PHYSICS OF OUR DAYS

Prospects for development of ground-based optical astronomy

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A number of refinements in ground-based optical telescopes and their detecting equipment, and also serious development of measures for neutralization of interference effects of the earth's atmosphere, permit the efficiency of observation of faint astronomical objects to be improved by at least an order of magnitude in the coming years. In the case of extragalactic astronomy and observational cosmology it is shown that progress in large ground-based optical telescopes has a decisive role in formation of contemporary concepts of the universe. Some of the problems of astronomy which will be solved by means of these instruments in the near future are discussed.

The study of the microworld and the study of the universe both require for their progress very complex and expensive instruments of contemporary science. The problems of elementary-particle physics are becoming more and more closely related to the problems of cosmology and cosmogony; the spectacular discoveries of the last decade are increasingly attracting to astronomy the attention of physicists, who can only dream about the energies, temperatures, densities, masses, and gravitation with which astronomers deal.

Ground-based optical astronomy is the oldest division of observational astronomy; at the present time it is being developed intensively. Observations in other spectral regions (radio, ultra-violet x-ray, and gamma) do not exclude optical observations, but supplement them. The identification of radio and x-ray sources with optical objects led to the discovery of quasars, pulsars, x-ray stars and was a very important step toward understanding the natures of these objects.

The prospects for ground-based optical astronomy must be known to observers, so that they can determine the place of their own investigations in the general development of practical astrophysics; they are of interest also for theoreticians, who wish to have an idea of the feasibility of various experiments at the present time and in the future.

We will limit our discussion to observations of nighttime astronomical objects, without discussing ground-based observations of the Sun, although very substantial progress is being observed also in this area. The spectral region in which most ground-based astronomers are making observations is 3200–12 000 Å. Longer-wavelength regions of the spectrum are also being studied, and in recent years these observations have provided a number of very interesting results. Radiation with $\lambda < 2900$ Å is blocked by the earth's atmosphere. The spectral region mentioned above is characterized by the following features:

1) Good transparency of the earth's atmosphere. The radiation of a star located at the zenith is attenuated by only 20–30%; on approach to the horizon the absorption increases approximately as the secant of the zenith distance. For a given height above sea level the transparency of the atmosphere at different points differs insignificantly.

2) Comparatively weak luminescence of the night sky. Measurements show that the brightness of the background of the night sky in which celestial objects are observed in the blue region of the spectrum ($\lambda \approx 4000$ Å) corresponds to the radiation of one star of 22^m (or 1.6×10^{-6} photons/cm^2-sec-Å) from a square second of the celestial sphere.[1] The luminescence of the night sky is made up of three components: the total luminescence of the stars and their scattered light, the zodiacal light, and the chemiluminescence of the upper layers of the earth's atmosphere. Transportation of a telescope to a height of 200–300 km removes the atmospheric component of the background (in the blue part of the spectrum about 2/3 of the total background), but leaves the galactic and zodiacal components unchanged. In other spectral regions the ratio of the brightnesses of the components of the night sky background may be different. In the infrared region the thermal radiation of the atmosphere and the telescope begin to play a role.

3) High quantum yield of radiation and image detectors. For current astronomical photographic emulsions the generalized quantum yield $(\text{signal/noise})^2_{\text{out}}:(\text{signal/noise})^2_{\text{in}}$ can reach $\sim 10^{-2}$, and in photocathodes the quantum yield (number of photoelectrons per photon) lies in the range $(1\text{–}70) \times 10^{-2}$. Detectors for $\lambda > 1.2\ \mu$ at the present time are significantly poorer. It is evident that observation of faint objects in the region 3000–12 000 Å reduces to achievement of a sufficient signal-to-noise ratio in the photon image.

Let us consider the effect of telescope parameters, the atmosphere, and the detecting apparatus on the observation of faint point objects in the background illumination of the night sky. The history of observational astrophysics shows that it is just the study of faint objects which most often leads to revelation of new facts. We note that a telescope which has the capability of efficiently detecting these objects can be very successfully used also for study of brighter stars and galaxies; the reverse statement is untrue.

Although the angular dimensions of stellar disks are extremely small, the image of a star in an image detector in the focal plane of a telescope has finite dimensions; if the focal length of the telescope is comparatively small, the size of a stellar image is 20–30 μ, which corresponds to the diameter of the circle of confusion of contemporary photographic emulsions; in systems with longer focal lengths it is βf, where β is the angular diameter of the atmospheric distortion spot and f is the telescope focal length. The earth's atmosphere through which observations are carried out is an optically nonuniform medium; a plane wavefront coming from a star is deformed by the atmosphere in such a way that the angles between its individual parts turn out to lie inside a cone with angle β at the vertex. These parts are smaller than the diameter of a large telescope and their combined action leads to smearing of the image.

For the further discussion we will introduce the following designations: D is the telescope diameter, f is its focal length, β is the angular diameter of the stellar image in the image detector, n_*(photons/cm^2-sec) is the illumination from a star, S(photons/cm^2-sec-sr) is the brightness of the background night sky luminescence, t is the image accumulation time (exposure, and η is the quantum yield of the image detector.

We will take the detector quantum yield as unity and neglect the factor $\pi/4$. Then N_*, the number of photons of a star's radiation collected by a telescope in an exposure time t in a spot of diameter β, will be given by $N_* = D^2 n_* t$; the number of background-sky photons reaching this spot is obviously $D^2\beta^2 st$. We will consider two cases: bright and faint stars.

If $N_* \gg D^2\beta^2 st$, we will consider this star bright. In this case the statistical fluctuation of the number of photons (in our case also of the photoelectrons) will be $\Delta N_* = D n_*^{1/2} t^{1/2}$. In order to measure the brightness of the star with a relative error B, it is necessary that

$$\frac{\Delta N_*}{N_*} = \frac{1}{D n_*^{1/2} t^{1/2}}, \quad n_* = \frac{1}{B^2 D^2 t}, \quad \frac{1}{n_*} = B^2 D^2 t. \tag{1}$$

The real quantum yield η of the image detector is taken into account by replacement of t by ηt.

Thus, the penetrating power of a telescope in measurement of the brightness of a bright point object ($N_* \gg D^2\beta^2 s$) is proportional to the square of the telescope diameter, which agrees with the widely held intuitive opinion. The telescope efficiency does not depend on β and s (however, for different β and s the same object may turn out to be bright or faint for a given telescope). If we make a specific evaluation, for example, for a telescope of diameter 6 m, then for a quantum yield of 10% it is capable of reliably detecting brightness pulsations of 1% and duration 1 msec in objects brighter than 6^m in a single recording.

Let us turn to observation of faint objects for which $N_* = D^2 n_* t < D^2\beta^2 st$. Measurement of the brightness of objects 2–3 times fainter than background is a common practice in contemporary astronomy. In this case

$$\Delta N = D\beta s^{1/2} t^{1/2}, \quad \frac{\Delta N}{N_*} = \frac{\beta s^{1/2}}{D n_* t^{1/2}} = B, \quad \frac{1}{n} = B\,\frac{D}{\beta}\,\frac{t^{1/2}}{s^{1/2}}. \tag{2}$$

We see that the penetrating power of the telescope depends on the first power of its diameter and on the first power of the diameter of the star image spot. The telescope efficiency is proportional to $t^{1/2}$ or, more accurately, $(\eta t)^{1/2}$ and inversely proportional to $s^{1/2}$ (Fig. 1).

Thus, the quality of the image provided by a telescope is as important as its diameter. A contemporary telescope must be not only large but also of high quality. A telescope of diameter, say, 5 m which for one reason or another forms a stellar image of diameter 2″.5 is equivalent to a one-meter instrument with an image quality 0″.5. Reduction of the background by removal of the telescope beyond the atmosphere improves its penetrating power by $\sqrt{3}$ times, i.e., by $0^m.6$.

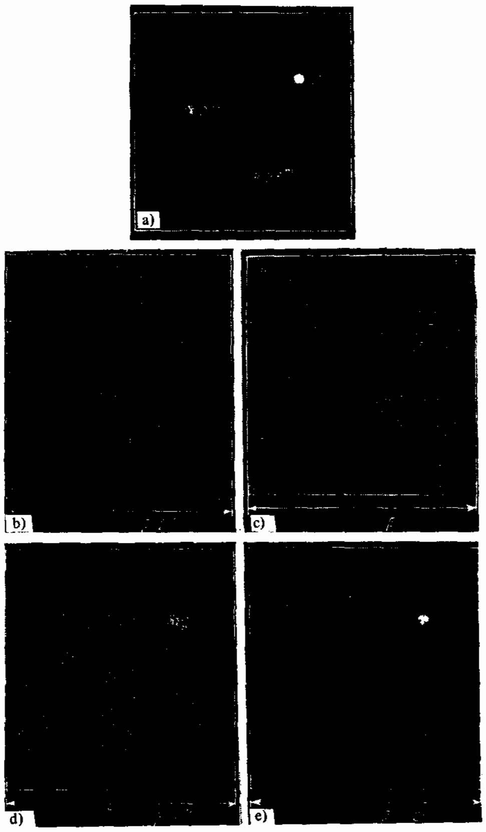

FIG. 1. Observation of faint stars in background of night sky illumination, simulated by computer. Three objects of magnitude 21, 22, and 23, are photographed at η = 10% in a telescope with D = 4 m and an exposure time t = 1 sec. Fig. a shows the hypothetical case of photography without background; Figs. b–e show photography at $s = 22^m$ with □″ and β = 2″, 1″, 0.5″, and 0.25″. Evidently for t ≈ 10^4 sec (about three hours) β = 0″.5 and η = 10%, $m_{\lim} \approx 27.5^m$. The photographic plate is inferior to photoelectric devices in quantum yield by about an order of magnitude and has fog (a significant number of grains turn out to be developed in an unexposed plate); as a result of this the statistics of image detection are poorer and the exposure time corresponding to Fig. 1 amounts to several tens of seconds. Thus, we see that improvement of the image quality β is an extremely effective method of increasing the telescope's penetrating power.

At the present time in infrared detectors ($\lambda > 1.2\ \mu$) the intrinsic noise is very high and usually exceeds the signal from the sky background and the object. If the detector noise $n_D \gg D^2 n_* D^2\beta^2 s$, then $\Delta N = n_D^{1/2}$, $\Delta N/N_* = N_D^{1/2}/D^2 n_* = B$ and $1/n = BD^2/n_D^{1/2}$. The efficiency of the system in observation of an object therefore turns out to be proportional to the square of the telescope diameter and does not depend on the image quality.

If less noisy infrared detectors with high quantum yield are ever developed, the calculation of observability must be carried out with Eqs. (1) and (2). An improvement of β is necessary in this case, since this permits reduction of the amount of background radiation recorded by the detector. Apparently it does not follow that we should reduce the requirements on image quality of infrared telescopes of the future.

We will develop these considerations in application to the photographic recording of images, which is widely used in contemporary astronomy. Since photographic emulsions have a sensitivity threshold (they do not react to an energy less than some minimum), and the exposure time is limited by refraction, bending of the telescope tube, and drop in sensitivity of the emulsion with increasing exposure, it is possible to determine the telescope aperture for which the sky background and all objects exceeding it in brightness will be recorded. If the emulsion sensitivity threshold corresponds to m photons/cm^2 and the focal length of the telescope is f, then

$$mf^2 = D^2 st, \qquad \frac{D}{f} = \frac{m^{1/2}}{(st)^{1/2}}. \tag{3}$$

We will consider two cases of observation of faint stars ($n_* < \beta^2 s$) in a background of night sky illumination. Let the resolution of the emulsion be p (for present-day astronomical plates this is 20–30 μ):

1) $n_* < \beta^2 s$, $p > \beta f$–short-focus instrument, faint object. Then from Eqs. (2) and (3) we have

$$\frac{1}{n_*} = B\frac{Df\,(mf^2)^{1/2}}{ps^{1/2}\,(D^2 s)^{1/2}} = B\frac{m^{1/2}f^2}{ps}, \qquad \frac{1}{n_*} \sim f^2.$$

2) $n_* < \beta^2 s$, $p < \beta f$–long-focus instrument, faint object. Then from Eqs. (2) and (3) we have

$$\frac{1}{n_*} = B\frac{D\,(mf^2)^{1/2}}{\beta s^{1/2}\,(D^2 s)^{1/2}} = B\frac{m^{1/2}f}{\beta s}, \qquad \frac{1}{n_*} \sim f.$$

Thus, for exposure to the sky background (and this is a necessary condition) the efficiency of a short-focus telescope is proportional to the square of its focal length ($m_{\text{lim}} \sim 2 \log f$), and that of a long-focus telescope to the focal length ($m_{\text{lim}} \sim \log f$). The relations obtained can be checked by evaluating the upper limit from photographs obtained in instruments with different focal lengths for the condition that the sky background is recorded. With present-day emulsions the sky background is recorded in the blue region of the spectrum in two hours for a telescope aperture 1:7.5. It is important that the photographic procedure (type of plates, hypersensitization, development) be strictly identical; otherwise, differences in quantum yield difficult to take into account will arise.

In Fig. 2 we have shown the limiting stellar magnitude achievable by the Mount Wilson and Palomar telescopes, as a function of their focal length. The limiting magnitudes have been normalized to $\beta = 1''.25$. Here we have also shown the limiting magnitudes obtained with electronic image detectors in small telescopes (1.5–2 m) for $\beta = 2''$, which also have been normalized. The advantage is explained by an increase in the factor ηt. The dashed line shows the curve for $\beta = 0''5$.

Thus, there are no fundamental limitations to the improvement of the penetrating power of ground-based optical telescopes.[1] We will now discuss the means of further increasing the penetrating power. Here the strong factors are D and β, and the weaker factors are t, η, and s.

* * *

Let us now discuss the optical systems of contemporary ground-based telescopes and the trends in their development. The optical system must have good quality ($\beta_{\text{tel}} \ll \beta_{\text{atm}}$), the necessary aperture (1:7–1:8) providing detection of sky background in 1.5–2 hours, and a sufficiently wide angle. It must be realizable with the technology available to the observatory building the telescope and must retain its characteristics during operation (rotation of the instrument, variation of temperature).

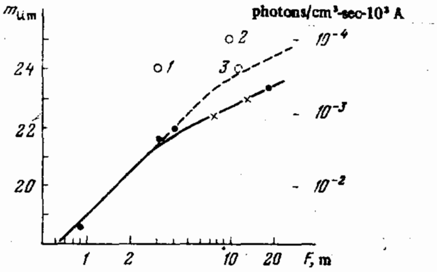

FIG. 2. Limiting stellar magnitude accessible in various telescopes as a function of their focal length. Solid curve–calculation for $\beta = 1.25''$, p = 18 μ, and s = 22$^{\text{m}}$ with □″. Points–data for Mount Palomar and Tautenberg telescopes, crosses–data of Mount Wilson observatory reduced to $\beta = 1.25''$ and s = 22$^{\text{m}}$ with □″. The dashed curve corresponds to $\beta = 0.5''$; the gain in the limiting magnitude in comparison with $\beta = 1.25''$ is 1$^{\text{m}}$. Use of a new technique for image detection increases ηt and consequently the limiting stellar magnitude of the telescope. Photography on a fine-grained emulsion with good storage characteristics and summation of negatives improved the limiting magnitude of the Palomar Schmidt telescope of 122 cm diameter by ~2.5$^{\text{m}}$, raising it to ~24$^{\text{m}}$ (1) [24]. The 1.5-m telescope of the Cerro Tololo Observatory and the 2-m reflector of the Haute Provence Observatory with electronographic detectors gave $m_{\text{lim}} \approx 24^{\text{m}}$ and 25$^{\text{m}}$ (2, 3) [25,26]; the data have been reduced to $\beta = 1.25''$. Use of the new image-detection technique brings small telescopes to the level of large telescopes working with old detectors. In combination with large high-quality telescopes working under favorable atmospheric conditions, the new image detectors permit achievement of m_{lim} = 28–30$^{\text{m}}$.

The first parabolic reflector was built by Newton; Gregory and Cassegrain proposed a two-mirror system, which increased the focal length, with the main mirror of parabolic shape. As is well known, a paraboloid forms an image of an infinitely distant star on the optical axis in the form of an ideal point; however, the quality of the image deteriorates greatly off the axis. By placing in front of the focal plane of the parabolic reflector a lens system of appropriate design, it is possible to improve somewhat the quality of the image over the field (Fig. 3).

In 1922 Chretien[2] proposed a two-mirror optical system of the Cassegrainian type with a main hyperbolic mirror; its wide-angle properties are significantly better. If in this system, which has been called the Ritchey-Chretien (R-C) system, one deviates somewhat from the hyperbolic mirror shape and adds a lens element in front of the focus, it is possible to achieve very high image quality over a very large field (Fig. 3.[3] At the present time practically all large telescopes are built according to the Ritchey-Chretien arrangement.

Achievement of a high-quality optical system requires considerable mathematical calculation by computer. The calculations are carried out by the ray-tracing method, in which the computer simulates the behavior of several tens of light rays through various points of the telescope's optical system. By changing the parameters of the optical system, it is possible to find an optimal solution combining good image quality with a large field and technical feasibility.

Calculation of the optical system includes a determination of the permissible eccentricities (the relative location of the optical elements can change as the result of bending of the frame on which they are mounted) on direction of the telescope to various points of the sky, and also the permissible limits of deviation of the mirror parameters from the calculated values. It is also necessary to calculate the parameters of the optical test

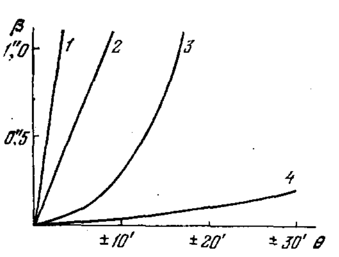

FIG. 3. Image quality calculated for telescopes of different optical systems. 1—parabaloid, D = 1.5 m, D/f = 1/5; 2—the same parabaloid with a two-lens Ross corrector mounted in front of the focal surface (1935); 3—Ritchey-Chretien two-mirror system with hyperbolic main and secondary mirrors (1927); 4—Ritchey-Chretien system calculated by computer, with mirrors slightly deviating from hyperbolic, and a two-lens quartz corrector located near the focal surface (1971).

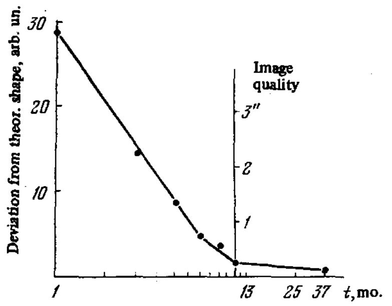

FIG. 4. In preparation of astronomical mirrors, the deviation from the theoretical surface shape at first decreases rapidly, and then much more slowly. The dynamics of preparing the 3.6-m diameter hyperbolic quartz mirror for the joint European Southern Observatory (ESO) shows that about a month after starting the polishing, the mirror could provide images of diameter ~3". The mirror preparation lasted about three years. The concentration of radiation in the image formed by the finished mirror is shown in Fig. 5.

elements with which the optical surfaces of the telescope mirrors will be checked in the laboratory. Of course, in this case it is also necessary to calculate the permissible errors in the parameters of the test elements and the eccentricities of the test arrangement. The data obtained permit evaluation of the feasibility of the telescope's optical system from the technological point of view.[4] Construction of a large high-quality astronomical optical system is a long and complicated process consisting of several interrelated steps which affect each other (Fig. 4). The essence of the mirror construction process is that the designer should by various technical means be able to change the shape of the surface of the glass disk in a desired direction and to monitor these changes unambiguously. Usually the length of the room in which the mirror preparation is carried out does not exceed several tens of meters; therefore the optician must investigate the mirror shape by sending light to it from a finite distance, usually from its center of curvature. Since neither parabolic nor hyperbolic mirrors form a point image with this type of illumination, an auxiliary optical element (lens or mirror) must be placed in the path of the rays, which converts the spherical wavefront leaving the point source to a front at all points perpendicular to the normal to the theoretical mirror surface. In this case the optician will see through the compensator what appears to be a spherical mirror and can use various means for studying a spherical wavefront to monitor it. The compensating element usually has dimensions substantially smaller than the curved mirror being investigated and, as a rule, has spherical surfaces; convex hyperbolic mirrors are investigated in the same way, but the monitoring spherical mirror must be larger than the mirror under study.[5,6]

During the investigation the mirror is in a state of neutral equilibrium in a mount which compensates its weight with an accuracy of ~10^{-3} in all positions in which it must operate in the telescope. This is usually achieved by a system of levers and pneumatic supports (reliefs). Before beginning the study of the mirror in the mount, it is necessary to be satisfied that the compensation of its weight is sufficiently accurate. For this purpose it is customary to provide the possibility of monitoring the mirror shape in a horizontal and an almost vertical position of the mount. Since the forces which act on the blank during processing are quite significant and for a large mirror may reach several tons, it cannot be shaped in the mounting used for measurement. It is necessary either to transfer the mirror to a special processing mount or to change the measuring mount in such a way that the mirror is not deformed and the mount not damaged during the processing. A good mirror-processing technique results in a surface of rotation; there should be no azimuth-dependent errors.

The shape of the mirror surface is monitored to an accuracy of about 1 μ by means of mechanical measuring devices; beyond that point, optical methods are used. Preparation of an astronomical mirror of diameter 3–4 m occupies several years. The finished mirror is checked by several independent methods: usually the compensation method mentioned above and Hartmann's method are used. The latter consists of covering the mirror with an opaque diaphragm with small openings whose centers form a regular grid with sufficient accuracy. The mirror is illuminated from the center of curvature by a point source of light and the spots formed by reflected waves on a photographic plate placed near the source are photographed. In this way it is possible to determine several tens (for a small mirror) or several hundred (for a large mirror) normals to the surface; analysis of these data by computer permits a picture of the mirror surface to be constructed.[7]

Methods also exist for study of the completely assembled optical system of the telescope, which are used to check it under laboratory conditions.

Observational astronomers must also be provided methods of adjustment which permit the location of the optical components to be monitored during use.

We see that creation of a high-quality optical system for a large telescope is a difficult and complex problem; we will discuss the organizational aspect of the solution of this problem later.

No less a role than that of the telescope's optical system with its tube and mount is played by the mechanical part of the instrument which permits its optical axis to be directed to any point of the sky and to follow a selected object in its diurnal motion. Without dwelling on this very important group of questions, we note only that the size of the main element of the diurnal-motion drive is usually larger than the telescope mirror diameter and has a fabrication accuracy close to optical. It is considered necessary to provide the maximum possible accuracy and smoothness of operation of the telescope's mechanical system, introducing only a minimum amount of correction from the following systems.

The optical system of a telescope can conveniently be characterized by a curve showing what fraction of the light collected by the mirror is located in a circle

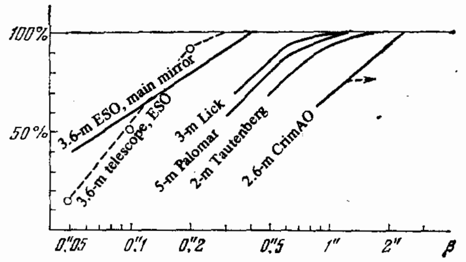

FIG. 5. Results of laboratory studies of several astronomical mirrors, obtained by a geometrical method (without taking into account diffraction and atmospheric distortions). The quality of the optical system is characterized by the diameter of the circle in which is collected a certain fraction of the light from a point source incident on the mirror. In the fifties and sixties, attention to the quality of the optics of large telescopes was somewhat reduced (the Pyrex parabolic reflectors at the Lick (3 m), Palomar (5 m), Tautenberg (2 m), and Crimean (2.6 m) Observatories). The principal hyperbolic mirror of the European Southern Observatory (ESO) of fused quartz and the entire optical system of this telescope collectively show significantly better image quality with much greater thermal stability. The high-quality quartz mirror of the orbital observatory Copernicus shows in flight a mean image quality of 44% in a width 0.3" (ref. 27) (for a diffraction image, 45% of the light falls in a region of width 0.05").

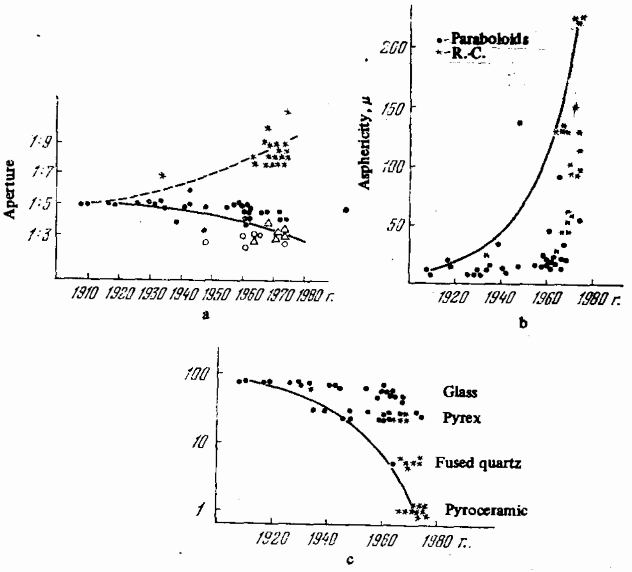

FIG. 6. Evolution of the parameters of the mirrors of contemporary large reflectors. a) Aperture of telescopes: asterisks–Ritchey-Chretien focus, solid circles–direct focus of parabolic telescopes, triangles–direct focus of hyperbolic telescopes (with corrector), hollow circles–Schmidt cameras. b) Asphericity of main mirrors of contemporary telescopes: asterisks–hyperbolic mirrors, solid circles–parabolic mirrors. c) Thermal expansion coefficient of materials ($\times 10^{-7}$) from which large telescopic mirrors are made. The overwhelming majority of contemporary large telescopes have a main hyperbolic mirror of quartz or pyroceramic.

Image quality and optics quality of several large telescopes

Observatory	Mirror diameter, m	Start of operation	Materials	Percent of light in circle of given diameter per Hartmann test	Best resolution for stars	Reference
Mount Palomar	5.0	1949 г.	Pyrex	0".3–57% 0".6–87% 1".2–100%	0".12	9, 10
Mount Wilson	1.5	1908 г.	Glass	—	0".1	8
Pic du Midi	1.0	1966 г.	Pyrex	—	0".2	11
McDonald	2.05	1939 г.	»	—	0".1	9, 12
	2.7	1969 г.	Quartz	0".14–87% 0".31–100%	—	13
Lick	3.0	1959 г.	Pyrex	0".34–70% 0".67–95% 1".35–97%	0".2	9, 14
ESO	3.6	1974 г.	Quartz	0".05–40% 0".3–90%	—	15

of a given diameter: The results of the investigation are usually presented in this form. Such a curve can be constructed by means of a computer if the relief of the mirror is known. In Fig. 5 we have shown the concentration of light in a stellar image, determined by geometric means, for some of the telescopes in existence and under construction. The first high-quality large telescopes were built at the end of the last century and the beginning of the present one; in particular, the 60-inch parabolic reflector at Mount Wilson, which has been in use since 1908, can form an image close to the diffraction image.[8] The contemporary large Ritchey-Chretien telescopes collect a substantial fraction of the light in a circle of diameter ~0.1".

Although the first large high-quality mirrors were prepared from ordinary mirror-type glass, a stable optical system can be obtained more easily from material with a low thermal expansion coefficient. In the 1930's glass with an expansion coefficient $\sim 70 \times 10^{-7}$ began to be replaced by Pyrex, and later in the post war years by fused quartz, and then by pyroceramics (Cer-Vit, Zerodur)–specially crystallized glass with practically zero expansion coefficient,[16] $(0 \pm 1) \times 10^{-7}$.

A measure of the difficulty of preparing a mirror is its asphericity–the deviation of the edge of the mirror from the sphere tangent to its center. Present-day optical specialists are capable of preparing a mirror approximately 25 times more "difficult" than their predecessors who worked at the beginning of the century. Practically all large telescopes being built at the present time have the Ritchey-Chretien optical system (Fig. 6).

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We will now discuss the optical properties of the earth's atmosphere. Although this question was clarified long ago, at the present time one nevertheless encounters in the popular literature (and not only in the popular literature' statements that it is impossible to achieve from the earth's surface an angular resolution better than a few seconds of arc.[17] However, observations with resolution of the order 0.1" are common practice in existing observatories, in which the atmospheric conditions, as a rule, leave much to be desired (see the table). The quantitative methods of studying the optical properties of the atmosphere which have been developed at the present time have permitted unambiguous selection of the points for installation of new large telescopes, at which atmospheric interference is significantly reduced.

A phenomenological description of the distorting effect of the earth's atmosphere can be obtained by observing stars in telescopes of different diameters. In large instruments ($D > 1$ m) the stellar image has the form of a stationary, smeared, sometimes pulsating, but always motionless disk; a small telescope ($D = 10$–20 cm) forms an undistorted diffraction image of a star, which flickers as a whole with frequencies up to 10–20 Hz. Consequently, the characteristic size of the wavefront distortions lies roughly in the range 0.3–0.8 m. The wavefront distortions are due to temperature inhomogeneities in the earth's atmosphere. It is obvious that the diameter of the smearing spot in a large instrument, β, is close to α–the amplitude of flickering of the undistorted image in a small telescope. In order to select, by means of a small expeditionary instrument, a place where a large reflector will operate with minimal atmospheric interference, it is necessary beforehand to plot the function $\beta = \varphi(\alpha)$ by making simultaneous measurements of these quantities in one of the existing observatories. Unfortunately, in 1935 Danjon and Couder[18] made the a priori assumption that there were no atmospheric distortions of the wavefront larger than 20 cm: The criterion of image quality was assumed to be t–the deviation of a 20-cm portion of the wavefront from planarity. Only in 1970 were the t criterion and α criterion calibrated with a large reflector.[19] It turned out that the t criterion does not provide the possibility of determining β. However, the selection of the location for many existing observatories was carried out with just this criterion. Even with the correct α technique, it is necessary to find beforehand regions where one expects minimal atmospheric distortions. Here we are assisted by meteorological considerations, namely, that the promising locations are those which are close in their meteorological conditions to a free atmosphere not perturbed by the layer adjacent to the earth. Such places are isolated mountain peaks with low winds in the altitude zone 2000–3000 m; the air which changes its nocturnal temperature from contact with ground strongly cooled by radiation can quietly flow away to points below. Images in the 3000–4000 m zone are poorer as the result of the high wind velocity; in addition, serious difficulties arise with acclimatization of the observers. Such considerations led J. Stock[20] to select several Chilean summits; O. V. Demenev indicated the promise of Mount Sanglok in the Tadzhik SSR, where measurements with the α criterion gave very good results (unfortunately, Sanglok is in the vicinity of the Nurek industrial complex). O. A. Semenova and L. N. Babushkin turned their attention to the region of the Minchukur meterological station (Mount Maĭdanak); analysis of meterological data extending over many years[21] showed convincingly that very good images can be expected here, as was confirmed by observations with the α technique.

At the present time the idea of an isolated summit as a place with excellent nocturnal atmospheric conditions has no competitors.

On an isolated summit the free atmosphere is very close to the surface of the ground. A microthermometer placed at a height of 15–20 m shows practically complete absence of temperature fluctuations; the value of α shows very good correlation with the sum of the temperature fluctuations in the layer adjacent to the ground. The free atmosphere at a height ~20 m gives $\bar{\alpha} \approx 0.2''$–$0.3''$.

A histogram of the α distribution is well described by a γ distribution; it is also convenient to give it in integral form (Fig. 7). We see that at a height of 20 m above isolated summits we can expect in a year no fewer than several hundred hours of clear nocturnal weather with $\alpha < 0''.5$. The integral histogram of α completely characterizes a given point: The relative effectiveness of different points may turn out to be different, depending on the required value of α. Thus, for $\alpha = 0''.5$ for an identical amount of clear weather a point with $\bar{\alpha} = 3''$ is poorer than a point with $\bar{\alpha} = 0.5''$ by 22 times.[22]

As a rule the telescope and its tower in contemporary style appreciable spoil β in comparison with α, since the tower changes the aerodynamics of the summit, produces around itself as the result of radiative cooling a large amount of cooled air, and dissipates the heat produced by the electronic instrumentation. The primary problem of the current stage of telescope design is development of a set of procedures which permit achievement of $\beta = \alpha$. At the present time there are a large number of methods which permit quantitative study of the thermal and aerodynamic characteristics of existing telescopes. It is possible that towers designed on the basis of the results obtained will have a form rather unusual for contemporary astronomy (Fig. 8). The deterioration of β in comparison with α as the result of the lack of aerodynamic and thermodynamic conformity of 20-m tower in one of the new Chilean observatories is shown in Fig. 7b.

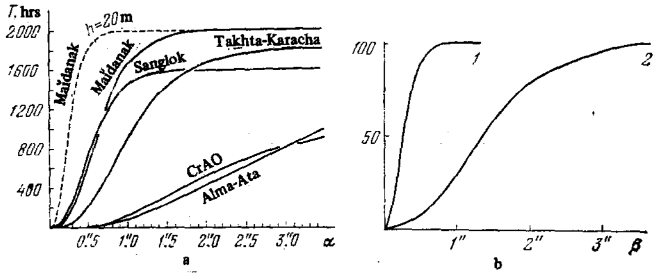

FIG. 7. Integral histograms of image quality α, showing: a) annual amount of nocturnal clear time with images better than a given quality; b) deterioration of image as the result of the tower effect. In Fig. a the curves have been plotted from reduced meteorological data and the results of astroclimatic measurements made in 1968–1970 at the P. K. Shternberg State Astronomical Institute by means of a two-ray device calibrated with large instruments. The dashed line is a prediction of the image quality for a telescope mounted at a height of 20 m above the summit of Maĭdanak and matched with the free atmosphere. In Fig. b: 1–histogram of α calculated for height of 20 m; 2–histogram of β of a high-quality telescope of diameter 1.5 m, mounted on a tower of height 20 m on the summit of La Silla in Chile with a similar value of $\bar{\alpha}$. Development and perfection of a set of measures to match tower and telescope thermally and aerodynamically with the free atmosphere will lead to a significant improvement in the image quality of ground-based telescopes.

A specific feature of large telescopes is the fact that they are intended almost exclusively for fundamental observations. Usually only one telescope of a kind is made, and the important parts are very rarely modernized. A contemporary telescope takes about ten years to build and is used for about 100 years or more (telescopes built at the beginning of the century are being used successfully at the present time). Experiment shows that telescopes designed without substantial participation by the user (the observatory) are not successful. In the world's largest observatories at the present time, groups of astronomers have been build up who are very familiar with the problems of large-telescope design and who actively take part in the development of new instruments. The observatory will take on itself, as a rule, the preparation of the optical system of the instrument and the development of the attitudes associated with it. The characteristic time of preparation of a high-quality optical system is 3–5 years (Fig. 9); no one has yet been able to accelerate the preparation of astronomical mirrors. The cost of a telescope is proportional to the square of its diameter (Fig. 10),[23] and the difficulty in preparation of the optical system is proportional to the cube or fourth power. Therefore the diameter of the next telescope is rarely increased by more than a factor of two in comparison with the predecessor; a detailed quantitative investigation of the newly created instrument under working conditions is obligatory.

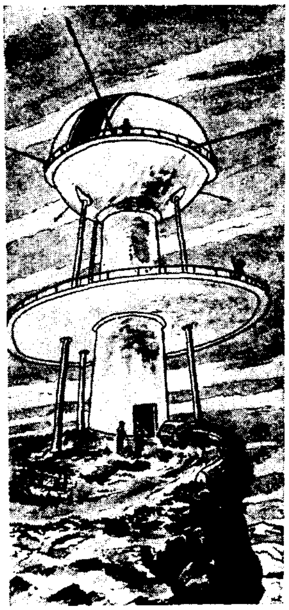

FIG. 8. Artist's conception of the general appearance of the tower of a ground-based telescope matched thermally and aerodynamically with the free atmosphere. In construction of such a tower it is necessary to make aerodynamical studies which make it possible to avoid the cold air near the earth being thrown to the height of the instrument and to avoid the appearance of cold air near the radiation-cooled parts of the tower, cupola, and telescope.

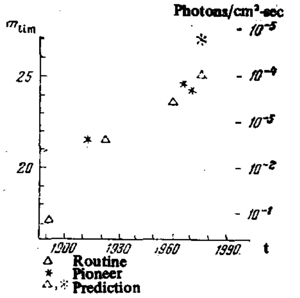

FIG. 11

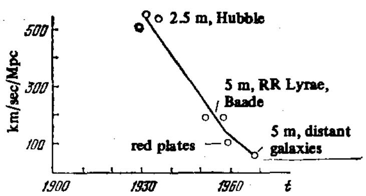

FIG. 12

FIG. 11. The trend in development of contemporary ground-based astronomy is to observe fainter and fainter objects. It is interesting to note that the pioneer results obtained in various telescopes with the expenditure of great effort become a routine observation in later, more refined telescopes. High-quality ground-based telescopes at the end of the twentieth century will be able to study approximately one thousand times greater volume of space than contemporary telescopes.

FIG. 12. The development of practical astrophysics has permitted reduction in the value of one of the fundamental constants of the world—the Hubble constant—by about a factor of ten in comparison with its value in 1929 when the proportionality of the red shift in the spectrum of galaxies to their distance was discovered. The observation of fainter objects and the conversion to use of red light have provided the possibility of improving the intergalactic distance scale of objects and therefore of increasing the "expansion age" of the universe.

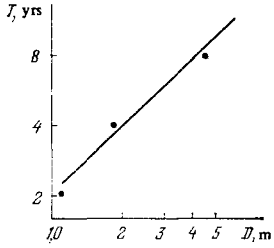

FIG. 9

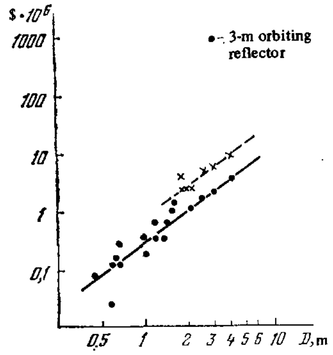

FIG. 10

FIG. 9. Time of preparation of a large telescope, as a function of its diameter. The main expenditure of time is required for preparation of a high-quality optical system. For the 100-inch telescope of the Mount Wilson Observatory, which commenced operation in 1918, the mirror processing required six years.

FIG. 10. The cost of a ground-based optical telescope is proportional to the square of its diameter. New telescopes (crosses) are somewhat more expensive as the result of the general economic situation and their better equipment with auxiliary apparatus. The 5-meter Palomar reflector cost ~6.5 million dollars; the amount spent by the Kitt Peak Observatory in building the contemporary 4-meter R-C telescope is ~10 million dollars. The 3-meter orbital reflector should cost about one billion dollars (see Astronomy and Astrophysics for the 1970's, U.S. National Academy of Sciences, 1973); as can be seen, its use in the visible region of the spectrum is inappropriate, since several high-quality terrestrial telescopes will provide a significantly greater amount of information at much lower cost.

Thus, contemporary practical astrophysics is completely formulated by the branch of astronomy with the possibility of quantitative measurement of all quantities of interest and with the clear promise of development (Figs. 11 and 12).

* * *

The development of astronomy would be impossible without construction of larger and larger telescopes. This is shown particularly clearly by the history of the development of contemporary ideas about the structure of the Universe.

The first high-quality reflectors came into use in 1908 and 1918. At that time it was assumed that the sun is near the center of a single all-encompassing Milky Way system, and disputes raged as to the nature of the faint nebulae, some of which showed a spiral structure. The suggestion was made that these nebulae are independent star systems comparable with the Milky Way, but there were no proofs of this. At the beginning of the twentieth century the number of nebulae was estimated as 120 000.

In the years 1908–1910 G. W. Ritchey obtained high-quality photographs of the nearest galaxies in the 60-inch telescope. In his photographs the nebulae M 33 and in part M31 were unexpectedly resolved into stars. Ritchey counted about 3000 nebula stars in M33 and approximately 1000 in M 101. In 1920 Lundmark reached the conclusion that in the nebula M33 stars are actually observed; and that M 33 is an extensive independent star system; however, Shapley continued to insist that the images of these "stars" were too soft and too smeared.

Examination of reproductions of the photographs of M 31 obtained by Ritchey permit us to identify in them a number of variable stars—cepheids, which were discovered later by Hubble and Baade. If Ritchey in 1910 had obtained a series of photographs of M 31 and M 33, he would have discovered and studied in them cepheids, and in 1913 when Hertzsprung calibrated the period-luminosity dependence for cepheids in absolute units, he would have been able to prove that the spirals are independent galaxies, eleven years before Hubble. However, we should not forget that Hubble used the standard plates of the 100-inch reflector with an exposure time of 40 min, while each plate of Ritchey's in the 60-inch reflector was the result of heroic effort and many-hour exposures.

In any event, in 1919 Ritchey prepared for publication an article in which he proved on the basis of his photographs that the spirals are other galaxies, but for "causes unrelated to the author" this article was never published.

To the merits of the 60-inch reflector we must add also the fact that it was used by Shapley for study of globular clusters. Assuming that the center of these systems coincides with the center of the galaxy, Shapley for the first time provided a model correct in principle for the structure of the galaxy, and the Sun turned out to be in the remote periphery of it. The 60-inch reflector turned out to be an extremely productive instrument; even at the present time a telescope of this quality, located in a place with a large number of days of clear weather and good images, could work very effectively.

The dispute as to the nature of the faint nebulae or spirals was finally solved by Hubble in the 100-inch reflector of the Mount Wilson observatory, which came into use in 1918. In the autumn of 1923 in searching for new stars he discovered in M 31 the first cepheid, and a year later he had already studied a dozen of them in M 31, M 33, and NGC 6822. The amplitudes of the variation in the shapes of the luminosity curves of these variable stars turned out to be normal, and this proved that we are dealing here with single stars. The period-luminosity dependence showed that the distances of these nebulae are an order of magnitude greater than the size of the Milky Way, and that the spirals are comparable with it in size and are independent galaxies.

Continuing the direct photography of other galaxies, Hubble, working with the cepheids, was able to establish that the luminosity of the brightest stars (they were $\sim 3^m$ brighter than the brightest cepheids) is approximately the same, so that they can be used to determine the distances of the more remote galaxies.

In 1925 Slipher, using the 24-inch astrograph at Flagstaff, obtained the radial velocities of 41 galaxies. The question of existence of a relation between the distances and the radial velocities had already been taken up in cosmology at that time, but not solved; Stromberg announced that "there is no sufficient basis to suppose that a relation exists between V_r and distances." De Sitter in 1917 knew only three radial velocities, one negative and two positive. Neither he nor A. A. Friedmann had available observational data when they constructed their models of the universe.

In 1929 Hubble determined the distance to 18 individual galaxies and to the clusters in Virgo, and a comparison with the radial velocities enabled him to establish the now famous Hubble law:

$$V_r = Hr$$

(the radial velocity V_r is directly proportional to the distance r).

Thus, the operation of the 100-inch reflector led to the present revolution in our concepts of the universe. It turned out that the Milky Way system is not a unique all-encompassing stellar universe, but only one of an incalculable number of similar stellar systems. A strange property of space was observed–its expansion. Cosmology obtained for the first time an observational basis, and this would have been impossible with telescopes of smaller size, for the problem consisted of photometry and spectroscopy of limitingly faint objects.

The scale of the universe, the average density of matter in it, and its age henceforth were determined by the value of Hubble's constant H, which he found in 1936 to be 536 km/sec/Mpc. The linear dependence of the velocity on distance was soon checked by Humason on the basis of spectrograms obtained in the 100-inch reflector. The first radial velocity obtained by him for NGC 7619 in the cluster in Pegasus was a factor of two greater than those known previously. In 1936 Humason obtained for a galaxy 17.9^m a radial velocity still ten times greater ($z = 0.13$).

Photographs in red light obtained by Baade in 1943 in the same 100-inch telescope (he achieved approximately 21.9^m in four hours of exposure) permitted him to resolve into stars the central portion of the Andromeda nebula and its elliptical satellites (Ritchey and Hubble resolved only the outer portions–the spiral arms populated with supergiants). These turned out to be red giants, identical to the giants of the globular clusters. As a result the useful idea of stellar populations developed.

In 1945—1949, photographing M 31 in various wavelengths, Baade was able to show that gas and dust are distributed nonuniformly in the galactic plane: they are concentrated in the spiral arms. The value of this discovery in understanding the nature of the spirals is well known.

It will not be an exaggeration to say that the bases of the contemporary nature of the world appeared only as the result of one single telescope: the 100-inch reflector at the Mount Wilson observatory. However, further progress would have been impossible without the completion of the 200-inch Hale reflector on Mount Palomar in 1949. In the first years of its operation the 200-inch reflector made a tremendous contribution to the solution of the problems of cosmology. In 1952 Baade announced that in M 31 the variable stars of the Lyrae RR type were inaccessible to the five-meter telescope. This meant that either they were weaker than assumed by 1.5^m or that cepheids were brighter than given by Shapley's calibration by 1.5^m. Baade favored the second solution, which after several years was confirmed by studies of cepheids in the open clusters of our Galaxy. This led to the value $H = 180$ km/sec/Mpc.

In 1958 Sandage showed that in critical cases Hubble (who photographed only in blue light) took for the brightest stars the compact H II regions, which are brighter than stars by about 1.8^m. Hubble's constant now became about 100 km/sec/Mpc. This removed a great difficulty in relativistic cosmology, for with the old value $H = 536$ km/sec/Mpc the expansion rate of the universe was found to be less than the age of the stars and the earth...

The current value of Hubble's constant (55 km/sec/Mpc) is based entirely on studies carried out with the 200-inch reflector: studies of cepheids in spiral and irregular galaxies (including NGC 2403, which already lies beyond the limits of the local group, in group M 81), determinations of the angular dimensions of the H II regions calibrated on the basis of cepheids (in their linear dimensions), and the radial velocities of the giant spirals of the field which are quite remote. In these studies a limiting value of about $23^m.5$ was achieved, although in individual investigations it apparently approaches 24.5^m (for such faint objects the scale of stellar magnitudes still is not determined very accurately).

With the 200-inch telescope Humason measured for the galaxy 17.3^m in Hydra $z = 0.20$, and in 1960 Minkowski in his last night of observation before retiring found $z = 0.46$ for the radiogalaxy 3C 295 (19.9^m) on the basis of a single emission line. This value was confirmed by

Oke only in 1971 by means of a spectrum obtained with a 32-channel photoelectric spectrometer. The accumulation time was eight hours.

The greatest red shifts presently known are $z = 3.53$ for the quasar OQ 172 and $z = 3.40$ for OH 471. Unfortunately, the red shifts of quasars cannot be used to determine the form of the dependence of m on z and for choice between different models of the universe, since the dispersion of their luminosities is too great. The problem of the search for normal galaxies with a large red shift remains, therefore, very urgent.

* * *

In conclusion we will say a few words on the prospects which are open for extragalactic astronomy with the coming into use of large telescopes of the Ritchey-Chretien system.

First of all, substantial progress will be made in solution of cosmological problems, since more accurate values will be obtained for the Hubble constant H and the retardation parameter q_0 determined by the form of the dependence of m on z for objects with identical luminosity. The systematic decrease in the values of H is explained by the increasing penetrating power of our telescopes. It turns out, in particular, that the characteristics of the series of objects which serve as indicators of distance are associated with the luminosity of the galaxies which contain them. Thus, the diameter of the H II regions increases with increasing galactic luminosity. Galactic giants are rare in space, and the nearest galaxies therefore are small and the H II region diameters determined from them have turned out to be too low, which has led in the last analysis to underestimation of H by about 1.5 times. However, in the more distant galaxies, among which there are giants, the cepheids which, as the result of the relation of the period of variation of the brightness and their luminosity, serve as the basis of the inner galactic scale of distances, become inaccessible. Cepheids in 30 galaxies are accessible to the 5-m reflector; so far seven of them have been studied, and in four other galaxies studies begun by Hubble in the twenties are still being continued. An increase of the limiting stellar magnitude to $26–27^m$ will permit study of cepheids in 100–200 galaxies, and the large field of R-C telescopes will permit a substantial acceleration of progress in study of cepheids in the Magellanic Clouds and the Andromeda Nebula (which have large angular dimensions), which is necessary to obtain more accurate luminosities of these stars. In the Andromeda Nebula, stars of the RR Lyrae type will become accessible, which also is extremely important for calibration of the distance scale and other problems.

An increase in the resolution will provide the possibility of determining the angular diameters of H II clouds in more distant galaxies. Study of supergiants, star clusters, and H II regions in a sufficiently representative selection of galaxies will undoubtedly lead to a reliable determination of Hubble's constant and will provide important data for understanding the mechanism of formation of stars and of the spiral arms with which are associated super giants, cepheids, and H II regions–gaseous complexes ionizable by just created hot stars.

The nature of the dependence of m on z, on which the value of the retardation parameter and the choice between different models of the universe depend, can be determined if we know the red shift of a sufficient number of very remote radiogalaxies or very bright galaxies in clusters (the luminosity of such galaxies is the same). It is also necessary to learn how to take into account the effect of evolution of the stellar population of the galaxies on their photometric characteristics, as well as the effect on them of the creeping of the ultraviolet portion of the spectrum into the visible region. For solution of the latter problem, extra-atmospheric observations are necessary, and for the first problem–detailed studies of the stellar population of the nearby galaxies.

Investigation of the star-shaped galactic nuclei, which recall a star cluster, is necessary for solution of the problem of whether they are "singular points" which create around themselves a galaxy (an assumption leading to a radical review of our physical concepts), or whether these nuclei appear in the course of evolution of galaxies.

The nature of quasars (which are almost all fainter than 17^m), the possibility of existence of a noncosmological red shift, the problem of stability of clusters and groups of galaxies (the conclusion that they are unstable will lead to the conclusion that matter is being created)–all of these problems, which are very important for our representations of the universe, require for their solution use of telescopes with maximal penetrating power, high resolution, and large field.

And who knows what new phenomena, what new problems will face us after the new R-C telescopes come into operation, and what impetus they will give to the further development of physics...

The necessity of very rapid construction of at least one such telescope in the Soviet Union is completely apparent. We must have the possibility to see in the sky everything which can be seen by others. And there is no need to formulate for orbital telescopes problems which can be solved much better and much more cheaply by terrestrial observations, whose possibilities are far from exhaustion.

[1)] In astronomy the radiation flux is measured in stellar magnitudes; the stellar magnitude m of an object is given by the expression $m = -2.5 \log (I/I_0)$, where $I_0 = 10^3$ photons/cm²-sec-Å for $\lambda = 0.556\ \mu$. The scale of stellar magnitudes for stars visible to the eye was proposed by Hipparchus in the second century B.C.; the brightest stars were assigned the first magnitude, and the faintest–the sixth magnitude. In 1856 the step of the stellar magnitudes was taken as 0.4000 on the logarithmic scale. For the Sun $m \approx -26.6$, and for the entire moon $m \approx -12.7$; the faintest stars observable at the present time by the largest telescopes have $m \approx 24$.

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