons
Mirror Diameter	100 inches
Mirror Weight	4½ tons

Mirror System:

	Focal Length	Focal Ratio
Newtonian	42 feet	5
Cassegrain	133 feet	16
Coudé	250 feet	30

The two men in the picture are riding the elevator in the 200-inch telescope dome, with the opening slot of the dome behind them. This elevator carries the astronomer up to a point where, with the telescope tube tilted into proper position, he can step across into the observer's "cage," which is at the prime focus in the upper end of the tube. The picture on page 32 shows an astronomer at work in the cage.

The Story of Palomar

In 1928, the International Education Board pledged $6,000,000 toward a new and bigger telescope. This pledge, for which responsibility was later assumed by the General Education Board and which was supplemented by funds from the Rockefeller Foundation, was made to the California Institute of Technology, of which Hale was a trustee; the Institute took the responsibility for building and operating the huge telescope and the observatory of which it was to be a part.

The first problem was to decide how big the new telescope should be. A telescope with a 300-inch mirror was briefly considered. It soon turned out, however, that cost, difficulties of transportation, and technical limitations prohibited anything that big. So the size of the projected telescope's mirror was dropped to a 200-inch diameter—still twice the size of the Mount Wilson colossus.

Size having been decided upon, the place to put the telescope was the next problem. Mount Wilson was out. The lights of Pasadena and nearby Los Angeles were already interfering with long-exposure work being done with the 100-inch. The next most logical place, Table Mountain, which is near Mount Wilson, was eliminated for the same reason—the lights of the San Gabriel Valley—and also because Table Mountain was on the edge of California's famous San Andreas fault, and therefore, in an earthquake zone too hazardous for a huge telescope.

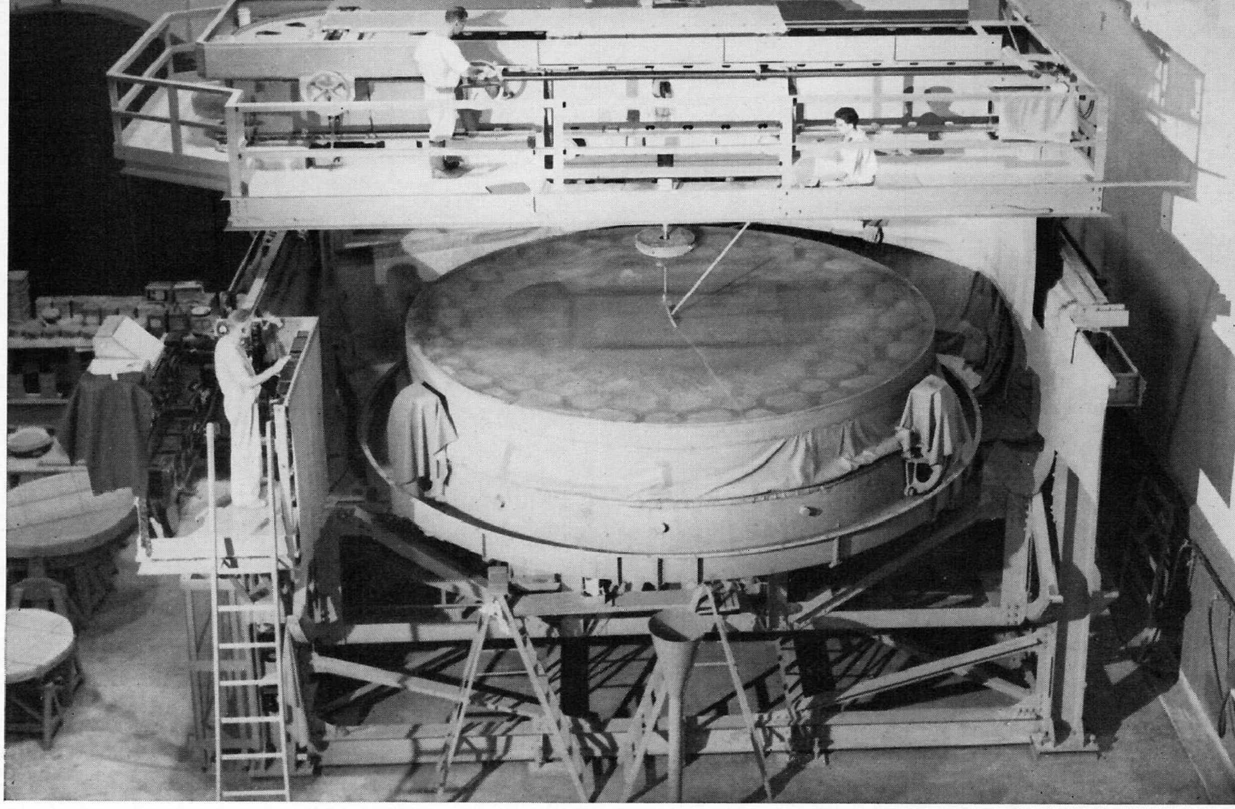
There followed a survey of possible sites that ranged from Mono Lake in the Sierras on the north to the Mexican border on the south, and from the Pacific Ocean on the west to Arizona on the east. The search ended on the top of Palomar Mountain.

Palomar Mountain is a block of granite 15 miles long and 5 miles wide. It has neither ledges nor hot desert sands near it to set up the convection currents that can ruin telescopic vision. It has an altitude of 6,100 feet; the observatory site is on a plateau below the peak, but still at 5,600 feet, a little over a mile. And, just as important a consideration as any of the foregoing, it is accessible. Unlike the two-foot-wide dirt trails that led up to Mount Wilson in its early days, a paved high-gear road built by San Diego County leads to the observatory on Palomar Mountain; and the 130-mile trip to the central shops, offices, libraries, and laboratories in Pasadena takes only about four hours by car.

Palomar Mountain having been selected, the next problem was the design of the mirror itself. It was not an easy problem to solve, either. A 200-inch mirror may have only twice the diameter of a 100-inch mirror, but it has *five* times the weight. The disk of glass from which the 200-inch mirror was to be ground would have to weigh about 20 tons.

The first choice of a material from which to make a mirror such as this would be fused quartz. Fused quartz responds less to temperature changes than any other usable substance. But a discouraging series of experiments proved that a fused-quartz mirror would be difficult, if not impossible, to make in a 200-inch size; and that even if it were made successfully, it would be enormously expensive.

The next choice was Pyrex, the tough glass that goes into many glass coffee-makers and much glass ovenware. It goes there because it can take large changes in temperature without much expansion or contraction, which



Grinding the 200-inch mirror. As the mirror rotated on turntable, grinding tool shown at back moved across its surface. Man with brush (above) ensured even distribution of grinding compound.

would mean breakage; and of course its insensitivity to temperature change makes it also a logical candidate for telescopic mirrors.

What is now the 200-inch mirror took shape at a conference held in New York in 1932, a conference attended by the men responsible for building the telescope and by representatives of the Corning Glass Works, the makers of Pyrex. Of the ideas that came out of the conference, perhaps the most significant was the one that introduced an altogether new style in telescope mirrors: a style that calls not for a solid slab of glass, as in the past, but for a thin face supported on a ribbed back. This construction not only made the eventual mirror lighter and easier to transport, but also provided pockets for counterbalancing supports that would be able properly to hold the multi-ton piece of Pyrex in the telescope in which it was to be mounted.

Corning men began the ticklish job with a "practice" disk 26 inches in diameter. Then they worked up through larger and larger disks (which have since been put to use as auxiliary reflectors in the telescope) until they felt ready to try pouring the 200-inch itself.

In February, 1934, everything was ready for the pouring of the glass that was to make the 200-inch mirror. The 114 "cores" that were to make pockets between the ribs in the back of the disk were bolted in place. Furnaces above and below the mold were ready to maintain a temperature of 2400 degrees Fahrenheit throughout the space that the 20 tons of molten glass would fill. The men began pouring the glass.

They had almost half of the required glass poured when one of the cores suddenly appeared on top of the molten glass lake. The intense heat had burned through the retaining bolts, and the core had floated to the surface. Before they were through pouring, two more cores had broken loose. The "mirror," if not a complete failure, promised to raise too many difficulties in the grinding and polishing process, and was set aside.

By December of the same year, 1934, the mold was ready for a second try. This time the cores, held in place by bolts of chrome-nickel steel and cooled by an air-circulating system, stayed in place. So far, at least, the mirror was a success.

The disk of glass was put in an "annealing" oven to "soak" for two months at high temperature, and then to cool off at a slow rate for eight months more. The next summer, with only three months of cooling left at the rate of one and one-half degrees a day, the nearby Chemung River flooded. The mirror in its oven was on the second floor of the laboratory; but the electrical equipment that controlled the oven was on the ground floor. For a day and a half Corning men worked at a protecting dyke to keep the flood waters away from the controls; but in the end the electric current failed. For three days the great disk bled its heat away. Finally the control equipment, moved to the second floor, took up its job, and the annealing continued for the scheduled three months. Through all this time, no one knew whether the flood had spoiled the disk or not.

When the oven was opened, however, the disk was found to be without flaw. The "mirror"—at this point a fairly rough 20-ton piece of glass, flat on one side and not unlike a waffle on the other—had been made. It arrived in Pasadena on Easter morning, in 1936.

In Pasadena, in the big, windowless "Optical Shop" already built for the purpose on the campus of the California Institute of Technology, grinding and polishing began. The disk was put on a turntable held high above the shop's floor by a heavy steel frame. Underneath were motors and linkages that could make the turntable revolve, thus turning the mirror beneath the grinding tools pressed down on its surface from above, and that could also tilt the disk to a vertical position for the optical tests necessary to guide the grinding.

The grinding and polishing tools ranged from 12 to 200 inches in diameter and were faced with Pyrex blocks for grinding or with a special pitch for polishing. All in all, the disk took 31 tons of grinding and polishing compounds, ranging from carborundum to a very fine grade of rouge.

Finally, on October 3, 1947, it was decided that the now-concave surface was adequate. After 11½ years in the Optical Shop, during which time 5¼ tons of glass had been ground off, the mirror was ready.

By this time, the dome and telescope mounting on Palomar Mountain were ready for the mirror, too. The mounting itself, holding a huge cement block as a temporary stand-in for the mirror, had gone through its paces. All

200-inch mirror on its 160-mile trip from Pasadena to Palomar. The haul up the mountain, in unexpected rain and sleet, took three tractors; this was the most worrisome part of the trip.

the huge assembly needed to bring it to life as a telescope was the mirror.

So, at 3:30 A. M. on November 18, 1947, a big tractor-and-trailer unit rolled out of the Optical Shop in Pasadena and headed for the top of Palomar Mountain. The starting hour had been kept secret, to avoid crowds; road blocks had been set up at several points to re-route traffic (the mirror on its big trailer left very little room for anything else on the road); weak bridges had been shored up to stand the load. Before the mirror crossed one particularly suspect bridge, 16 extra wheels were mounted on the trailer to distribute the 35-ton weight more evenly. On the long pull up the mountain, two more tractor units were called into play to help pull and push the mirror up the steep grade, which bad luck had made slick with a rain-and-sleet storm.

The mirror got to its telescope, however. Only one major operation remained to be done before it could go to work. The "mirror" at this stage was not a mirror at all, but a transparent piece of glass; it lacked a reflecting surface. So it was moved into the aluminizing tank which had been built as a permanent fixture of the 137-foot dome, and there coated with a thin layer of aluminum. And in December, 1947, almost 20 years after George Hale began to turn his vision into a solid glass and steel instrument, the first stars were seen reflected by the mirror of the Hale telescope.

There was nothing spectacular about the first "look." One of the astronomers on the project, using a small reading glass for an eyepiece, peered at the mirror. Asked what he saw, he replied, accurately enough, "Oh — some stars."

But the first few tests made it clear that the 200-inch would live up to expectations. After 18 months of tests and adjustments, the mirror had to be removed from the telescope to have a few millionths of an inch ground off around its edge; and then it was found necessary, also, to mount 12 fans around the mirror's under-surface to help defeat minor temperature differences that perturbed the disk. Now, however, the 200-inch is busy all of every cloudless night, taking pictures of objects in space some of which are almost a billion light years away — twice as far away as anything the 100-inch can photograph — and thereby opening up for human inspection a sphere of space with eight times as large a volume as that observable before.

Sometimes forgotten in the "glamor" of their 200-inch neighbor on Palomar Mountain are the 18-inch and 48-inch schmidt-type telescopes. In their way, the schmidt-type telescopes are as useful as the bigger reflecting telescopes that are so much more talked of. The very least that can be said of the 48-inch schmidt on Palomar Mountain is that it is a co-worker utterly essential to the 200-inch, and to the 100-inch on Mount Wilson; it is a vital weapon in the over-all attack on the problems of the universe.

A telescope like the 200-inch, while it can penetrate space to a great distance, has a very, very small field of view. To supplement it, a telescope would be needed which could photograph a large area of sky. This large field of view is the particular characteristic of the schmidt-type telescope. With a schmidt to do the "scouting" photography, then the 200-inch (and the 100-inch) could concentrate on the most promising areas revealed in the schmidt photographs.

So two schmidt telescopic cameras were built on Palomar. The 18-inch was in use before the war; the 48-inch was finished shortly before the Hale telescope went into operation.

The size of the correcting plate determines the light-gathering power of the schmidt. Hence, the instrument takes its dimensional name from its correcting plate rather than from its mirror. The 48-inch schmidt, for example, has a 72-inch mirror. The principal problem in making any schmidt-type camera lies in the correcting plate, which must be ground to the complicated curvature which mathematicians call a "fourth degree surface." Since the whole 48-inch schmidt weighs only a fifth of what the 100-inch and a twentieth of what the 200-inch weighs, the mounting and the control mechanism pose no very difficult problems. The history of the schmidt-type telescopic cameras lies rather in what they can do.

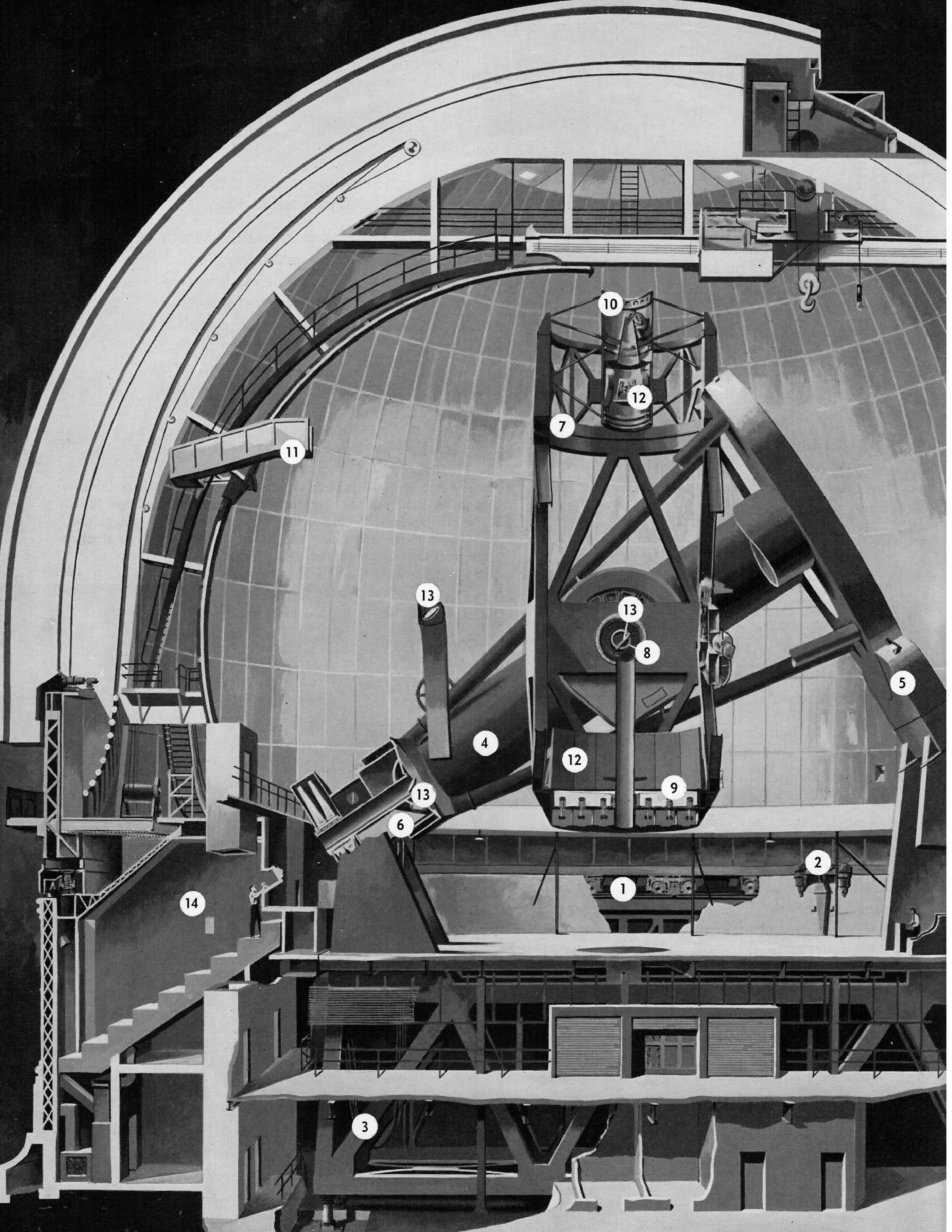
The 18-inch has already photographed a fair number of those astronomical rarities the supernovae, stars that suddenly (and so far inexplicably) flare up to a brilliance that would, if the sun became a supernova, turn the earth to a burned and lifeless cinder in a matter of minutes.

The 48-inch, for the first four years of its existence, will be engaged in a survey of the universe. Financed by the National Geographic Society, and known as the National Geographic Society-Palomar Observatory Sky Survey, it will cover every part of the sky visible from Palomar Mountain out to a distance of about 300,000,000 light years. It would take the 200-inch, if any group of astronomers chose to put it to the purpose, about 5,000 years to cover the same area of the sky.

The results of the Sky Survey will be published in the form of an atlas of nearly 2,000 photographic prints 14 by 14 inches in size. This survey should bring to light a very large number of new and unusual astronomical objects which will later be studied in detail by the 100-inch and 200-inch telescopes.

In this brief historical sketch of the Mount Wilson and Palomar Observatories, chronology has been the guiding principle, and telescopes finished have been forgotten thereafter in the story. Astronomically speaking, this is not the case. As things stand at present, every instrument of the combined Observatories is each doing its appointed part of the vast research job that may answer some of man's fundamental questions about the universe.

The 48-inch schmidt-type telescope has a 72-inch mirror (hidden by the big cover fitted over the bottom of the telescope tube). Since the instrument cannot be "looked through," it is guided, while a photograph is being made, with one of the two smaller telescopes that are mounted along its sides.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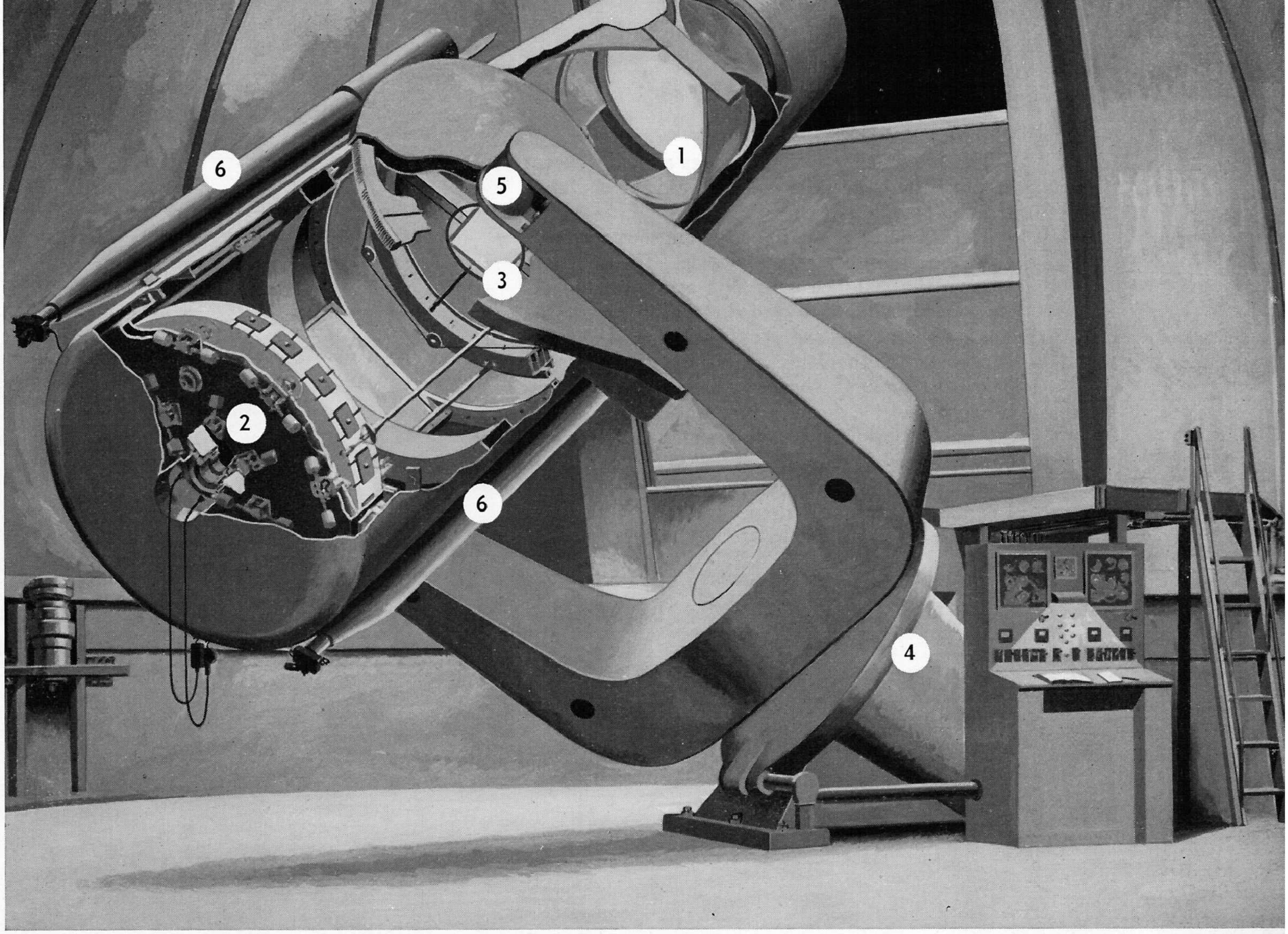


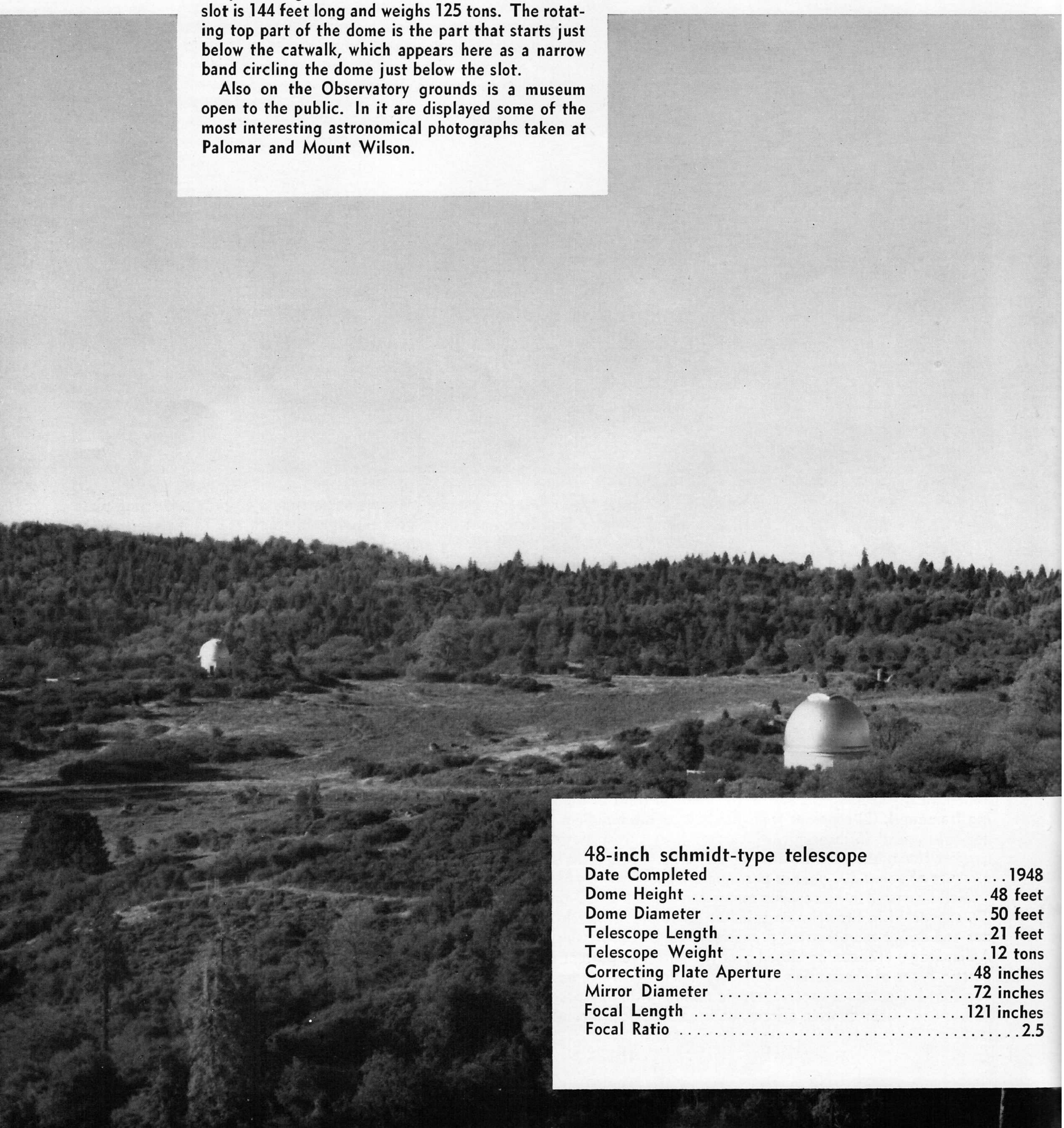
The 48-inch schmidt-type telescopic camera takes its name from a 48-inch correcting plate (1), a thin and complex lens that light must pass through to reach the 72-inch mirror (2). The mirror reflects the light to the photographic plate holder (3) in the center of the telescope tube; the holder, loaded outside the tube, automatically bends the glass plates to the right curvature and carries them up into position. The schmidt has only one polar bearing (4), a large ball bearing, which allows for east-west motion; the tube turns on bearings (5) in the tines of the fork that supports it to achieve north-south motion. The two tubes along the instrument's sides (6) are guide telescopes.

The dome of the 200-inch telescope is supported by 32 four-wheeled trucks (1) which run on smooth circular rails. When the instrument is at work, four five-horsepower motors (2) turn the 1,000-ton dome, automatically keeping the slot in the dome in front of the telescope. The telescope itself has a supporting framework (3) separate from the rest of the building. The "yoke" (4) rests on the north polar (5) and south polar (6) bearings, which permit east-west motion of the telescope. These bearings literally support the telescope on a film of oil three thousandths of an inch thick forced into the bearings at a pressure of about 300 pounds per square inch. These bearings reduce the friction to such an extent that a small one-twelfth-horsepower motor can make the 530-ton telescope follow a star. The telescope tube (7), supported in the yoke on spindles (8) to permit north-south motion, has the 200-inch mirror (9) at one end and at the other the prime focus cage (10), to which the astronomer is lifted by an elevator (11). A diaphragm (12) can be closed over the mirror to protect it when not in use and to "stop it down" for certain types of observation. Auxiliary mirrors (13) can be used to send the light from the mirror to the constant-temperature spectrographic room (14) in any position of the telescope. The floors below the "observing" floor contain offices, darkrooms, electric controls, and the like.

The two schmidt-type telescopes are alike except in size. The larger, the 48-inch, is in the center of the photograph below.

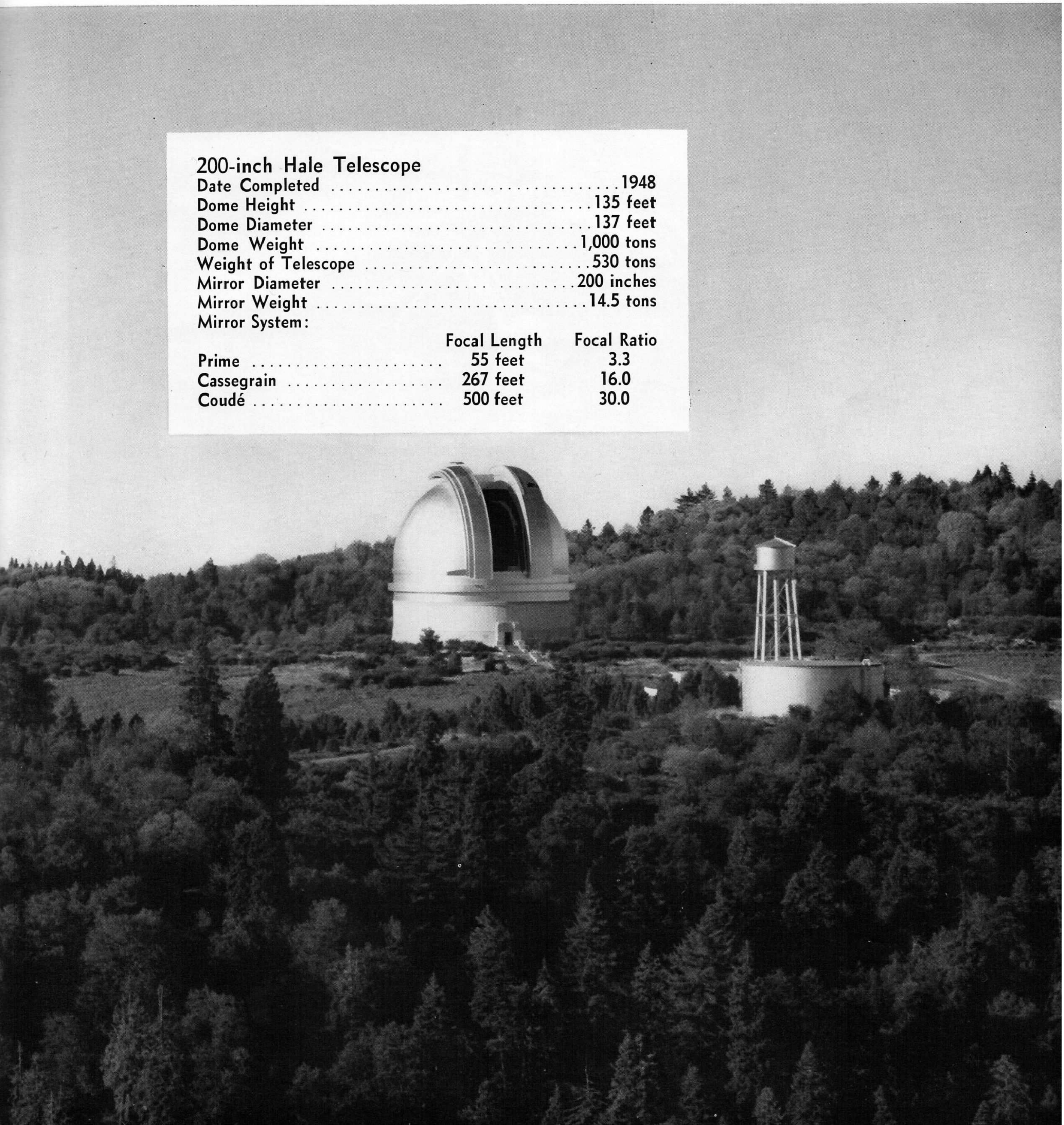
The 200-inch, at the right, is here shown with its dome slot open as for observation. The structure housing the 200-inch is as high as an average 12-story building. Each of the shutters that close the slot is 144 feet long and weighs 125 tons. The rotating top part of the dome is the part that starts just below the catwalk, which appears here as a narrow band circling the dome just below the slot.

Also on the Observatory grounds is a museum open to the public. In it are displayed some of the most interesting astronomical photographs taken at Palomar and Mount Wilson.



48-inch schmidt-type telescope

Date Completed	1948
Dome Height	48 feet
Dome Diameter	50 feet
Telescope Length	21 feet
Telescope Weight	12 tons
Correcting Plate Aperture	48 inches
Mirror Diameter	72 inches
Focal Length	121 inches
Focal Ratio	2.5

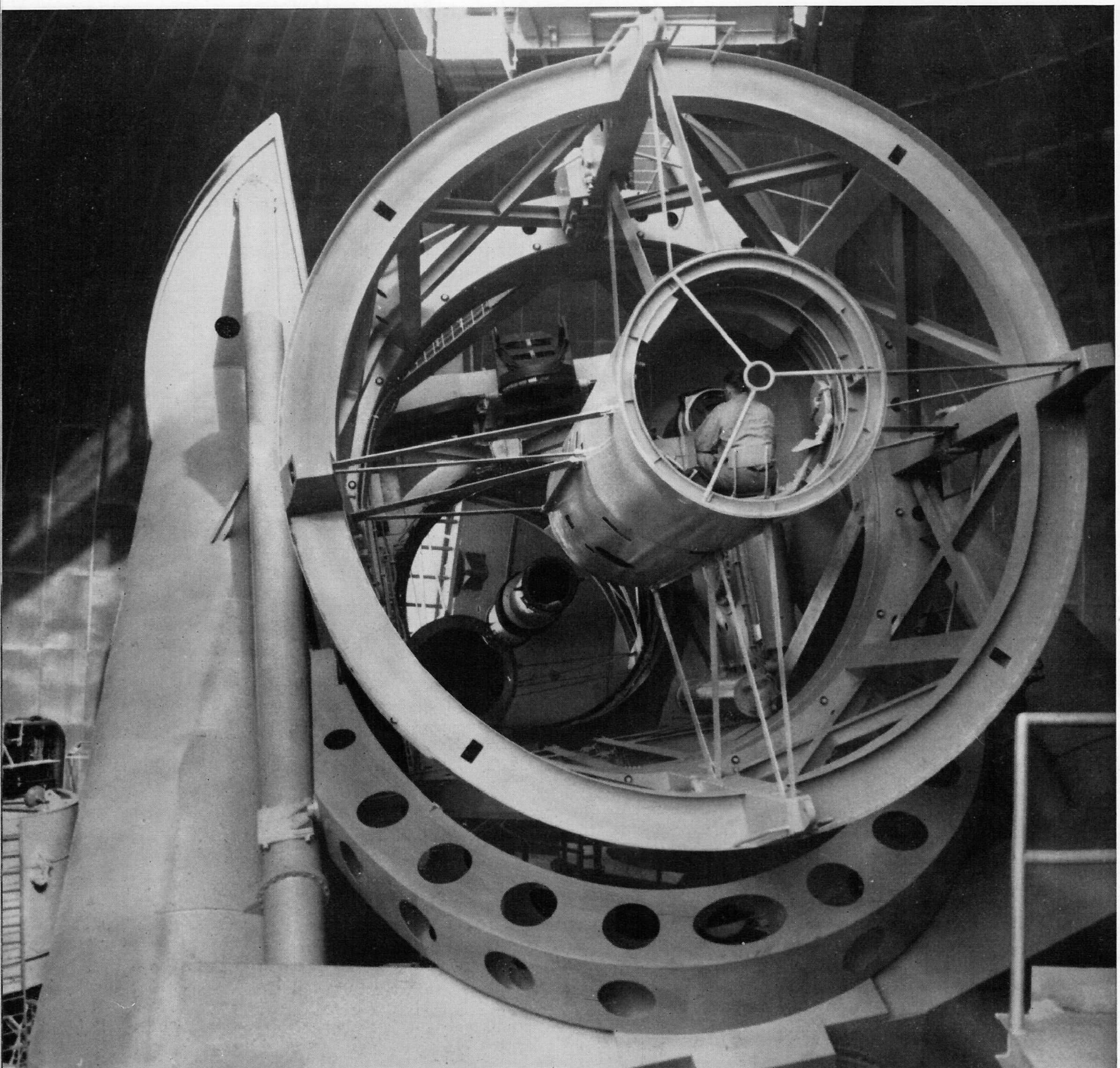


200-inch Hale Telescope

Date Completed	1948
Dome Height	135 feet
Dome Diameter	137 feet
Dome Weight	1,000 tons
Weight of Telescope	530 tons
Mirror Diameter	200 inches
Mirror Weight	14.5 tons

Mirror System:

	Focal Length	Focal Ratio
Prime	55 feet	3.3
Cassegrain	267 feet	16.0
Coudé	500 feet	30.0



An observer using the 200-inch can "ride" in the prime focus cage, where he has at hand a complete set of push-button controls for the telescope and a telephone connected to the main control desk. Light from the skies at the observer's back passes down around his cage to the 200-inch mirror, visible above, which reflects it back to the photographic plate that the observer is exposing.

A Night's Work

An astronomer does not live on a mountaintop. An astronomer connected with the Mount Wilson and Palomar Observatories lives in or near Pasadena, where the laboratories and libraries of the Observatories are located, where he spends most of his working hours, and where, incidentally, all the "discoveries" are made. Astronomical photographs reveal little without long laboratory study.

But each astronomer is allotted from three to six nights a month at one of the big telescopes, and when his chance comes he goes to one of the mountains. Once there, he moves into the dormitory where food, bed, books, and the company of a few other astronomers are available for his few free moments.

These dormitories are designed for day, rather than night, rest. The astronomer's room has thick black shades that shut out daytime sunlight, and noise is simply not allowed.

Astronomers are assigned telescope time according to the field in which they are interested. There are "light of the moon" and "dark of the moon" astronomers. Those interested in the direct photography of distant nebulae or stars must do their work in the dark of the moon, when there is a minimum of light from sources other than the one they wish to study. Those interested in spectroscopy can stand much more outside light. In general, therefore, the dark-of-the-moon period is devoted to direct photography, and the light-of-the-moon period to spectrographic work.

For the sake of being specific, consider an astronomer working at the 200-inch Hale telescope on Palomar. Assume, also, that he is a "dark-of-the-moon" observer, one interested for the time being in direct photography. This means that he will probably spend the night in the observer's cage at the prime focus position. The night assistant—the engineer who is always present to assume responsibility for the general behavior of the telescope—will spend the night at the control desk on the observing floor, far below.

The night assistant begins the night's work by opening the huge dome as early in the evening as possible, so that the mirror and the tube that holds it will have a chance to adjust to outside temperature before they go to work.

As night comes, the astronomer rides the prime-focus elevator up to the mouth of the observer's cage, steps across a 10-inch gap, 75 feet above the floor of the observatory, and settles himself in the chair in the observer's cage. He has brought photographic plates with him, perhaps enough to last the night.

Settled, he uses the intercommunication system to tell the night assistant at the desk below—in terms of degrees, minutes, and seconds of "declination" and "right ascension"—the location of the spot in space he wants to photograph. The night assistant sets his dials, pushes a button — and the great telescope swings to the proper aim. As it does so, the dome automatically turns to keep its slot in front of the telescope, and the canvas windscreen automatically rides up in the slot as far as the telescope's position will allow.

Lights in the dome go out. The observer looks into an eyepiece, to make sure the big mirror is reflecting the right area of the sky, and sets the cross-hairs of the eyepiece on a guiding star just outside the field he intends to photograph. He slides his photographic plate into place — and the exposure begins.

Until the exposure is finished, the observer keeps his eye on the guide star as the telescope swings imperceptibly across the sky. From time to time he presses buttons on a control panel—buttons like, and controlling the same movements as, the buttons on the main control desk—to keep the telescope aimed at his objective. These minute adjustments are made necessary by the changeable effects of the earth's atmosphere on the rays of light hitting his photographic plate.

The work in hand, the seeing, and other factors decide how long the observer remains in the cage. If he is devoting the night to a series of fairly short exposures, the chances are that at about midnight the lights in the dome will go on and he will come down out of the telescope for coffee and a sandwich—and also to get warm. Observing at the prime focus, particularly in winter, calls for heavy clothing; the temperature in the dome is often below freezing, sometimes going as low as 10 degrees above zero.

Much depends on the weather. Seeing may not become good enough to allow the taking of photographs until one or two A.M.—perhaps not at all. Or there may be good seeing most of the night. When the astronomer goes to the observatory, he can never tell how much productive work the weather will allow him. There may not be more than a dozen nights of very good seeing in a year—but it is on

Control desk of 200-inch Hale telescope. The night assistant can make the proper settings on the lower rows of dials in the right-ascension (east-west) and declination (north-south) panels, push the two buttons in the left foreground, and the telescope (whose position is indicated by the upper dials) will swing to the desired area. Automatic star-tracking drive then takes over.

Astronomical research begins with photographs taken by telescopes, continues with long and detailed study of those photographs—which range in size from 14-inch-square plates made with the 48-inch schmidt to spectrograms one-tenth of an inch long. One night's pictures may take weeks of study.

those nights that he can do his most important work, so he dares not miss them.

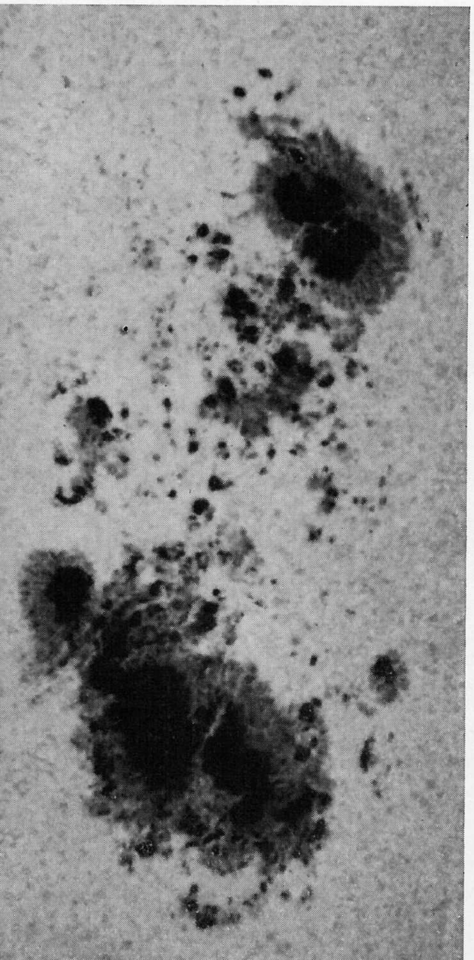
As day breaks, the astronomer, quite possibly somewhat cold and cramped, rides down from the observer's cage with his small collection of exposed plates. Then, if his turn at the telescope is over, he returns to Pasadena and begins a laboratory analysis of what he has "caught." He studies his results with comparators that can measure the position of points on his photographic plates with an accuracy of a few hundred-thousandths of an inch, and with microphotometers that determine the intensity of the light that affected the emulsion on the plates.

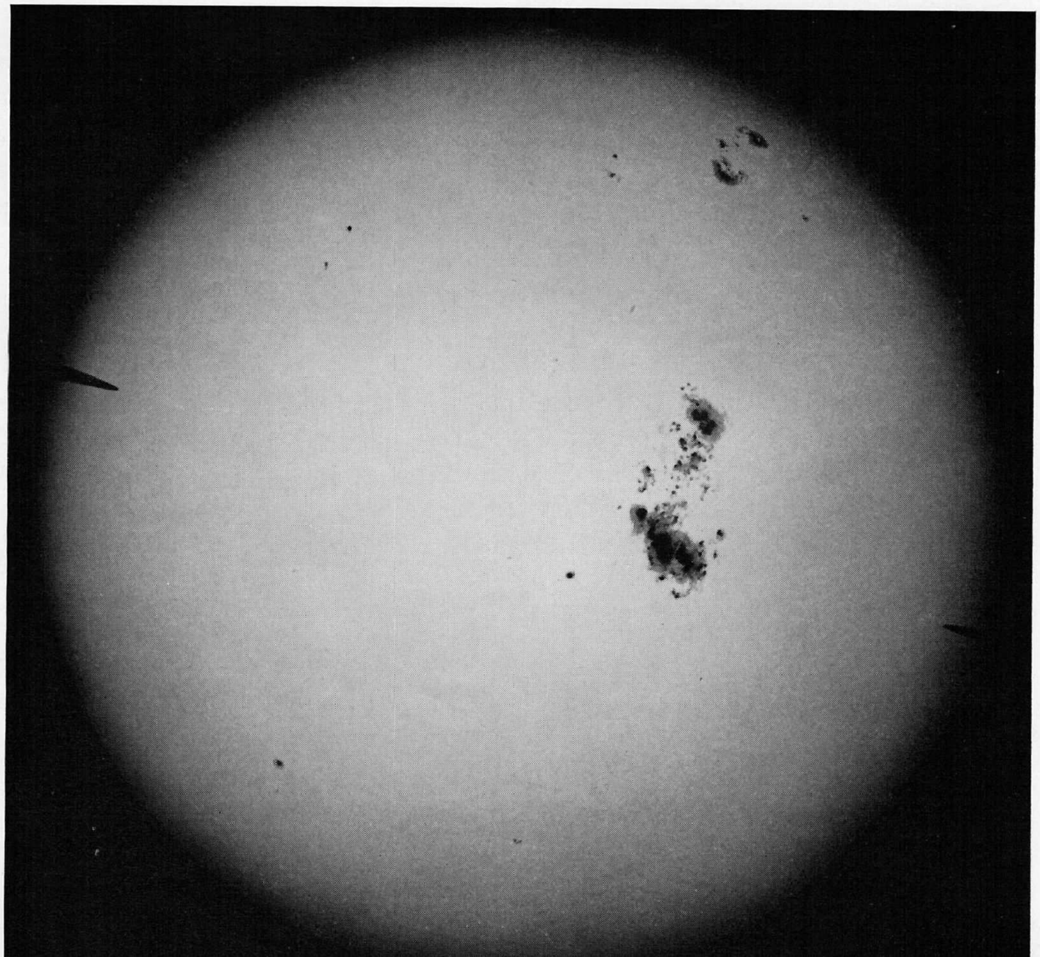
These measurements are then combined with similar measurements on plates taken in previous months, or even with those of other observers. Starting with these measurements, calculations, often long and tedious, then yield such facts as the distance, size, or motion of some star cluster or great stellar system such as one of the nebulae. If he is working with spectrograms, his measurements and calculations are likely to give such information as the temperature, density, or chemical composition of some star or nebula.

A good insight into the workings of modern astronomy can be gleaned from the fact that it may take the astronomer weeks or months to measure and interpret the material contained in the photographs he has taken in one night's work. In a nut-shell, one good night's work at the telescope means several weeks' work in the laboratory—work too slow and complex to report here, but work without which the big telescope's abilities would be utterly wasted.

Solar prominences—streams of hot gases—such as this one reach altitudes of many tens of thousands of miles above the sun's surface. There is evidence that such prominences eject particles, such as the nuclei of hydrogen atoms, that eventually stream down into the earth's atmosphere.

The photographs below, made on April 7, 1947, show one of the largest sunspot groups ever observed. The earth superimposed in scale on the picture at the right would be a dot one twenty-fifth of an inch in diameter, not much larger than the spot visible on the lower left part of the sun.





Questions in the Stars

There would be little purpose in giving here a detailed survey of modern astronomy. Such a survey would fill several volumes, in any case. But pointing out a few of the large-scale problems with which today's astronomers are concerned may serve to indicate the kind of work in which the telescopes described earlier in this booklet are engaged.

It should be clear to those who have read this far that astronomy can be broken down into two distinct parts: the part that relies on direct photography, and the part that relies on spectroscopy. When it comes to explaining current astronomical research, however, this division is not too helpful, because the two methods are often used on one astronomical problem. Take, for example, the problem of determining the direction of a star's motion. It takes direct photography—in the form of two or more photographs taken some time apart—to determine a star's motion perpendicular to the line of sight from the earth. But it takes spectroscopy to reveal, through minute displacement of the lines in a star's spectrum, the star's motion toward or away from the earth *along* the line of sight. The two astronomical methods, photography and spectroscopy, are similarly mixed up together in such areas of research as the study of variable stars, where photography reveals the degree and rate of variation and spectroscopy discloses some of the physical changes that accompany that variation. Finally, astronomical spectroscopy relies on direct photography (sometimes referred to as "positional astronomy") to locate faint celestial objects on which it is to concentrate.

Since, then, this most obvious way of dissecting astronomy for inspection has drawbacks, we will here arbitrarily divide astronomy into the parts that deal with the three spheres of space already defined: the solar system, the Milky Way system, and the observable universe beyond the confines of the Milky Way.

1. The solar system. The sun—"our" sun—is not only responsible for holding the solar system together and for making life possible on earth; it is also the only star close enough to the earth to be visible as more than a point of light. It is not surprising that astronomy began with the sun and is still hard at work studying it.

So far, astronomers have learned the temperature of the sun, which is roughly 10,000 degrees F. at its "surface" and perhaps 36,000,000 degrees F. at its center. They have learned what chemical elements are present in its atmosphere; the list includes most of the elements found on earth (and none that are not). They have learned that it rotates roughly once every 27 days. With great difficulty, because the earth's atmosphere interferes with the job, they have measured its output of light and heat. They have learned much about sunspots, and about the prominences that stream up from the sun's surface.

They have even proposed an explanation for the tremendous energy output of the sun, a theory involving the release of nuclear energy through the combination and recombination of atomic nuclei and nuclear fragments in a complex cycle that begins with hydrogen and ends with helium.

The study of the sun has just begun, however. Some of the questions still to be answered are these: What *are* sunspots, anyway?

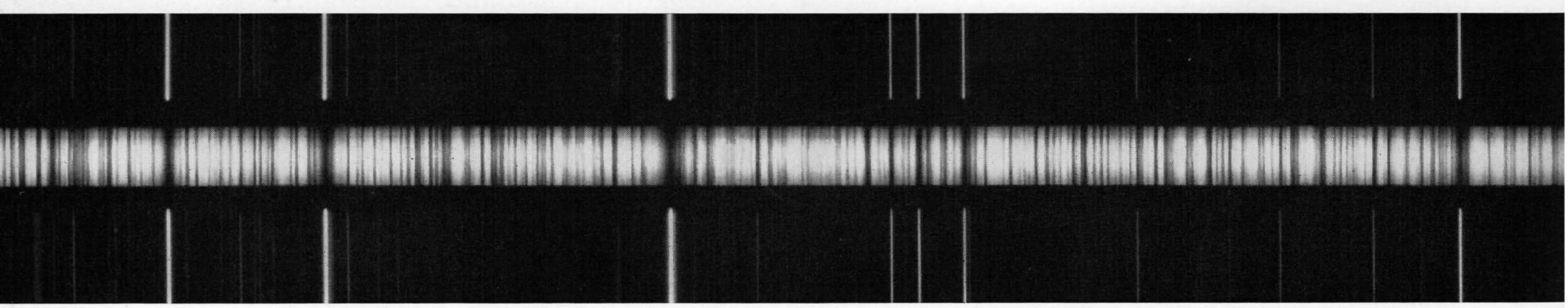
Why do they follow a rough 11-year cycle of recurrence? In what ways does the sun control the many earthly phenomena that are unquestionably affected by it: the Northern Lights, for instance, and violent magnetic storms, and radio reception? What are the significance and the effect of the powerful magnetic fields that accompany sunspots?

The rest of the solar system (planets, moons, asteroids, comets, and so on) does not receive much attention at the Mount Wilson and Palomar Observatories. Not that the earth's neighbors in space are uninteresting; the fact is rather that the Observatories' instruments are better suited to the investigation of other, fainter things. Factors outside of telescopes themselves—the chief factor being the distortion introduced by the earth's atmosphere—limit the detail that can be observed on, say, Mars; and this means that a small telescope may be able at any given time to take just as good a photograph of that brightly illuminated planet as a larger telescope can take. It has been said that using the 200-inch to study Mars would be like using the liner *Queen Elizabeth* to cross the Mississippi, and the simile has some value.

From time to time the big telescopes have taken and will take "looks" at objects in the solar system, but such looks will probably never become an important part of the research activities of these Observatories.

2. The Milky Way. The star system of which the solar system is a part contains a good many billions of stars, most of them scattered about at random, and some of them grouped in clusters. It also contains clouds of gas and dust; some illuminated by nearby stars, others dark and perceptible only because they cut off the light from the stars that must lie behind them. It also contains inert and lifeless stars of whose existence astronomers are sure because of indirect evidence.

In all this cosmic rubble that populates the Milky Way system, the stars, of course, receive most of the attention. And much of that attention is devoted to two problems: the *distances* of these stars from the earth, and their *chemical composition*.



Spectrum of the star Arcturus (center strip) in comparison with the spectrum of a laboratory iron arc (upper and lower strip). The appearance of dark lines in the spectrum of Arcturus opposite each of the bright iron lines provides proof of the presence of iron in this star.

The object shown in the photograph at the right is the Crab Nebula, in the Milky Way system about 37,000 light-years distant from the earth. Old Chinese records refer to what must have been a supernova that appeared in 1054 A.D. The Crab Nebula is quite probably a cloud thrown off by that supernova at the time of its "explosion." Spectrographic studies show that the nebula is still expanding at a rate of over 800 miles a second. Photo by 200-inch.

The measurement of large astronomical distances hinges on the fact that the apparent brightness of a light source varies as the inverse square of its distance from an observer. If the earth moved twice as far away from the sun as it is at present, the sun would seem only one-fourth as bright as it does now.

This means that if you know how far away a star is, you can determine its real or absolute brightness by measuring its apparent brightness as seen on earth and applying the "inverse-square" law mentioned above. Conversely, if you know the real brightness of a star you can compute its distance by comparing its real brightness with its apparent brightness and again applying the law.

In practice, astronomers years ago took sights on nearby stars from opposite ends of the earth's orbit, and thereby determined the distance to those stars. If you look at an object across the room and close first one eye and then the other, the object will seem to move; and actually the brain uses that apparent motion to judge how far away an object is. Astronomers do the same thing; but the earth moves their telescopic eye almost 190,000,000 miles between looks, while the average distance between human eyes is only about 2½ inches. The astronomer's depth-perception—or perception of distance—therefore reaches much farther; out to several hundred light years, in fact.

Having found the distance to nearby stars by this method, the astronomers could discover the real brightness of these stars. Fortunately, among them are certain types that always have the same real brightness. There are, for instance, the "Cepheid variables," stars that vary in brightness but whose maximum brightness corresponds closely to the length of time that it takes them to cycle from bright to dim and back again. There are also other types, distinguishable with the aid of the spectrograph, that always have the same (or approximately the same) real brightness.

So now the astronomers, having discovered the real brightness of various types of stars by knowing their distance from the earth, can turn around and compute the distance to other stars of the same type because they know their real brightness. It is one of the tasks of astronomy to refine measurements of this kind until the structure of the Milky Way is accurately determined.

Another important aspect of astronomical research in the Milky Way applies to stellar composition. In every spectrogram of every star appear certain dark lines, called "Fraunhofer lines" in honor of the observer who first studied them (in 1814). These dark lines, or "absorption bands," indicate the presence of specific elements in the star's atmosphere, where the atoms are in such condition that they absorb, rather than produce, the light waves that are characteristic of them.

From the distribution, intensities, and widths of these lines on spectrograms, astronomers can learn much about the chemical com-

The gaseous nebula NGC 2237. This large cloud of dust and gas is in the Milky Way in the constellation of Monoceros. Distant about 2,500 light-years from the earth, it is about 50 light-years in diameter. The bright parts of the nebula are illuminated by atoms in the cloud which are excited by nearby hot stars. The dark matter obscures the light of all background stars. Clouds such as these may contain the material from which stars are formed. Photo by 48-inch schmidt.

Messier 104—number 104 in Messier's catalog of celestial objects—is a giant spiral nebula, one of the brightest of a cluster of nebulae in the constellation Virgo. M 104 is about seven and a half million light-years from the Milky Way. The nebula is seen edge-on, and dust clouds lying along its rim are silhouetted against the mass of individual stars in the main body. Photo by 200-inch.

position, and much about the temperatures and pressures (and therefore much about the size and mass) of the stars in the Milky Way. They have learned that no stars contain any elements other than the 90-odd known on earth; that hydrogen constitutes a surprising proportion of (most of, in fact) the matter in the system; and they have reason to believe that the differences between stars lie not so much in the relative abundance of other elements as in the amount of hydrogen that they contain, and in the differing nuclear processes that accompany the various central temperatures and concentrations of hydrogen.

Stars are put in classes in accordance with the spectrographic record that they make in the earth's telescopes. These classes form a series ranging from the blue (hot and brilliant) stars down to the red (comparatively cool) stars. The sun falls in the middle of this series; it is a yellow star—medium hot, medium bright, medium sized.

It is probable that these various types of stars derive their enormous energies not from one, but from a variety of complex processes, all of which liberate nuclear energy. One of the things astronomers are trying to learn, today, is just what these processes are.

Another thing they want to learn is whether or not there is a uniform evolutionary cycle through which every star passes. If such a cycle were discovered and a time scale found to fit it, then the age of every star could be determined, and the problem of the origin and age of the universe would be brought much closer to solution.

A third question centers around the novae and supernovae. Every year, about 20 of the billions of stars in the Milky Way system "explode" into novae rising to a brilliance perhaps 50,000 times that of the sun. Once every few centuries, one of the billions explodes into a *super*nova, several million times the brilliance of the sun. The questions that these stellar flare-ups raise are many: What causes them? What forms does matter assume in the heart of these great bursts? Is there any way of knowing ahead of time whether or when a particular star (our sun, for example) is going to let go?

One of the most interesting questions of all, of course, is: How was the solar system brought into being? The answer to this question, if it is found at all, may well be found in dry and laboriously compiled statistics on stars and double stars and star-clusters and magnetic fields and dust clouds and so on. All of these things are most easily studied in the Milky Way.

3. The Universe. Beyond the boundaries of the Milky Way system are millions of other systems, many of which have the same spiral structure and are comparable in size to it. The nearest of these spiral nebulae is separated from the Milky Way by a distance equivalent to ten times the diameter of the whole Milky Way system, and the farthest of them that has been observed is almost a thousand times as far away as the nearest.

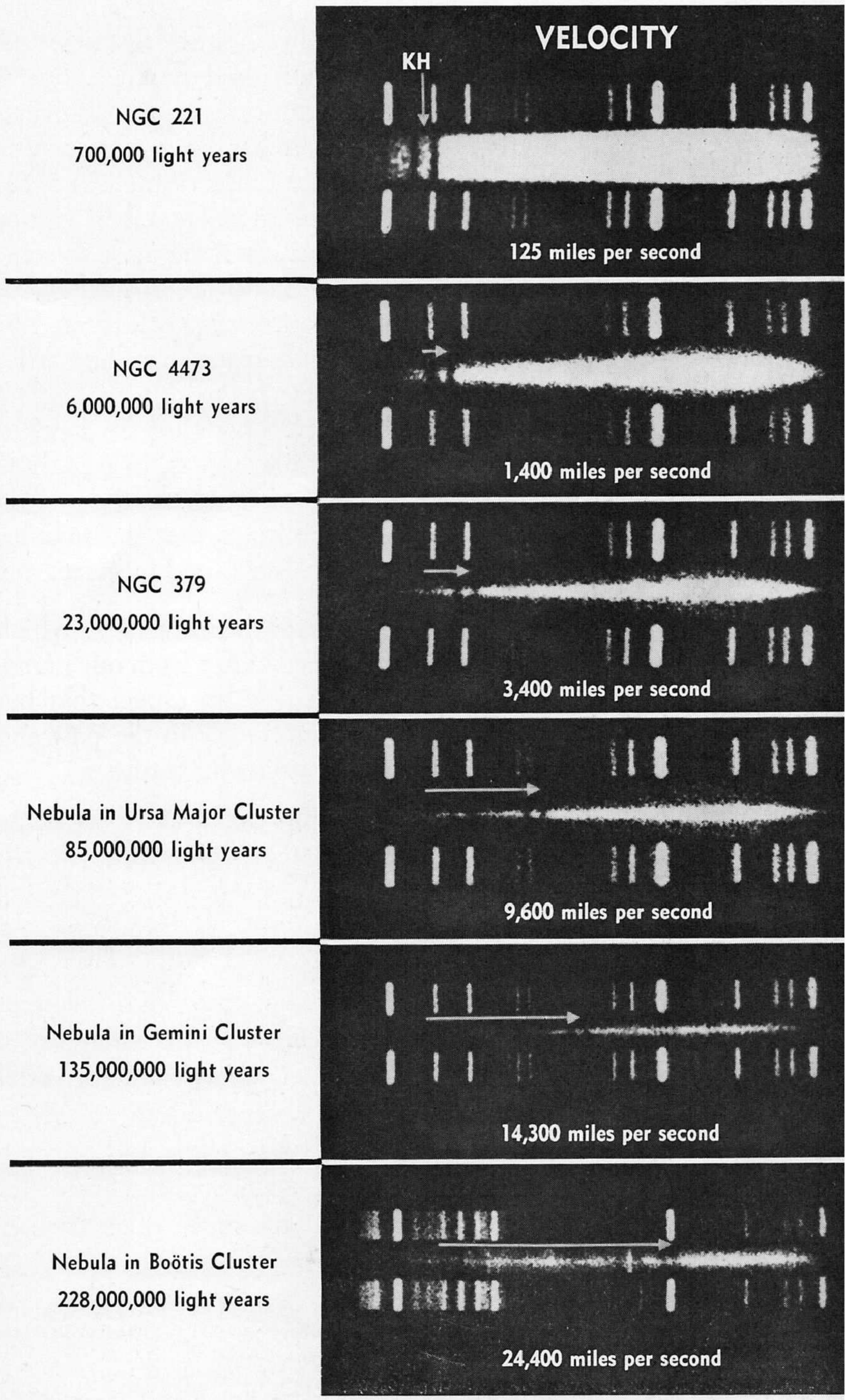
Much of the research being done on these distant nebulae is the same as that being done on objects in the Milky Way, for many of the nebulae are close enough so that telescopes —the biggest ones, at least—can distinguish and study individual stars in them. Only one of these spiral nebulae, however, the Great Nebula in Andromeda, is bright enough and near enough to be even dimly visible to the naked eye.

The study of individual stars in distant nebulae is particularly important when it comes to novae and supernovae, because these (particularly the latter) are rare enough in the Milky Way to make the additional examples in outer space welcome. No supernovae have occurred in the Milky Way system since astronomy came of age, but many have been observed in other star-systems. And, since a supernova can grow so brilliant as to produce an amount of light equivalent to the total light emitted by all the millions of other stars in its system, the study of these remote explosions can be quite detailed in spite of the tremendous distances involved.

Another field of research, one that has meaning only in terms of the star systems beyond the Milky Way, deals with the types of nebulae. It has been said that such nebulae are roughly comparable to the Milky Way, and they are: but they differ in shape, in size, and even to some extent in composition. There is some indication that the nebulae, like the individual stars in each of them, may go through an evolutionary cycle; the importance of discovering that cycle if it exists, and of assigning a time scale to it is obvious, as such information will eventually lead to a more accurate estimate of the form, size, and age of our *own* system.

Much of the study of the nebulae outside

Messier 51, at the left, is a spiral nebula with an irregular companion below it. At its distance—three million light-years—even the 200-inch can resolve only the brightest stars in the spiral's "arms." The contrast in the contents and structural patterns of the two systems is obvious, and points up the multitude of types of star systems that apparently exist. It was in M 51 that the spiral pattern was first detected by Lord Rosse in 1845.



Each of the spectrograms above shows the spectrum of a distant star-system in between two reference spectra created at the observatory and put on the same "plate." The nebulae whose spectra appear here are at distances increasing from top to bottom of the series, and the increasing "red shift" is indicated by the length of the arrows. The speeds that each red shift indicates are given. Not obvious from the illustration, but still a remarkable fact, is that the amount of shift in the spectrum is *directly proportional* to the distance.

the Milky Way applies neither to individual stars nor even to individual nebulae, but to the general characteristics of the universe itself. For instance, it has been necessary to determine how matter is distributed in space —whether there are more nebulae in one direction than another, or more close to some central point in space and fewer farther out toward some hypothetical edge of space. The study of the sample of space that the earth's telescopes have so far been able to explore indicates homogeneity. Though there are clusters of nebulae in various areas, just as there are clusters of stars in each nebula, the present available evidence indicates that the nebulae in general are evenly distributed in space.

There is one aspect of the universe in which the more distant objects differ from our immediate neighbors, however, an aspect that has taken a lot of laborious study in the past and will demand still more in the future.

As has been pointed out earlier (see p. 18), and is evident from the illustration on p. 45, the light from distant nebulae is shifted toward the red end of the spectrum. Furthermore, this shift becomes progressively greater, the more distant the nebula, increasing *in direct proportion to the distance.* This relationship has been found to be so unvarying that the red shift is now used to measure distance: Measuring the "red shift" of a nebula and comparing it with the curve already plotted provides an estimate of the distance of the nebula.

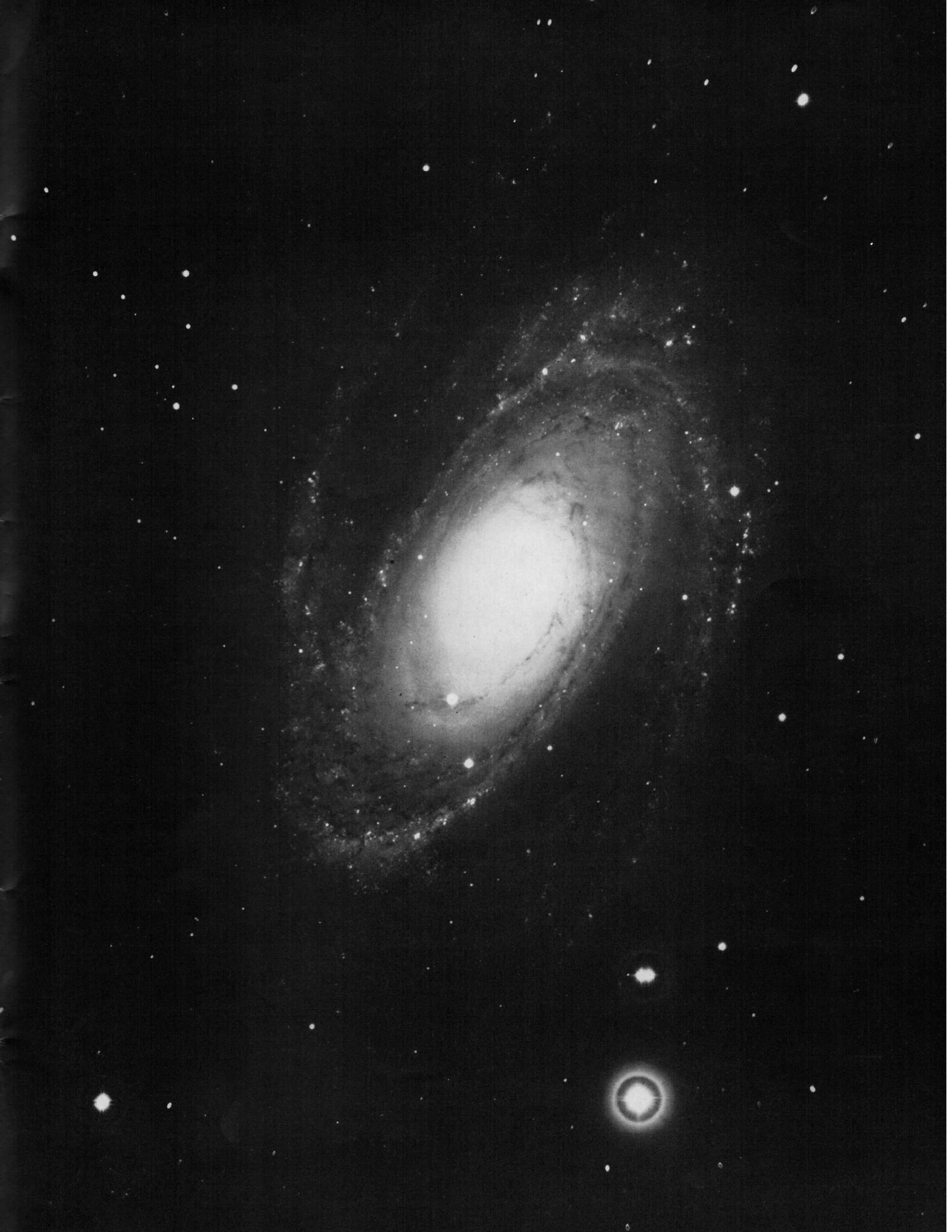
The simplest way of accounting for the red shift is to assume that the nebulae are moving away from the earth, and that the farther away they are the faster they are moving. It is this idea that has led to the concept of an "expanding universe." Actually, however, while motion seems the only logical explanation for the red shift at this time, there may be some other explanation based on some still-unknown principle.

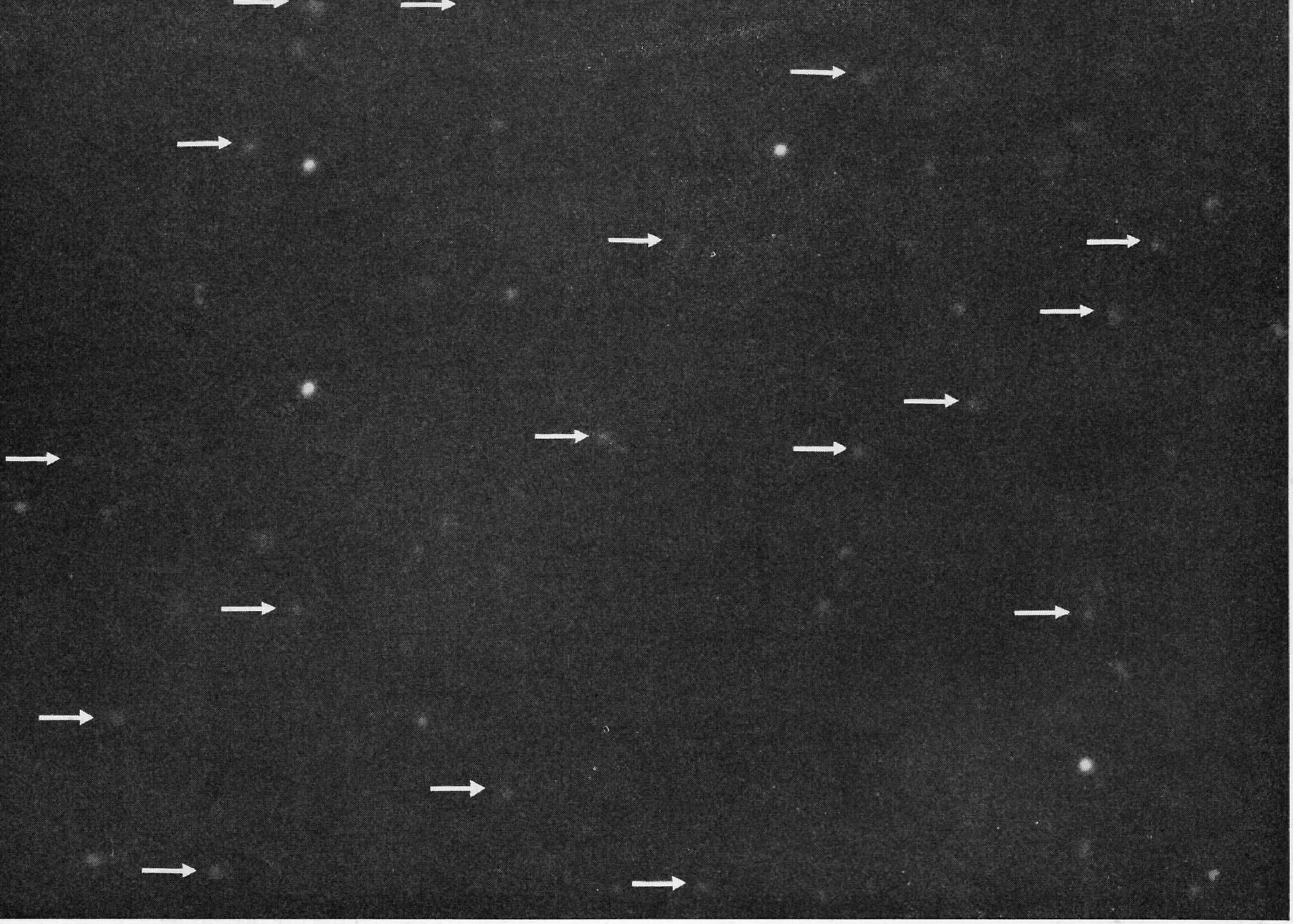
Measurement of the red shift is not too difficult in the case of the nearer nebulae; those at the outer range of the 200-inch, however, are little more than faint cloudy specks on a photograph. Their light is so faint that it cannot be spread out into a long spectrum, even with several consecutive nights of exposure-time; much of the red-shift measurement must therefore be done with spectrograms only about one-tenth of an inch long.

While the study of the stars and other objects in the Milky Way system may produce clues as to the formation of the solar system, this investigation of the whole observable universe may answer the still more fundamental question: How was the *universe* born?

Besides helping to answer that question, the study of the distant nebulae will provide vital information on the basic laws that control all matter, whether that matter be found here on earth or 6,000,000,000,000,000,000,000 miles away.

Messier 81, a spiral nebula about three million light-years from the Milky Way system, shows an interesting phenomenon common among such nebulae; the individual stars in its arms are what astronomers know as Type I star population, and are considerably brighter than those in its center (Type II star population). The 200-inch, in this photo, resolves many bright stars in the arms.





This photograph, which was taken with the 200-inch Hale telescope, shows objects near the present limit of the observable universe. Each of the minute, dim blurs indicated by an arrow is a system containing many millions of stars. If these systems are, as is probable, like most others in size and brightness, they are from 500 million to over 800 million light-years from the telescope.

The spiral nebula NGC 4565, pictured on the facing page, probably looks much as our own Milky Way system would look if seen edge-on. Like many other systems, it contains gas and dust clouds as well as billions of stars. At its great distance, even this 200-inch photograph resolves only a few super-giant stars in the nebula.

On the back cover is a 200-inch photo of Messier 16, a part of the Milky Way cloud in the constellation Serpens. The bright areas are clouds of dust and gas illuminated by nearby stars; the dark areas, clouds of obscuring matter which black out the stars behind them.

These and the other astronomical photographs in this book exemplify one of the principal kinds of work done with great telescopes. Many more such photographs are displayed and explained in the Observatories' two museums which are maintained for the benefit of the public—one on Mount Wilson, the other on Palomar Mountain.

An observation gallery in each of the two observatories provides an opportunity for the public to see the great telescopes themselves—the 100-inch Hooker on Mount Wilson and the 200-inch Hale on Palomar. These tools of the astronomer provide him with the raw material of astronomy—photographs and spectrograms, the minute measurement and analysis of which enable us to push our knowledge of the universe out to more and more distant frontiers in space.