9 June 1967, Volume 156, Number 3780 SCIENCE

Optical Astronomy in Perspective

Ground-based optical astronomy is throttled by lack of large telescopes, especially in southern latitudes.

Horace W. Babcock

The most distant planet of the solar system, Pluto, circles the sun in an orbit having a radius of 3.7 billion miles (5.9 billion kilometers), corresponding to a light-travel time of about 5½ hours. Science fiction notwithstanding, this represents the effective limit of space travel by man or his instruments in the foreseeable future. The entire universe beyond the limits of the solar system remains the domain of astronomy, open to investigation only by optical telescopes, radio telescopes, and special detectors for such exotic signals as occur in the form of x-rays, gamma rays, cosmic rays, and neutrinos. With light-travel time as the measure of distance, the nearest star is at 4¼ light years, the diameter of our Milky Way Galaxy is 80,000 light years, the distance to the great spiral galaxy in Andromeda is about 2 million light years, the Coma cluster of galaxies is at some 230 million light years, and the most distant identifiable objects in the universe—quasi-stellar sources—are at distances up to several billion light years.

In the general rapid scientific advances of recent decades, few branches of science have surpassed optical and radio astronomy in growth. The great increase of interest in astronomy results partly from the growth of all the physical sciences and of technology. New developments and discoveries, such as nuclear-energy production and nucleosynthesis, plasma physics, x-rays, gamma rays, information theory, computer applications, the electron multiplier phototube, and the photoelectric image tube, have tended to swing the activity of investigators to problems of astrophysical context.

Stellar evolution, dealing with the formation and subsequent life history of individual stars, is a young subject with large gaps, which is still undergoing rapid development. Almost all the progress in this field has come within the past 30 years. The study of the structure of our own Galaxy—the distribution of stars and interstellar material, their kinematics and dynamics—is scarcely older. Our knowledge of external galaxies as "island universes" similar to our own Galaxy has been firm for only 40 years. Cosmology, the study of the universe as a whole—its description, contents, structure, and evolution—is a subject still in its infancy; major choices as to the basic cosmological models have yet to be determined. One can feel sure that developments to tax the imagination of the ablest theoreticians will be forthcoming: indeed, some are here now! The quasi-stellar sources were unknown 7 years ago. In that short interval there has occurred new multiplication of prospects and problems to challenge astronomers and physicists alike, on the most profound level. No branch of science is more active, or has greater potential for growth in expanding the intellectual horizons of mankind.

In all of this, optical astronomy occupies a central position and will continue to do so. The results that have been achieved have depended upon observations made with a very limited number of large telescopes, mostly venerable and erected before World War II with private funds. It was in this country that the modern reflecting telescope was proven, first with instruments of modest aperture—24 and 36 inches—and later through a sequence culminating in the 200-inch Hale Telescope (Fig. 1) at Palomar (*1*). This giant, still the largest and most capable of optical instruments, was built with funds from private sources committed nearly 40 years ago. It went into operation in 1949. There are only two other telescopes in existence with aperture greater than 100 inches. One is the 120-inch reflector of the Lick Observatory, completed in 1957 and built with funds from the State of California. The other is the 105-inch telescope of the Crimean Astrophysical Observatory. It is a fact, of course, that radio astronomy is an indispensable partner of optical astronomy in some areas of current research, and that we confidently expect ground-based astronomy to be supplemented importantly by observations made with telescopes on orbiting satellites.

The expansion of the frontiers of research in astronomy and astrophysics is reflected in the increase in rate of publication of papers in these fields. For example, the *Astronomical Journal* printed 175 pages in 1950, increasing to 873 pages in 1965. The *Astrophysical Journal* showed an increase from 1248 pages in 1950 to 4254 pages in 1966, and in this interval it changed from bimonthly to monthly publication. The interest in astronomy and its potential for future growth are illustrated by a striking increase in

The author is director of the Mount Wilson and Palomar Observatories, Pasadena, California.

the number of graduate students working for advanced degrees in the several American universities offering such opportunities. The number of such students was about 170 in 1957, increasing to 800 in 1966.

The research activities of professional astronomers and the training of graduate students are seriously and increasingly hampered by a lack of telescopes, especially of large modern telescopes at good sites. At the major observatories, observing time is heavily oversubscribed. For example, at the Mount Wilson and Palomar Observatories allotments of observing time are made up to 14 months in advance; for years, nearly all research proposals have had to be curtailed, and some worthy ones must be rejected entirely, simply because the necessary facilities do not exist.

For front-rank research, large, well-instrumented telescopes in good locations are essential. A modern research telescope requires and deserves a mountain site where the seeing is good, where the sky is free of glare from city lights, and where there is a high percentage of clear nights with skies of "photometric" quality. There is no substitute for light-gathering power, or telescope aperture. The limiting stellar magnitude of the 200-inch telescope is about 24, and at this faint level the instrument collects only about 100 photons per second in the whole recordable spectrum. The most distant and the faintest objects are often the most rewarding, and even though improved photographic plates and modern photoelectric detectors and image tubes are greatly increasing the capability of all telescopes, large and small, these increases are not keeping pace with the new observational problems that are being uncovered.

There are real advantages in the largest telescope that can be produced, and there are also great advantages in the use of a proven design. Therefore it would be wrong to settle for a compromise on the issue of aperture when the plans of the very successful 200-inch Palomar telescope are available. Experience shows that much of the prime observing time of the 200-inch telescope is devoted to objects near the observational limit, where, even with the most sophisticated ancillary equipment, exposure times of several hours are common. It is a fallacy to assert that the same results can be obtained with a smaller telescope by simply extending the exposure time—a fallacy for two reasons. (i) Exposures longer than a few hours yield diminishing returns because of greater average hour angle, more atmospheric absorption and dispersion, more chance of interruption by clouds, and reciprocity failure of the photographic process. The density obtained in the photographic emulsion is a function of It^{-q}, where I is the light intensity, t is the exposure time, and $q>1$. Reciprocity failure is generally quite serious for long exposures. (ii) Demands for telescope time invariably exceed the saturation level, so that extending one observation necessarily curtails another.

Funding of Large Telescopes

My thesis is that vital support has been woefully small in recent years for construction of the large telescopes necessary for the orderly advance of astronomy. I argue not that space science, with plans for orbiting telescopes, has been oversold, but that support of construction of new instruments for ground-based astronomy has been comparatively neglected. Perhaps unwittingly, in pointing out some of the technical advantages offered by the possibility of using instruments in orbit above the earth's atmosphere (the avoidance of atmospheric absorption and of image degradation), astronomers have failed to drive home the point that space telescopes will supplement but not replace ground-based instruments. It was, however, properly stated in early recommendations of the Space Science Board that orbiting telescopes should be planned and used only for those observations that could not be made from the ground.

The difficulties of American astronomers in obtaining funds for construction of large telescopes is not due to lack of effort. Proposals have been carefully prepared, engineering plans exist, and site surveys have been made. At least three outstanding telescope projects have been advanced in the past 4 years, but they have been met with indecision, delays, or rejection. These are (i) a proposal by the Carnegie Institution of Washington to erect in Chile a 200-inch telescope similar to the Hale Telescope at Palomar Mountain in California; (ii) a proposal by the Associated Universities for Research in Astronomy (AURA) to construct a 150-inch reflector in Chile; and (iii) a proposal by the University of California to build a 150-inch (or larger) reflector in Australia (jointly with the Australian Government). The Carnegie Institution has centered its efforts on private sources of funds, while the other two proposals went to agencies of the United States government.

Ample justification for these three proposals and more was provided in a study sponsored by the National Academy of Sciences. In 1962 the Academy established an eight-man Panel on Astronomical Facilities, headed by Albert E. Whitford. Two years later the panel produced, and the Academy published (*2*), a carefully prepared and well-conceived document, "Ground-Based Astronomy, a Ten-Year Program," better known as the report of the Whitford committee. This is an admirable and conservative report, of value to anyone concerned with planning for basic science in this country.

In summary, as regards optical astronomy, the principal recommendations of the Whitford committee, together with associated costs, are as follows:

1) Construction of three large telescopes of the 150- to 200-inch class ($60 million). The Kitt Peak (Arizona) 150-inch instrument (now under construction by AURA) is considered to be the first of this group.
2) An engineering study ($1 million) for construction of the largest feasible optical reflector.
3) Construction of four intermediate-size telescopes of the 60- to 84-inch class ($4 million).
4) Construction of eight small modern telescopes of 36- to 48-inch aperture ($3.2 million).

The total cost of the optical facilities and the engineering study is $68.2 million, with no operating expense included. The total recommended program for optical and radio astronomy over a 10-year period requires an investment in ground-based facilities of the order of one half of 1 percent of the investment going into the space effort. This large disparity in cost is indicative of the relative ease of acquiring data with ground-based instruments.

While items 3 and 4 of the foregoing summary are at present receiving good support or consideration, no tangible progress has been made toward fulfilling recommendation 1, for construction of three large telescopes of the 150- to 200-inch class. Construction of the Kitt Peak 150-inch reflector was assured before the Whitford report was published. This telescope will be in great demand; perhaps 100 American astronomers will request observing time, although, as the report mentioned, for effective prosecution of research, each large telescope can best accommodate from 12 to 15 research astronomers.

The greatest outstanding need is for a 200-inch telescope at the best available site in the Southern Hemisphere. Such a telescope, development of the site, and two smaller companion instruments would cost, in all, $20 million. The 200-inch telescope could be completed in 8 years and would have a useful lifetime of well over half a century, during which time it would be in use every hour of every clear night. The resulting gains to science would be tremendous. By contrast, one cannot refrain from pointing out that the first of the four scheduled orbiting astronomical observatories (launched in April 1966) cost American taxpayers $62 million ($50 million for the scientific equipment and $12 million for launching), according to press reports. Unfortunately, this well-conceived experiment transmitted no data because of an equipment failure. Expenditures for this one orbiting observatory, which, at best, might have had a lifetime of 1 year, would have been ample for the construction of three 200-inch telescopes on the ground, completely equipped. Certainly a more equitable distribution of funds would have a great and valuable impact on basic science.

American contributions to the rapid development of modern astronomy and astrophysics have been slanted heavily toward the observational, for two reasons. Mountain observatory sites near the West Coast of the United States have provided seeing conditions greatly superior to those at sites in Europe and in other parts of North America, and private fortunes of individuals interested in science were occasionally available in the past to finance construction of observatories. There is no compelling reason to believe that the era of private funding has ended, but certainly the American lead in observational astronomy is now being seriously challenged, and it may one day be lost unless the current trend is reversed. This challenge is readily documented; one need only look at the current progress in telescope construction and planning by Western European countries, Canada, the U.S.S.R. and Australia.

Progress by Other Countries

In 1953 the idea of a European Southern Observatory arose in discussions between Walter Baade, astronomer of the Mount Wilson and Palomar Observatories, and Jan H. Oort, director of the University of Leiden Observatory in the Netherlands (*3*). After some 6 years of organizing and financing, a group of five European countries joined in forming the European Southern Observatory (ESO) and initiated active planning. With some financial help from the Ford Foundation, ESO began site development and construction in Chile in 1963. Under Otto Heckmann as director, ESO now has one 40-inch telescope in operation and is pushing the construction of a 60-inch telescope, a 40-inch Schmidt photographic telescope, and a 140-inch reflector (ESO's principal instrument). The design of the last is well advanced, and the fused silica disk for its mirror has been successfully produced by the Corning Glass Works in the United States. It is understood that, since observing time with the ESO instruments will be at a premium because it must be shared by numerous observers from several member countries, individual projects for the construction of sizable telescopes are being advanced independently by Denmark, France, West Germany, and Italy.

Canada is well advanced in the engineering and construction of a 150-inch reflector, to be known as the Queen Elizabeth II Telescope. It will be located on a mountain site in British Columbia. The fused silica mirror is now in production. Argentina has placed an order for an 84-inch reflector, to be furnished by a manufacturer in the United States.

Astronomers and telescope engineers in the U.S.S.R. have been active in recent years in promoting observatory construction. A 105-inch reflector has been built for the Crimean Astrophysical Observatory, and a similar instrument is now believed to be under construction for the Erevan Observatory. More significantly, a major

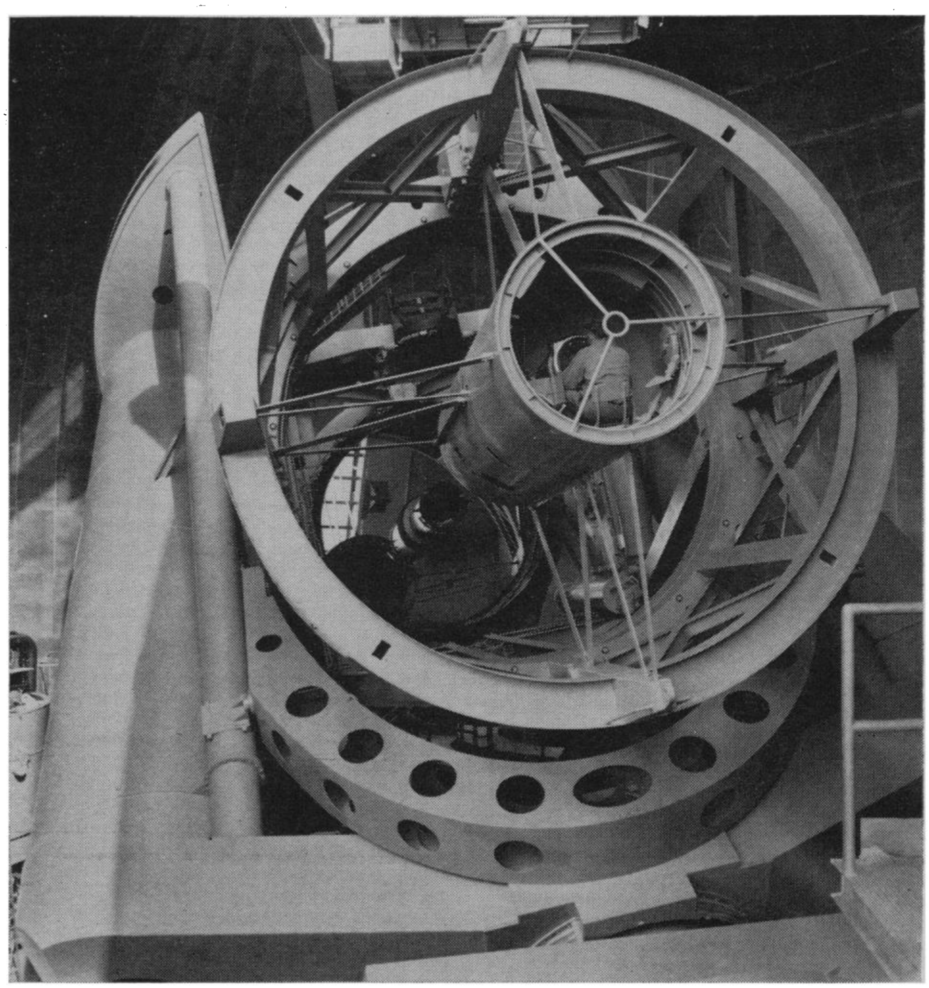

Fig. 1. The 200-inch Hale Telescope: interior of the tube as viewed from the upper end. The mirror is seen at the bottom, below the prime-focus observer's capsule.

project being promoted by the Russian astronomers—construction of the world's largest telescope, of 240-inch aperture—is well under way. The main features of the design were announced in 1963, and it is understood that the mirror, of borosilicate glass, has now been successfully cast and is undergoing optical finishing. This telescope is to be located within the U.S.S.R., presumably at a site in the Caucasus Mountains.

Construction in England of the 98-inch Isaac Newton Telescope is nearing completion, while serious site testing has been carried out at the better locations in Australia by the Mount Stromlo Observatory of the Australian National University, by the Carnegie Institution, and by the University of California. The Australians have announced an intention to construct a reflector of the 150-inch class, perhaps jointly with another group.

Why the Southern Hemisphere?

Currently we find a serious imbalance in astronomical knowledge when we compare objects and problems in the Northern and Southern hemispheres. This has not always been so, because early observers, beginning with John Herschel (1792–1871), continuing with David Gill (1843–1914) and Lewis Boss (1846–1912), and continuing later with the Lick Observatory astronomers, went south with telescopes in a strong effort to gain a complete and balanced knowledge of the astronomical problems of their day. If Herschel had not completed the catalogs of nebulae, star clusters, and double stars at Capetown, if Gill had not begun systematic parallax measurements of southern stars, if Boss had not measured positions and proper motions of 15,000 southern stars at San Luis, Argentina, and if the Lick-Mills expedition had not measured radial velocities of southern spectroscopic binaries at Santiago, Chile, astronomy would be in a very awkward state today. The need for data from southern skies is no less urgent in astronomy now than it was in the 19th century.

The current interest of astronomers in constructing telescopes in the Southern Hemisphere is enhanced by the fact that the southern skies have a greater concentration of astronomical riches than the northern skies have, whereas most of the world's large observatories are located in the north. Also, a balance between north and south is needed in acquiring fundamental data. Furthermore, it has become evident from recent site surveys that observing conditions at the best southern sites are superior to conditions prevailing at the large northern observatories.

It is impossible to predict all of the scientific problems that await the completion of a 200-inch telescope in the Southern Hemisphere. But it is abundantly clear from the work that has been done with small and intermediate-size instruments that countless astronomical objects await exploration and that discoveries and breakthroughs are assured. The predictable scientific problems awaiting attention are urgent and numerous. They have been presented and discussed elsewhere (*3, 4*); here it is appropriate to refer to only a few that are outstanding.

The nearest external galaxies are the Large and Small Magellanic Clouds (Fig. 2), located not far from the south pole of the celestial sphere. The Clouds are at about one-tenth the distance of the great spiral in Andromeda, and they offer, for comparison and calibration, aggregates of stars of all types grouped at the same distance. Even so, the fainter stars of the Magellanic Clouds require very large telescopes for adequate study. In the apt words of L. H. Aller, the Clouds are truly the Rosetta Stones of astronomy.

Once the absolute luminosities of the bright stars in the Magellanic Clouds have been calibrated, these luminosity criteria can be used in the study of other galaxies which are near enough so that precise distance indicators are available yet sufficiently distant to possess a cosmological red shift. These two conditions are so restrictive that, in the northern sky, there are few galaxies in the narrow distance range where both conditions are met. More than twice as many galaxy candidates are available in southern latitudes, because the southern sky is filled with nearby galaxies. But, more important, only in southern latitudes are galaxies found whose red shifts are not distorted by a local kinematic disturbing effect due to the local supercluster. Most students of the problem concede that only from southern galaxies, where this disturbing effect is absent, can satisfactory distance determinations be made. This is the road to an accurate value for the Hubble constant, relating distance to red shift, which is fundamental in cosmology. It will tell us the age of the universe.

Another approach to the problem of the age of the universe is the age-dating of the oldest stars in our Galaxy. For such stars we look to members of the globular clusters that populate the halo of our stellar system. The age of a cluster is found by determining the Hertzsprung-Russell diagram for its member stars and applying the theory of nuclear burning to the configuration. Two factors are involved. (i) The Hertzsprung-Russell diagram must be observed down to the main-sequence termination point, because it is there that theory tells us how much nuclear fuel has been consumed in the interior of the relevant stars. But this termination point is very faint—apparent magnitude 19, in northern clusters. Such a level is difficult to observe with précision. In the southern skies are the brightest globular clusters, not far from the nuclear region of our own Galaxy. In particular, two of these clusters, ω Centauri and 47 Tucanae, are nearer and brighter by fully two magnitudes than any in northern skies. In these clusters, we can expect to observe the main sequence accurately, and the observations will permit more precise calibration. (ii) Even if the observations were perfect, a second factor would have to be known before an age could be found. This is the ratio for the abundances of hydrogen and helium. This ratio can be determined observationally by direct spectrographic analysis of the bluest stars of the cluster. Even the 200-inch telescope is barely adequate to provide such data for northern clusters because they are so faint. A preliminary determination of the ratio is available for the southern cluster NGC 6397, obtained by astronomers using the 74-inch Australian reflector, but the spectrographic dispersion they were forced to use was too small to provide a definite answer. Greater precision is needed.

The cosmological problem requires deep-ranging surveys of the distribution and red shift of remote galaxies and quasi-stellar sources in the southern skies. It is important to search, by observation, for any lack of isotropy in the expansion of the universe. Any lack of isotropy that can be definitely established will indicate nonradial motion. Such an effect has recently been

Fig. 2. The Large Magellanic Cloud. This photograph was made by Karl Henize in red light with a 10-inch telescope. The Cloud is approximately 5 degrees across and is located some 20 degrees from the south pole of the sky. Its distance from the earth is about 180,000 light years.

predicted from Gödel's special solution of Einstein's equations, which admits of a general rotation of the universe as a whole. If this prediction happens to be correct, the rate of rotation can actually be evaluated by finding the shear coefficients of the anisotropy.

In recent years the optical identification of radio sources has been extremely fruitful. Now that thousands of accurate radio positions are becoming available through the work of the Australian radio astronomers with the 210-foot dish at Parkes, powerful optical telescopes are more than ever needed in the Southern Hemisphere for such identification and analysis.

Quasi-stellar objects in large numbers are awaiting identification and investigation with powerful optical equipment. The latest results indicate that the number of these objects, including both radio-emitting and radio-quiet types, may exceed 100,000 over the entire sky to an optical (blue) limit of magnitude 19.7.

The excellent observing conditions that prevail at the best locations in the Southern Hemisphere constitute yet another reason for erecting telescopes there—one that was not anticipated before the recent site-testing operations were undertaken. Extensive observatory-site surveys have been conducted by ESO in Africa, by AURA (following a beginning by the Yerkes Observatory) in South America, and by the Carnegie Institution in Australia and in Chile, in addition to the work in Australia, mentioned above, of the Mount Stromlo Observatory group and of the University of California. Site surveys have also been made in New Zealand. The consensus is that, while good conditions may be found in Africa and in Australia, truly excellent and probably unequaled sites are available in Chile, where long tests with recording photoelectric monitors have shown that the seeing is unsurpassed and that more than 65 percent of all nights are completely free of clouds for 6 hours or more. Such evidence strengthens very importantly the arguments for locating there the largest optical tools that astronomers can command. I believe that American astronomers are generally of the opinion that the Whitford report was too conservative. At least one 200-inch telescope should be built in Chile, and two major instruments there would not be excessive. Furthermore, the recommended design study for a telescope even larger than 200 inches should be implemented.

It is clear that observational astronomy is at a crucial stage, and that unparalleled opportunities are now at hand which, if grasped, will ensure for decades to come the future of this, the oldest of all the sciences.

References

1. I. S. Bowen, *Telescopes*, vol. 1 *of Stars and Stellar Systems*, G. P. Kuiper and B. M. Middlehurst, Eds. (Univ. of Chicago Press, Chicago, 1961), p. 1.
2. "Ground-Based Astronomy, a Ten-Year Program," *Nat. Acad. Sci.-Nat. Res. Council Pub. No. 1234* (Washington, D.C., 1964).
3. J. H. Oort, *ICSU (Intern. Council Sci. Unions) Rev. World Sci.* 3, No. 1, 30 (1964).
4. L. H. Aller, "Why Go South?," *Astron. Soc. Pacific Leaflet, No. 406* (1963); S. C. B. Gascoigne, *Nature* **197**, 1240 (1963).

Leaf Epicuticular Waxes

The waxy outer surfaces of most plants display a wide diversity of fine structure and chemical constituents.

Geoffrey Eglinton and Richard J. Hamilton

In a plant, a surface which is exposed to the atmosphere usually has a layer which contains wax and is called the cuticle (*1*). Stems, fruits, petals, and leaves may all be covered with wax, though leaf waxes have received most attention. As Fig. 1 shows, the cuticle itself, which is a layer of cutin composed of cross-linked hydroxy fatty acids, is generally bounded by a layer of wax. Next, usually, comes a layer of pectin, and then the cellulose cell wall. Some workers believe that intercellular cytoplasmic bridges sometimes appear in the cutin, having extended through the pectinaceous layer. The amount of epicuticular wax varies greatly with species but can be sizable —for instance, it may be up to 4 percent of the green weight of the leaf and up to 15 percent of the dry weight. These figures might represent a wax layer of up to 50 micrograms per square centimeter of leaf surface.

The wax, when present, undoubtedly serves to preserve the water balance of the plant, and its other protective functions may include minimizing mechanical damage to leaf cells and inhibiting fungal and insect attack. Thus, it may be that the light-scattering character of the rough-textured wax layer and the light-absorbing powers of trace constituents, such as polyphenolics, in the cutin shield the plant from excessive ultraviolet radiation. Agricultural sprays must come in contact with the cuticle if they are to be effective, and the presence or absence of wax (as well as its composition and fine structure) seems to govern the wettability of leaves and the penetration of the spray chemicals.

It has been suggested that the physical arrangement, the morphology, of the epicuticular waxy covering is all-important, but the chemical constituents must also determine its role to a very considerable extent. Interest in epicuticular wax is by no means a new phenomenon. De Bary (*2*) established, as early as 1871, that the waxy covering of plants is made up of closely packed minute plates or rods which are clearly visible under the light microscope. Chibnall and his colleagues (*3*), in the period 1930 to 1950, examined the chemical composition of the waxes by means of fractional crystallizations, precision melting point determinations, and x-ray powder diagrams. Academic study of the waxes is now probing more deeply, with the help of newer techniques and analytical

Dr. Eglinton is senior lecturer in the chemistry department, University of Glasgow, Glasgow, Scotland; Dr. Hamilton is lecturer in the department of chemistry and biology, Regional College of Technology, Liverpool, England.