12 June 1964, Volume 144, Number 3624 SCIENCE

Determination of Stellar Distances

The Navy's new telescope at Flagstaff, Arizona, was especially designed for measuring stellar parallaxes.

K. Aa. Strand

The principle involved in measuring the distance to a star is as simple, and much the same, as that a surveyor uses to determine the distance of a geographic site or object which is either inaccessible or awkwardly located for direct measurement of its distance. His method is illustrated in Fig. 1, taken from the famous mathematical tables of Tobias Mayer (*1*). The base line *OP* is of known length; the surveyor measures the angles *R* and *S* and, by simple geometry, determines the length of *OQ* and *PQ*. In the astronomical measurement the base line *OP* equals the radius vector of the earth's orbit (or 150 million kilometers) and angle *R* is 90 degrees. Angle *Q* (not angle *S*, as in the surveyor's method) is measured, through measurement of the parallactic shift of the star. From these three values the side *PQ*, or the distance to the star, is readily computed.

However, because of the tremendous distances to the stars, the parallactic shifts (apparent shifts caused by the earth's revolution around the sun) of even the nearby stars are such small quantities that, even today, this type of research is still considered one of the most difficult in observational astronomy.

The Navy has a new telescope which was designed especially for measuring stellar parallaxes, although it is in many respects an all-purpose telescope. It is a reflector with a primary mirror 61 inches (155 cm) in diameter and a focal length of 15.2 meters. It is located at the Naval Observatory's station near Flagstaff, Arizona.

The main observing program with the new telescope is the determination of the distances to intrinsically faint stars within 30 parsecs (*2*) or 10^{15} kilometers of the sun. Since the telescope will be used primarily for determining the positions and the motions (real or reflected) of the stars in a branch of astronomy generally called astrometry (*3*), it has been called an astrometric reflector.

The telescope is described later in this article in more detail, but for the benefit of those not very familiar with the problem of determining stellar distances, I shall begin by describing the earlier phase of this work.

Early History

It was only a century and a quarter ago (1837–1839) that the first successful measurements of stellar distances were announced. In almost simultaneous determinations, the parallax of the double star 61 Cygni was measured by Bessel at Königsberg, that of α Lyrae (Vega) was measured by W. Struve at Dorpat, and that of the double star α Centauri (the sun's nearest neighbor) was measured by Henderson at the Cape of Good Hope. The determination of these parallaxes marked the attainment of new degrees of refinement in instrumentation and observation, and is rightly considered among the greatest achievements in observational astronomy.

The earliest attempt by the astronomers to measure the distances to the stars was a method which is illustrated in Fig. 2. Two stars, S_1 and S_2, which make an angle of 180 degrees when the earth is at E_1, were selected. Half a year later the earth will be at E_2, and the angle between the two stars will be less by an amount equal to the sum of the angles subtended by the diameter of the earth's orbit as seen from the two stars. If the original angle is not exactly 180 degrees, or if both stars are not in the plane of the earth's orbit, the problem is slightly more complicated, but the basic idea remains the same.

Since it is not feasible to measure angles as large as 180 degrees on the sky, this method requires determination of the absolute coordinates of the stars, but even to this day such determination cannot be made with sufficient accuracy for this problem, because of inherent observational errors.

Copernicus used this method in the 16th century, but found no detectable effect and concluded that the stars must be at least 1000 times more distant than the sun. Toward the end of the 16th century Tycho Brahe tried to measure the effect with more refined instruments, but he, too, failed. Rather than accept the remote distances of the stars which the lack of detectable effect suggested, he concluded that the earth did not revolve around the sun.

As instrumentation improved, astronomers over the next several centuries attempted to use the same method to detect the parallactic effect, but the results were always negative.

Independently of each other, Galileo and Huygens proposed another method in the 17th century. Their idea was to measure the difference between the parallactic displacement of two stars adjacent to each other in the sky but at different distances from the sun.

The author is scientific director of the U.S. Naval Observatory, Washington, D.C.

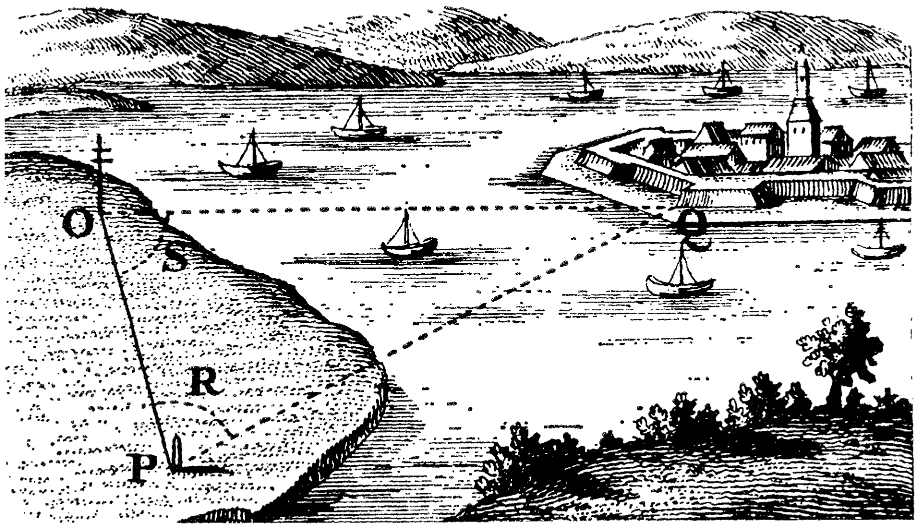

Fig. 1. The surveyor's method of determining the position of Q with respect to O and P. [Tobias Mayer (*1*)]

The orbital motion of the earth causes both objects to describe small ellipses on the sky—larger for the nearer stars and vanishingly small for the very distant ones. This method has advantages in that the parallactic shift can be obtained with far greater precision from differential measurements of star positions than from the absolute positions.

Toward the end of the 18th century William Herschel started an observing program with the intention of determining the differences in parallactic shift between adjacent stars separated by a few seconds of arc. He did not succeed in measuring a stellar parallax in this way, but he found instead that many of the pairs of stars he had measured were physical systems in which the components clearly showed orbital motions with respect to each other. In such systems the distances of the two stars from the solar system are nearly identical, and therefore they show no parallactic shift relative to each other.

There are, of course, optical double stars whose members are at widely different distances from the solar system though they are seen nearly in the same direction in space. An example is Vega and its companion, which was used by Struve in his determination of the parallax of Vega. The companion has a magnitude of 10.5 and is separated from Vega by 43 seconds of arc. Bessel measured the parallax of 61 Cygni with respect to two optical companions located 462 and 706 seconds of arc, respectively, away from 61 Cygni itself.

Differential measures of this kind were made for a large number of stars during the 19th century, with more or less success.

Before reviewing the efforts that were made in the 19th century to determine stellar parallaxes, let us briefly consider the principle of measuring the trigonometric parallax of a star.

In Fig. 3 are shown two positions of the earth in its orbit around the sun, half a year apart. The nearby star whose parallax is to be determined is seen displaced against the distant background stars. The nearer the "parallax star" is to the solar system, the larger will be the displacement due to the earth's orbital motion. The amount of displacement gives, therefore, a measure of the distance of the star. If the stars used as a basis of comparison are at nearly the same distance from the solar system as the parallax star, the displacement will be inappreciable, as Herschel found for the companions in binary star systems. The size of the earth's orbit relative to the distance of the star is much exaggerated in the diagram of Fig. 3; actually, even for α Centauri, the star nearest the solar system, the angle π (called the parallax) is only 0.76 second of arc, or the ratio of the radius r to the distance d is 1:275,000. Measurement of the angle π is further complicated by the fact that the nearby star, in addition to its parallactic movement, also in general has a translational motion (proper motion) with respect to the background stars.

The results of the 19th-century astronomers Struve, Bessel, and Henderson, who pioneered in measuring stellar parallaxes, are indeed quite remarkably accurate when we consider how primitive their instruments were by modern standards. Struve, at the Dorpat Observatory, used a refractor of only 9-inch (23-cm) aperture to measure the parallactic shift of Vega with respect to its faint optical companion. The actual measurements were made with a filar micrometer attached to the eye end of the telescope. A filar micrometer is an instrument used to the present time for measuring the relative positions of companions in close double-star systems; Struve showed unusual skill in using it and obtained results of very high precision—a precision which has not been surpassed by observers since his time.

Bessel measured the parallax of 61 Cygni with a heliometer built by Fraunhofer. It had a 6¼-inch (16-cm) objective divided along a diameter, and each half-lens produced an image of the star. By shifting the half-lenses

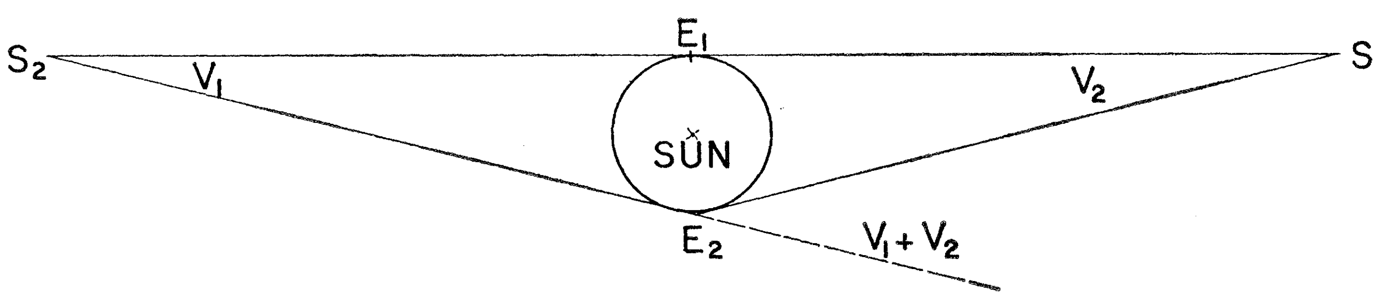

Fig. 2. An early but unsuccessful method of measuring distances to the stars.

with respect to each other by means of controls operated from the eyepiece of the telescope, the two images could be made to coincide. The shift in the position of the two lens halves gave a measure of the separation of the images.

Henderson made his determination of the parallax of α Centauri with a mural circle, an instrument which was used to measure the meridian altitudes of stars. This type of telescope was not particularly well suited for parallax observations, but the fact that he succeeded was the result of a happy combination of his skill as an observer and the fact that he had picked the star which still has the largest known parallax, equal to 0.761 second of arc, according to modern determinations. The values Henderson obtained for the parallaxes of the two components of α Centauri were 1.38 and 0.91 seconds of arc, respectively; these values are of the right order of magnitude according to the root mean square errors of ± 0.13 and ± 0.25 second of arc, respectively, for the two determined values.

Struve's first series of observations of α Lyrae (Vega) were made on 17 nights between November 1835 and December 1836. He found a parallax of 0.125 second of arc—a value which is practically identical with the best modern value (0.123 second of arc), but in view of the probable error of ± 0.055 second of arc which he obtained, he concluded that the parallax very probably would lie between 0.07 and 0.18 second of arc. In a later determination he practically doubled his first value, obtaining a parallax of 0.261 second of arc.

Bessel's determination of the parallax of 61 Cygni was the most convincing of the results of the three investigations. He obtained values for the parallax of 0.369 second of arc relative to comparison star *a* and 0.260 second of arc relative to star *b*. The combined value, 0.314 second of arc, determined with a mean error of ± 0.019 second of arc, is very close to the modern value of 0.292 second of arc.

Throughout the remainder of the 19th century many attempts were made to determine stellar parallaxes, but the results were invariably poor; even the best of these results have been superseded by modern determinations and are now of only historical interest. Toward the end of the century the first attempts were made to substitute photographic observations with refractors for the slow process of measuring parallaxes by visual means. However, the results of the early photographic observations were even more distorted by systematic errors than the results of the visual observations were.

In Newcomb's book *The Stars* (*4*), published in 1901, there is a list of the stellar parallaxes that had been determined up to the turn of the century. There are only 72 stars in the list; moreover, for 17 of them the parallaxes were doubtful, and for one, the parallax was entirely unreliable.

Modern Techniques

The modern era of measuring stellar parallaxes began in 1903, when Schlesinger, using the 40-inch (102-cm) refractor at the Yerkes Observatory, introduced a new method. This consists of taking a series of photographs on which the position of the parallax star is referred to a "background" of three or more reference stars. With his photographic techniques Schlesinger obtained results with an accuracy not achieved before. He selected an emulsion and a filter which would keep the

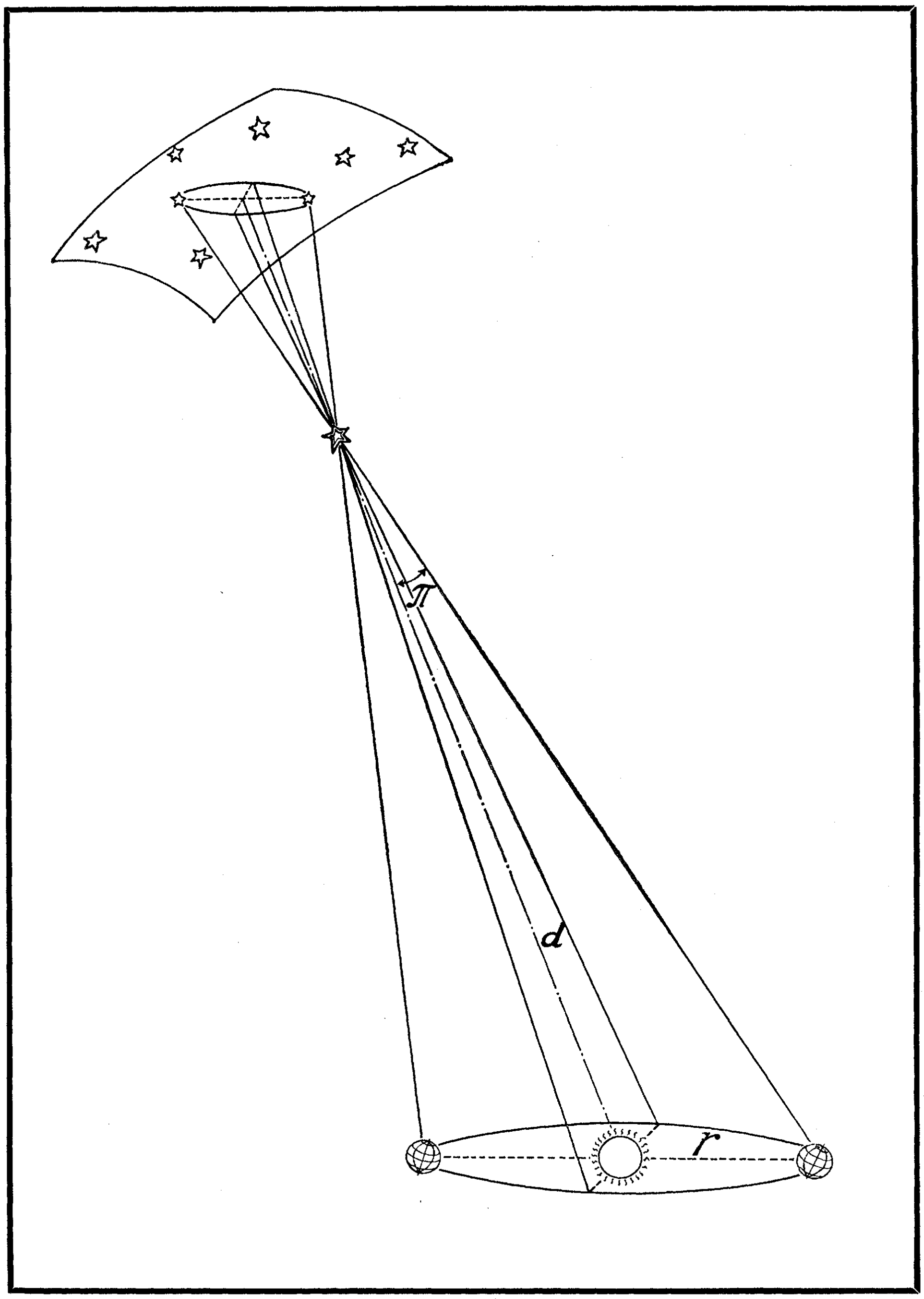

Fig. 3. The parallax of a star is the angle at the star subtended by the radius vector of the earth's orbit. The "parallax star" describes during the year an orbit against the background of the more distant stars. From the dimension of the orbit the parallax is determined.

range of light close to the wavelength region corresponding to the minimum focal length of the refractor's focal curve, and he used a rotating sector in front of the plate to reduce the brightness of the parallax star to that of the comparison stars. In addition, he made his observations close to the meridian. Contributing factors in his success were his methods for measuring the positions on the plates and for simplifying the required calculations. After leaving the Yerkes Observatory, Schlesinger instituted parallax-measuring programs first at the Allegheny Observatory and later at Yale University's Johannesburg Station in South Africa. He built, in both places, large refractors for these programs. Other important contributions to the determination of stellar parallaxes were made at the Cape of Good Hope, McCormick, Greenwich, Mt. Wilson, Sproul, and Van Vleck observatories.

The joint efforts of these relatively few observatories are impressive: the *General Catalogue of Trigonometric Stellar Parallaxes*, assembled by Louise Jenkins (*5*) and published by the Yale University Observatory in 1952, lists parallaxes of 5822 stars, based upon approximately 10,000 individual determinations. Progress since that date has been somewhat slower, because some observatories have discontinued work in this field while others still active in the field, such as the Allegheny and Sproul observatories, have considerably increased the number of photographs they take for determining each parallax in order to make the determination more exact.

The parallactic shifts measured on the photographic plates in determining a parallax are, even for the nearer stars, very small—often shifts of only a few microns. As a result, it is necessary that the telescope used be one of sufficient focal length to provide relatively large-scale shifts on the photographic plate, and that the greatest possible accuracy of measurement be obtained.

Since photographs taken on different nights or during different seasons and years are used in combination for determining a parallax, it is important that the optical performance of the telescope be kept as constant as possible.

Statistical investigation of the accuracy of the parallaxes in the catalogue mentioned shows that the average accidental error is ± 0.011 second of arc, corresponding to ½ micron on the scale of a telescope of 10-meter (33-ft) focal length. On the average, 12 to 15 plates were used for an individual parallax determination and the telescopes used ranged in focal length from 14.4 meters (Yerkes refractor) to 6.9 meters (refractors at the Cape and Greenwich observatories); slightly higher accuracy was obtained with the telescopes of greater focal length.

In a recent study (*6*) of the accuracy of parallaxes obtained from the longer series of 50 plates—a study in which data from Allegheny, Sproul, and Yerkes observations were compared—the external probable error was estimated to be of the order of ± 0.006 second of arc. The use of additional plates would not materially increase the accuracy because of certain latent sources of instrumental error.

As a result, the accuracy of determination for a stellar parallax of 0.030 second of arc is, at best, 20 percent; this is generally considered the practical limit below which an individual parallax determination becomes of little value except for statistical purposes. A parallax of 0.030 second of arc corresponds to a distance of 33 parsecs (100 light years) or a distance of 10^{15} kilometers.

Ninety-five percent of the 11,000 parallaxes determined so far have been obtained from plates made with long-focus refractors.

Aside from the fact that the refractors were the only large telescopes available when the parallax programs were started, they were considered particularly well suited for this work because they had a large-scale field of approximately half a degree in angular extent, and minimum optical distortion. The long-focus refractors have other advantages as well, such as control over the scale of the plates and permanency of the optical system.

These advantages are mentioned repeatedly in the astronomical literature, yet there had been no specific evaluation showing superiority of the refractor over the reflector in astrometric research. Thus, some of the work previously done with reflectors in this field has been discredited and new attempts have been discouraged. It is only within the last few years, primarily from work done at the Sproul Observatory (*7*), that it has been shown that the large refractors do not possess permanency of the optical system to the degree that had previously been assumed.

As far as stellar parallax determinations are concerned, I have recently published a comparison between those made by van Maanen with the 60-inch (152-cm) reflector at the Mount Wilson Observatory (built in 1917) and those obtained with the refractors at the Allegheny, Yerkes, and McCormick observatories; I found no difference in accuracy (*8*).

Van Maanen obtained his plates at the Cassegrain focus (*9*) of the reflector, which has a focal length of 25 meters and a scale of 8.2 seconds of arc to 1 millimeter. He investigated the optical errors, in particular the effect of the coma (*10*) on the images, and found that a field within a radius of 10 minutes of arc from the optical axis could be used without perceptible errors (*11*). He also stated that slight changes in the optical system might occur when the mirrors were replaced after silvering. However, the maximum change in the inclination of the optical axis after adjustment was approximately 2 minutes of arc, a change which would not introduce an error of more than 0.001 second of arc in the final parallaxes, and which obviously could be neglected.

Van Maanen also determined parallaxes with the 100-inch (254-cm) Mount Wilson reflector, but here he encountered considerable difficulty because of the large accidental errors introduced by the plate material. More serious were the large systematic errors which many of the parallaxes showed by comparison with parallaxes obtained with refractors. A further analysis of the data shows that in those cases where the parallax stars were so faint that comparison stars of the same magnitude could be found so close to the optical axis that their images were not affected by coma, the parallaxes obtained with the Mount Wilson reflector are in good agreement with those obtained with refractors (*8*). It may therefore be assumed that the parallaxes obtained with the reflector are in effect as accurate as those obtained with the refractor, provided the measured star images are well within the coma-free field of the reflector.

The total length of the comatic image, K, depends upon its distance (β) from the optical axis and upon the f-ratio (D/F) of the telescope, in accordance with the formula

$$K = \frac{3}{16}(D/F)^2 \beta$$

where both K and β are expressed in seconds of arc, D is the aperture, and F is the focal length of the telescope.

Assuming, under good seeing conditions, an optimum image size of 1.2 seconds of arc for the axial image of the 100-inch telescope, Ross (*12*) concluded from empirical data that the coma would first be detectable for $K = 1.62$ seconds of arc—that is, according to the foregoing formula, would be at a distance of 3.6 minutes of arc from the optical axis. It may be seen from this that the useable field for precise astrometric work is very small in this case.

From experience I have found that, in view of the large number of plates that must be obtained for each parallax determination, the program becomes very unwieldy if the exposure times are longer than 15 minutes. The reason for this is that each plate should contain two to three exposures, and the photographs should be taken close to the meridian. In view of these considerations the practical limiting magnitude of even the largest refractors now in existence is of the order of 13.5 magnitude for trigonometric parallaxes.

In recent years, survey of proper motions by Luyten (*13*), at the University of Minnesota, and by Giclas (*14*) has led to the discovery of many hundreds of intrinsically faint stars of apparent magnitude below the effective limiting magnitudes of the large refractors. The proper motions of these stars indicate that they are nearby objects with measurable parallaxes. These stars, called red dwarfs, white dwarfs, and subdwarfs, differ drastically both in size, density, and energy generation from the solar or general main sequence stars (Fig. 4). They are therefore of great astronomical interest. Determination of the physical properties of these objects requires a knowledge of their energy generation, which can be evaluated only after their distances are known. In view of their low apparent magnitude it is necessary to use reflectors for obtaining the plate material for these determinations.

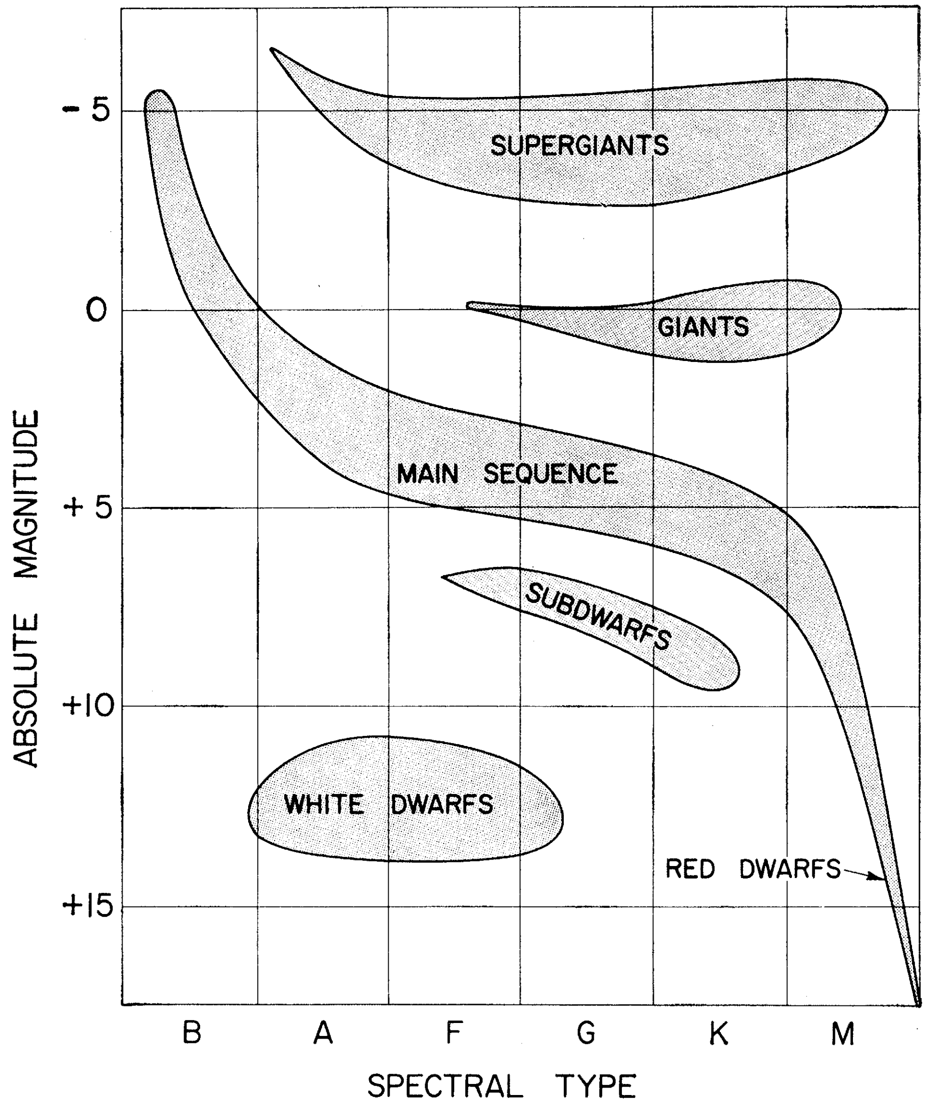

Fig. 4. The Hertzsprung-Russell diagram. Most stars, including the sun, belong to the main sequence. The intrinsically brightest stars are the supergiants; the faintest are the white dwarf and red dwarf stars. A magnitude difference of 5 corresponds to a difference in brightness (luminosity) of 100. Research in recent years indicates that there is probably one or more sequence of stars below the white dwarfs.

The Astrometric Reflector

For the reader not familiar with the work done at the U.S. Naval Observatory, I would like at this point to quote the statement of its mission: "To make observations of the positions of celestial bodies with the highest precision; to determine and promulgate precise time both astronomical and physical; to conduct astronomical and astrophysical research; and to derive and publish predicted positions and phenomena of celestial bodies so as to meet the needs of navigation, astronomy, astronautics, geodesy, and other sciences."

Certain of these programs are international in scope and are carried out in cooperation with the national observatories of France, Germany, Great Britain, and the U.S.S.R., among others. The research programs in astrometry and astrophysics of the Naval Observatory have been primarily long-range programs which require a team rather than a single observer; this, in combination with the instrumental requirements, makes such programs often too costly to be undertaken by an individual academic institution. Measurement of the parallaxes of the faint stars was considered to be in this category, and in view of recommendations by several international conferences that such a project be carried out, the Naval Observatory decided, in the spring of 1959, to acquire a telescope primarily designed for this purpose.

The engineering design for both the telescope and the observatory was started in the fall of that year, with C. W. Jones, Engineering, of Los Angeles, as the contractor. The Southwest Division of the Bureau of Yards and Docks, U.S. Navy, supervised construction, and I served as technical director. Construction of the telescope was started in November 1961, with the firms of L & F Machine Company of Los Angeles and Boller and Chivens, Inc., of South Pasadena, California, as contractors. The telescope was completed in November 1963.

It differs in many respects from other large reflectors built in recent years, especially in regard to the ratio of focal length to aperture of the primary mirror. There has been a tendency in recent years to decrease this f-ratio from the traditional $f/5$ to values as small as $f/3.3$ for the 200-inch (508-cm) Palomar reflector and $f/2.75$ for the Kitt Peak 84-inch (114-cm) reflector.

The chief aim in decreasing the f-ratio is to decrease the overall cost through construction of a less massive telescope and a smaller observatory dome.

For astrometric work, such as the determination of stellar parallaxes, the small f-ratio is decidedly a disadvantage because of the small size of the coma-free field; this field, for the 200-inch reflector, is less than 12 millimeters in diameter on the photographic plate, or 2.9 minutes of arc. When a wider coma-free field is desired, it is necessary to use a coma corrector such as that devised by Ross (*15*). However, when the coma correctors are used for the prime focus of a telescope of small f-ratio, there is distortion and variation of scale with color of the star, which is not desirable in astrometric work of high precision.

Fig. 5. The rough silica blank for the primary mirror being examined at the Bradford plant of Corning Glass Works shortly after it was taken out of the furnace. [Corning Glass Works]

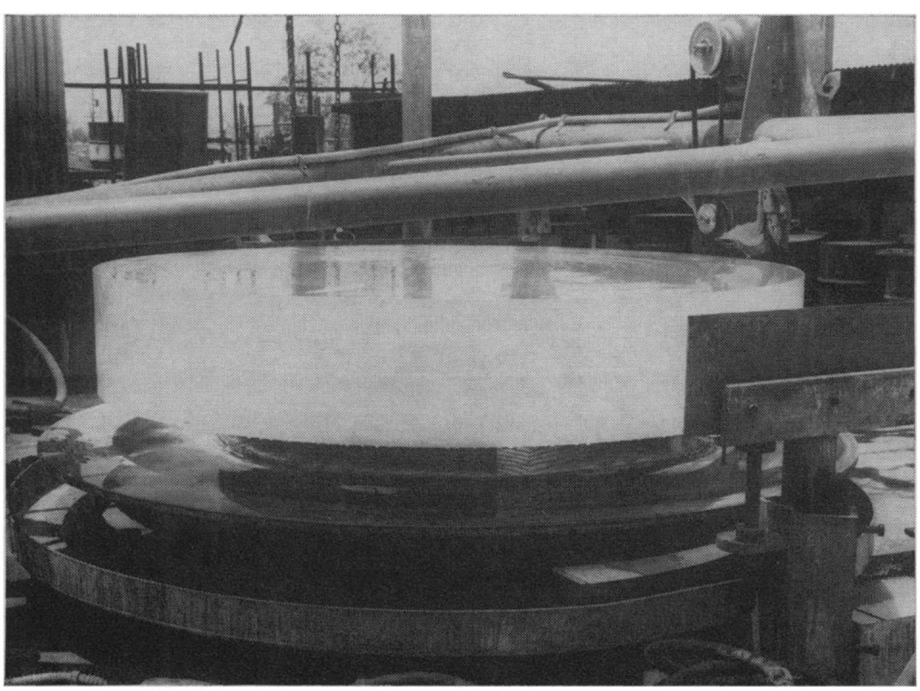

Fig. 6. The quartz disk for the primary mirror after rough grinding. This is the largest quartz disk by volume ever successfully manufactured. [Davidson Optronics]

The Navy's new astrometric reflector was therefore designed with an f-ratio of $f/10$, which, according to the formula given earlier, provides a coma-free field 29 minutes of arc in diameter. While the large f-ratio could be achieved by using a primary mirror of low f-ratio in combination with a Cassegrain secondary mirror of sufficient magnification, the collimation of a telescope becomes increasingly difficult as the f-ratio decreases and the secondary magnification increases. On the other hand, an optical system with sufficient focal length and a flat secondary mirror is ideal for astrometric work because, barring major shifts of the secondary mirror, the optical alignment requires only that the secondary mirror be perpendicular to the optical axis of the primary mirror.

Various factors were considered in determining the dimensions of the Navy's new telescope. Since exposure times longer than 15 minutes were considered impractical, and since the telescope was intended to photograph stars down to magnitude 18.0 within this time interval, the aperture of the primary mirror had to be not less than 60 inches (152 cm). While a larger aperture would provide a fainter limiting magnitude, a telescope of larger aperture and with the required f-ratio of $f/10$ would be too large to have the desired stability. The question of costs would also be a serious problem as the costs of telescopes generally increase by nearly the cube of the ratio of the apertures of the primary mirrors.

Optical Materials

An important decision was the choice of the material from which the mirrors were to be produced. The ideal situation for obtaining plates of a star field to be used in a parallax series is to observe the field on the meridian, with the sun setting in the west or rising in the east. Such an ideal is never realized; it is in any event essential that the observing time include the early evening and the early morning hours. However, the early-evening drop in temperature frequently produces such distortion in the figure of the optical mirror that the images formed by the optics are useless. To minimize such temperature effects it is essential that a material with a low coefficient of expansion and high thermal conductivity be used for the mirrors. A metal mirror has high thermal conductivity, but it was felt, in designing the telescope, that the art of producing metal mirrors of high optical performance had not advanced to the point where use of metal for the mirrors could be seriously considered.

Low-expansion glass, such as Pyrex, was introduced with construction of the 200-inch Palomar telescope, and it has since been used extensively for large optics. Quartz, which has a coefficient of expansion only one-fifth that of Pyrex (6×10^{-7} per degree Celsius), is obviously a more desirable material, and since Corning Glass Works had already produced a 36-inch (91-cm) silica disk for the Princeton Stratoscope II project, this firm was consulted about the possibility of producing the two mirrors for the astrometric reflector by their fused-quartz process from gaseous silica. After a preliminary hearing, Corning Glass Works, in May 1960, quoted prices and a firm delivery time. Specifications for the disk of the primary mirror called for a solid blank not less than 158 centimeters in diameter and no less than 26.8 centimeters thick. At that time, the maximum thickness obtainable with the fused-quartz process for a blank of this diameter was 9 centimeters. For this reason the firm was permitted to manufacture the blank by laminating four plates with three seals. This was accomplished by stacking the four plates on top of each other in the furnace and heating them to the melting point (1700°C); at this temperature they sealed together.

The rough blank (Fig. 5), weighing 1360 kilograms, was successfully manufactured and delivered to Davidson Optronics in West Covina, California, in May 1961 for rough grinding (Fig. 6) and testing for strains and for determining the inclusions (air bubbles) prior to acceptance of the mirror for figuring. Tests showed a maximum strain in the entire blank well below the maximum acceptable stress, and it had only 30 air bubbles, of the order of 0.25 millimeter or less in diameter,

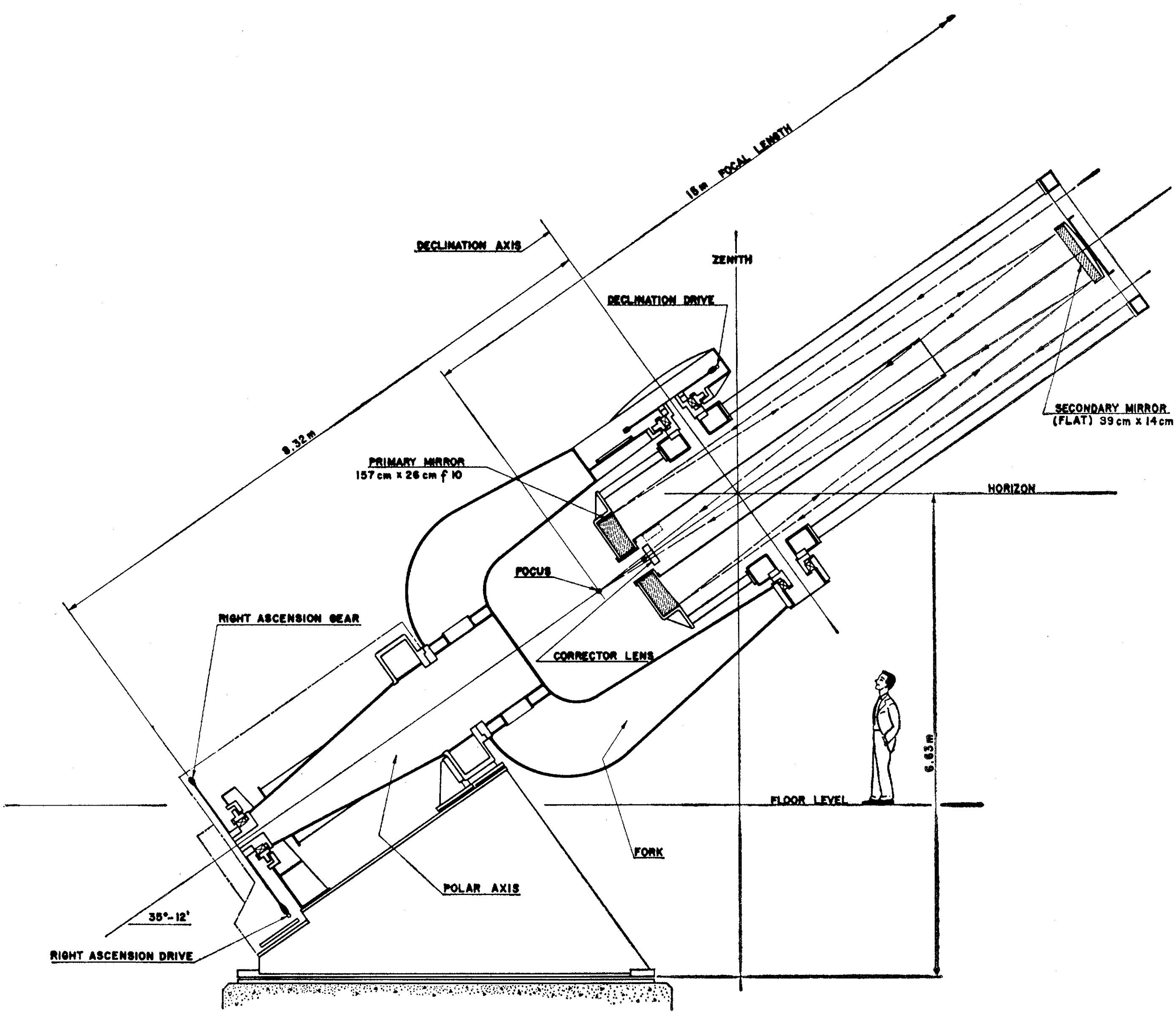

Fig. 7. Schematic diagram of the Navy's 61-inch reflector at Flagstaff, Arizona. [U.S. Navy]

in the area exposed to the stars. This was only 3 percent of the maximum allowable inclusions stated in the specifications. The secondary mirror, 89 centimeters in diameter and 15.2 centimeters thick, weighing 204 kilograms, showed strains less than one-third the maximum allowed.

The Telescope Mounting

The mounting of the astrometric reflector is of the fork type commonly used in modern telescope design (Fig. 7). The fork rotates about an axis pointed toward the North Celestial Pole; the telescope tracks a celestial body in its daily apparent motion through rotation of the fork around this axis. The fork holds the truss structure that holds the secondary and primary mirror cells. The truss structure rotates around an axis called the declination axis.

The total length of the fork from the center of the declination axis to the face of the fork resting against the polar axis is 4.72 meters. The fork, of welded steel, weighs 11,200 kilograms and is constructed of 2.5-centimeter steel plates reinforced by internal stiffening partitions. The fork inevitably has a certain amount of deflection as the telescope is pointed toward the sky in various directions. The total deflection in the fork in extreme positions was found to be less than 10 seconds of arc—considerably less than the amount specified as tolerable and not enough to create any noticeable errors in the orientation of the telescope field for long exposures, such as have occurred with the 120-inch (305-cm) Lick reflector (*16*).

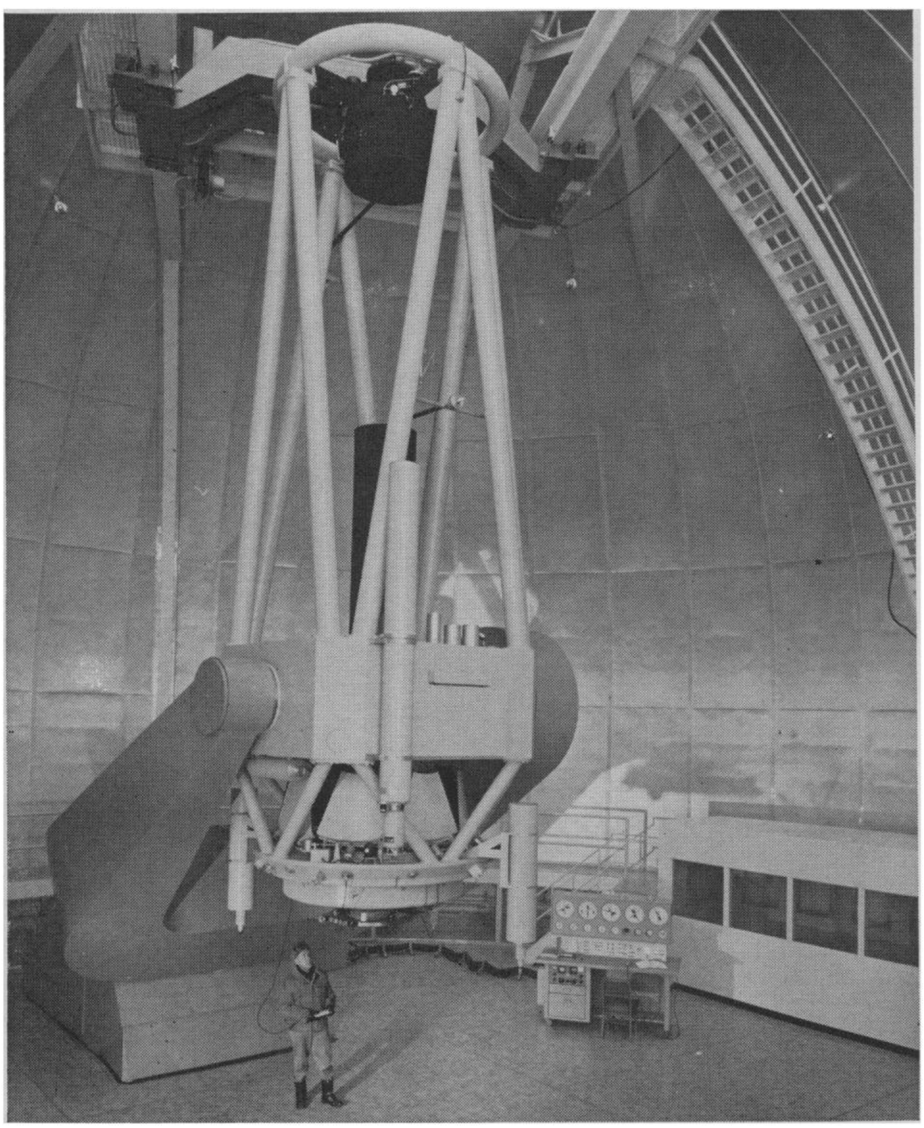

Fig. 8. The completed telescope pointing toward the zenith. The support struts for the primary- and secondary-mirror support systems are seamless steel tubing arranged in parallelograms according to the principle developed by Mark Serrurier. At lower right is the control console, which contains all the necessary indicators for operating the telescope. The observer is holding a small control box with a push-button system with which he can move the telescope in right ascension and declination. [U.S. Navy]

The tube of the telescope is the supporting structure for the cells holding the primary and secondary mirrors (see Fig. 8). It consists of a hollow square center section which is connected by means of truss structures with rigid rings at either end of the telescope. The truss structures were designed on the principle first proposed by Mark Serrurier and used successfully in the construction of the 200-inch Palomar telescope. The truss structures deflect the primary cell, under the pressure of gravity, to the same degree that the secondary cell is deflected; in this way the mirrors are held in a fixed relationship, regardless of where the telescope may be pointed.

The primary-mirror support struts hold an annular steel casting 2.24 meters in diameter, on which the cell is mounted (see Fig. 9). The primary and secondary mirrors, with their cells, weigh 5000 and 750 kilograms, respectively, while the total weight about the declination axis is 14,750 kilograms.

The rotating weight about the polar axis is 36,000 kilograms, and the weight is carried by a combination of oil-pad and standard ball bearings. The bearing closest to the fork, which supports most of the weight of the telescope, consists of three oil pads. The surface of each pad matches the journal surface of the polar axis against which oil flows at an average pressure of 54 kilograms per square centimeter. The oil film is only 0.075 millimeter thick. Precise machining of the polar axis is essential for precise tracking of the telescope. Although the polar axis is 3.65 meters long and the largest diameter is 2.1 meters, the bearing surfaces at each end of the axis had to be precisely machined to within 0.025 millimeter.

The low friction of the oil pads permits use of a single worm-and-gear wheel for all three speeds of motion of the telescope around the polar axis—such as fast motion, setting on a star field, and tracking at the sidereal rate.

The worm wheel is 2.29 meters in diameter and has 720 teeth; it was specified that the maximum tooth-to-tooth error and the total composite errors should not exceed 5 microns. Actual testing of the mounted telescope showed that the accuracy of the wheel-and-worm combination was well within the specifications. The periodic error is of the order of 0.25 second of arc over a 2-minute period; this is insignificant by comparison to the size of the measurable photographic image, which is of the order of 1.3 seconds of arc.

Corrections in the tracking of the telescope are made directly through the right ascension and declination drives. They are controlled automatically through photoelectric monitoring of the position of a star image in the field, the image being kept centered on top of a pyramid-shaped prism (*17*).

Optical Support System

Even though both mirrors are solid, they are of sufficient size to require support systems to prevent flexure due to their own weight. Initially it was planned to provide air-tight cell housing for both mirrors, so that air could be used to provide the back-axial support, cancelling most of the weight of the mirrors. Because of difficulties encountered in trying to seal the air behind the primary mirror, the plan was changed and support was provided by a buoyant neoprene bag filled with air, with a variable air pressure dependent upon the attitude of the telescope. The radial support of the mirror (support at the edge) is provided hydrostatically by means of a buoyant neoprene tubing resting against the mirror and partially filled with mercury. The mirror "floats" on mercury axially and receives in this way the support necessary to prevent flexure.

The support system for the secondary mirror is similar to that for the primary mirror, except that here the original idea of using an airtight system for axial support has been used and a vacuum has been applied. Because of the pressure supply and regulating system, the weights of the mirrors are cancelled axially, except for a necessary pressure against the defining pads in the mirror cells. The correct pressures, which must vary with the sine of the altitude of the telescope to provide the necessary support, are calculated by an analog computer.

Accuracy of the Optical System

The accuracy of the combined figure of the parabolic primary mirror and the flat secondary mirror was determined by means of Hartmann tests, the star images being photographed through a Hartmann screen. In tests made under average or above-average seeing conditions, a Hartmann constant of 0.11 was obtained, indicating an optical system of very superior quality. Profiles constructed from the Hartmann tests failed to show any deviations from true paraboloid greater than 1/20 of the wavelength of visual light, or 2.5×10^{-2} micron. The same test also showed that 100 percent of the light was within a circle of 75-micron (1.0 second of arc) diameter (*18*).

The position of the two mirrors with respect to each other is monitored by means of an autocollimator; this projects illuminated targets to the front of the secondary mirror and the back of the primary mirror, which are reflected back and viewed together at the eyepiece of the collimator. The tilt of the secondary mirror is adjusted by means of motors controlled from the eye end of the telescope.

Precise knowledge of the point on the photographic plate where the optical axis of the telescope intersects the plate is important if the full field is used. To establish this point, a built-in source with a beam splitter projects one image directly on the photographic plate and another by way of the two mirrors; the latter image is projected three times from the secondary mirror and twice from the primary. The point where the optical axis intersects the plate will be halfway between the two images on the plate.

A coma corrector is incorporated in the optical system, to be used when a large field with coma-free images is desired for purposes other than high-precision astrometric work. The corrector lens assembly, located 15 centi-

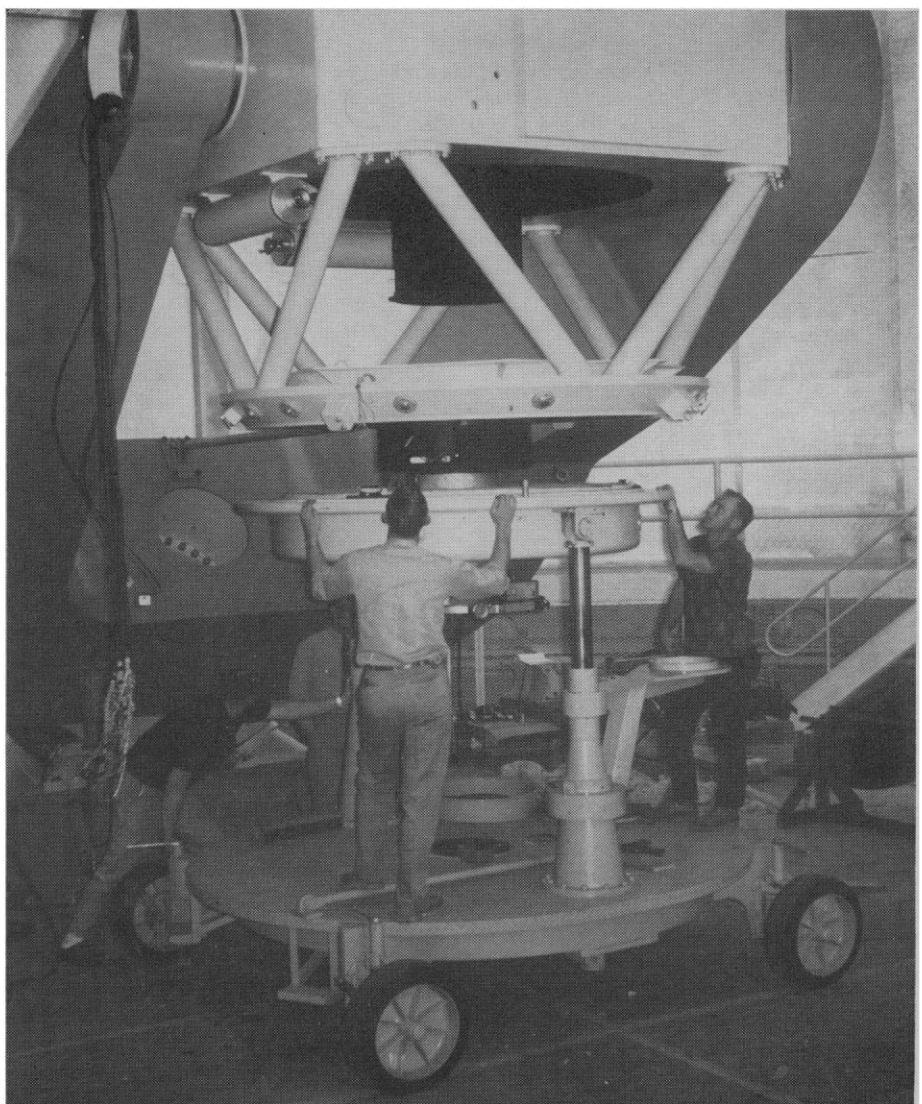

Fig. 9. The cell holding the primary mirror in process of being attached to its supporting ring at the lower end of the tube assembly. The cart holding the cell is used whenever the mirror is removed from the telescope. [U.S. Navy]

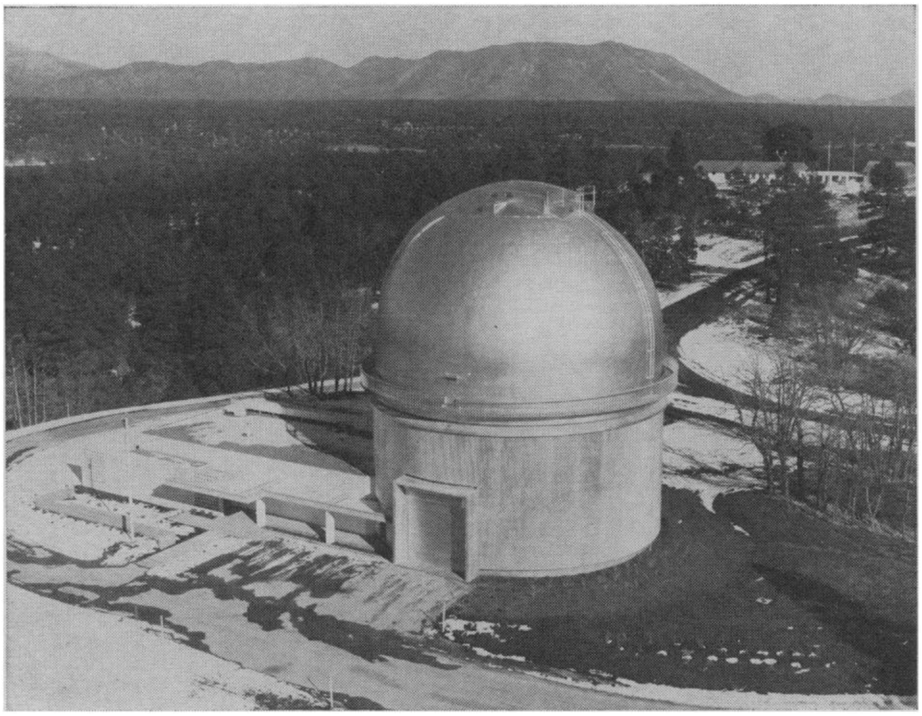

Fig. 10. The U.S. Naval Observatory's Flagstaff Station. The dome building houses the astrometric reflector. The wing to the left contains the offices, library, and darkroom. [U.S. Navy]

meters in front of the face of the primary mirror, is driven by a motor and folds in and out of the optical path in a plane parallel to the mirror. Since the corrector in the "out" position is hidden in the shadow of the secondary mirror, no vignetting is produced.

Instrumentation

The telescope is operated from a control console (see Fig. 8) which has dials that show the position of the telescope (in terms of right ascension, declination, hour angle, and altitude) and indicators of temperatures at various parts of the telescope, of pressures behind the mirrors, and of other parameters.

For the photographic work on stellar parallaxes, a special multiple-exposure camera is used, in which timing of exposures and transport of plates between exposures is automatic.

For other work, a spectrograph (with dispersions from 55 to 330 Å/mm), a photoelectric photometer, and a Meinel camera are under construction. The Meinel camera (*19*) will convert the 155-centimeter telescope to a fast *f*/2 camera in which provision is made for using narrow-band pass filters and a prism for obtaining miniature spectra of very faint stars.

The Flagstaff Station (Fig. 10) is approximately 8 kilometers west of Flagstaff, Arizona. It is at an elevation of 2300 meters, and the observing conditions are excellent: there are many clear nights and the atmosphere transparent and calm.

The observatory building was designed with the principal aim of keeping the temperature of the telescope always close to the night-time temperatures, even though the outside daytime temperature may rise as much as 10° to 15°C.

The stationary structure is a cylindrical building 10 meters high with an outside diameter of 20 meters. The outer wall is of reinforced concrete 30 centimeters thick, covered on the outside with a 5-centimeter cellular glass insulation. A corrugated aluminum shield is separated from the glass insulation by a spacing of 20 centimeters; this permits free flow of air between the solar screen and the wall insulation.

The dome has an outside diameter of 20 meters and is 15 meters high. The outer skin panels are contoured 0.6-centimeter steel plates welded together in place and painted with aluminum. The inside skin consists of trays 6 centimeters deep, filled with crumpled aluminum foil. A 30-centimeter space between the two skins is vented at the top and the bottom of the dome; thus the air can circulate and carry away much of the heat that is absorbed by the outer skin when it is exposed to the sun. Because of the combination of insulation and air circulation, the daytime temperature in the dome seldom rises more than 1° or 2°C above the night-time temperature.

The dome, weighing 150 tons, revolves on 20 carriage assemblies with a peripheral speed of 19½ meters per minute, making one revolution in a little over 3 minutes. Because of the high precision of the welded dome rail, only two 2-horsepower motors are required to turn the dome. The slit opening of the dome is 4.6 meters wide; the shutter consists of two horizontally moving shutter halves operated by four synchronized drive units.

Attached to the north side of the dome building is a one-story office building. Special care was taken to avoid radiation of heat and light from the building, lest such effects disturb the observing conditions.

The Observing Programs

From past and present surveys of the proper motions of stars we know that there are several thousands of stars with measurable trigonometric parallaxes, but too faint to be observed effectively with refractor telescopes. Even if the Navy's astrometric reflector were used exclusively for this type of work for 10 to 20 years it would not be possible to measure the parallaxes for more than a small fraction of the stars. Thus there must be careful selection in planning the observing programs, with observation of representative samples of the various types of stars that make up the faint part of the Hertzsprung-Russell diagram. Many of these stars are already known to be binary systems, and undoubtedly many more will be found. In particular, those binaries with white-dwarf components should receive special attention, so that their orbital motions, and thereby their masses, can be determined. This is another field in which little information is available at present; masses are known for only three white-dwarf stars, and only one of these is considered a bona fide white dwarf.

Other programs will compete with these studies for observing time. Among these will be photometric and spectroscopic investigations of individual stars and members of galactic clusters.

Conclusion

As we have seen, there were centuries of futile attempts before the first successful measures of stellar parallaxes were made. By modern standards the instrumentation used for these measures was crude, and thus the results obtained were remarkable. Even with modern instrumentation, such as the new Navy telescope, all possible precautions must be taken to attain the required precision. The displacements to be measured on the photographic plates are in all cases small, only a fraction of the diameters of the photographic star images from which the parallactic shifts are determined. Even with the fine optics of the new telescope the photographic images will have diameters of the order of 100 to 150 microns (1.3 to 2.0 seconds of arc), while the parallactic shifts to be measured will in most cases be less than 5 microns, and the mean error for the resulting parallax will be about 0.5 micron. With such tolerances there is little room for either instrumental or human error.

References and Notes

1. J. T. Mayer, *Mathematischer Atlas* (Augsburg, 1745).
2. One parsec = 3.1×10^{13} km = 3.3 lt yr—the distance corresponding to a parallax of 1 second of arc.
3. *Astrometry* is defined in *Webster's New World Dictionary* as "the branch of astronomy dealing with the measurement of planets, stars, etc. and their positions and movements."
4. S. Newcomb, *The Stars* (Putnam, New York, 1901), pp. 323–326.
5. L. F. Jenkins, *General Catalogue of Trigonometric Stellar Parallaxes* (Yale Univ. Observatory, New Haven, Conn., 1952).
6. K. Aa. Strand, *Basic Astronomical Data* (Univ. of Chicago Press, Chicago, 1963), pp. 58–59.
7. S. L. Lippincott, *Astron. J.* **62**, 55 (1957).
8. K. Aa. Strand, *ibid.* **67**, 706 (1962).
9. *Cassegrain focus* refers to the optical arrangement of a reflector in which the secondary mirror reflects the convergent beam of the primary mirror through a hole in the center of this mirror to the focal plane behind it.
10. The coma is the comet-shaped image, produced by an optical system, of a point source of light not on the optical axis.
11. A. van Maanen, *Contrib. Mt. Wilson Obs. No. 111* (1915); *No. 391* (1929).
12. F. E. Ross, *Astrophys. J.* **77**, 243 (1933).
13. W. J. Luyten, "Final Report of Bruce Proper Motion Survey," *Publ. Obs. Minnesota No. 15* (1960), vol. 2.
14. H. L. Giclas *et al.*, *Lowell Obs. Bull. No. 89* (1958); *No. 102* (1959); *No. 112* (1961); *No. 120* (1963).
15. F. E. Ross, *Astrophys. J.* **81**, 156 (1935).
16. S. Vasilevskis, *Astron. J.* **67**, 464 (1962).
17. R. H. Weitbrecht, *Review Sci. Instr.* **28**, 122 (1957).
18. The Hartmann test plates were evaluated by R. K. Riddle of the U.S. Naval Observatory. The detailed data will be published elsewhere.
19. A. B. Meinel, *Astrophys. J.* **124**, 652 (1956).

CURRENT PROBLEMS IN RESEARCH

The Role of Afterimages in Dark Adaptation

Bleached receptors continue to signal in darkness, causing afterimages and elevated visual thresholds.

H. B. Barlow and J. M. B. Sparrock

Our knowledge of dark adaptation is in a curious state, for photosensitive pigments certainly regenerate in the dark, but the increase in the amount of pigment is insufficient to account for the drop in threshold. Granit, Munsterhjelm, and Zewi (*1*) obtained the first experimental evidence of this when they compared the electroretinogram response and the pigment concentration of frog and cat retinas after exposure to bleaching lights, and Rushton (*2*) has given a convincing demonstration in man. He showed that, during dark adaptation, the rods do not normally start functioning until over 90 percent of their rhodopsin has been regenerated. Since this final 10 percent increase in pigment concentration accompanies a greater than hundred-fold drop in visual threshold, sensitivity is obviously not directly proportional to pigment concentration, but there appears nonetheless to be a definite relation between them. Dowling found in rats (*3*), and Rushton found in human cones (*4*) and rods (*5*) that it is the logarithm of sensitivity which is directly proportional to pigment concentration. This is a neat empirical relation, but it is theoretically puzzling, and the mechanism underlying the drop in threshold remains unexplained.

Since the changes in threshold during dark adaptation are not accounted for by changes in the proportion of incident quanta absorbed, it is logical to ask if changes in noise level are involved. This is a major factor limiting the performance of radiation detectors, and Barlow has argued both that it is important at the absolute threshold of human vision (*6*) and that it is the noise level that changes during dark adaptation (*7*). The experiment reported here was designed to test this idea, and the results are consistent with it. First, some supporting psychophysical evidence must be given.

When investigating factors influencing the shape of dark-adaptation curves, Crawford (*8*) found a simple way to represent the results. He determined the steady background light that would raise the threshold of a superimposed test stimulus to the value for that stimulus alone after a particular time in the dark. In this way Crawford looked upon dark adaptation as the decrease, with time, of a hypothetical veiling light which he called the "equivalent background." The important simplification achieved by this approach is that the plot of equivalent background against time turns out to be independent of the parameters (for example, area) of the test stimulus used to determine threshold. Rushton (*9*) has recently confirmed and extended these observations in many important ways.

Dr. Barlow, at the time this work was done, was assistant director of research at the Physiological Laboratory, Cambridge, England; he is now affiliated with the School of Optometry of the University of California, Berkeley. Mr. Sparrock is Medical Research Council scholar at the Physiological Laboratory, Cambridge.