\[
\begin{array}{cc}
\gamma & e \\
1908 & +3.6 \quad 0.21 \\
1921 & -5.9 \quad 0.42 \\
1922 & -9.5 \quad 0.46 \\
1923 & -0.7 \quad 0.40 \\
\end{array}
\]

The observations of 1923 were made with the dispersion of three prisms; those of the earlier years, principally with single prism dispersion.

THE POSSIBILITIES OF INSTRUMENTAL DEVELOPMENT.

BY GEORGE E. HALE.

Nothing is more encouraging to the scientific investigator than the rapid multiplication in recent years of the possibilities of instrumental development. In astronomy the opportunities for advance have been vastly enlarged by the remarkable progress of physics and chemistry and the many new instruments and methods thus rendered available. To appreciate our advantages, we have only to glance rapidly over the history of science and contrast present possibilities with those of the past.

The beginning of the new year, practically coinciding with the annual inundation of the Nile, was fixed by observations of the heliacal rising of Sirius before 4000 B.C. Throughout their entire history the Egyptian priests were astronomers, yet their sun-dials, water clocks, and the crude "Merchet", a measuring instrument for determining the time from observations of stars near the meridian, apparently underwent no important improvement down to the Greek occupation of Egypt. The Babylonians, although much more effective observers than the Egyptians, have left us no instruments, unless the "astrolabe" found in the palace of Assurbanipal may be thus classed. The Greeks invented several instruments, which are described by Ptolemy in the Almagest. Most of these consist essentially of a graduated arc of a circle, provided with adjustable sights and supported in the plane of observation. So completely did these instruments embody the ingenuity of the Greeks that they were adopted without important change by the Arabs, Hindus, and Chinese, and served for the equipment of Tycho Brahe's great observatory in the period of revival of the sixteenth century. Tycho devoted special attention to the improvement of instruments, which he constructed in his own shops. But though spectacles had been worn since the end of the thirteenth century, he little suspected the great opportunity they placed within his grasp.

The history of lenses is full of interest. It is very improbable that the disk of rock crystal, oval in shape and ground to a plano-convex form, which was found by Layard in Sargon's Palace at Nimroud, was actually intended for use as a lens, in spite of Sir David Brewster's contrary opinion. Nor can it be safely affirmed from their minuteness
of detail and perfection of execution that the finely engraved gems of antiquity were cut under lenses. Pliny the elder and others state that globes filled with water were used as burning glasses, and Seneca remarks that "letters though small and indistinct are seen enlarged and more distinct through a globe of glass filled with water." Yet while defects of vision were frequently discussed by many classic authors, they made no reference to the simplest optical aids and myopia was repeatedly declared to be incurable down to the end of the thirteenth century, when spectacles first came into use.

Roger Bacon and his teacher Grossteste undoubtedly understood some of the properties of lenses and concave mirrors, but the evidence advanced to support the opinion that Bacon used telescopes for astronomical observations is not convincing. The early history of the telescope remains rather obscure, but from our point of view the most important fact is its application in astronomy by Galileo and the revolution in human thought effected by his discoveries. His sudden recognition and utilization of a principle which had certainly been applied in the case of spectacles for three hundred years quickly transformed the equipment of the observatory and laid the foundation of astrophysical research. In 1630 Francesco Generini saw the feasibility of using the telescope for increased precision in pointing, presumably by introducing threads into the focal plane of the eye-piece. About ten years later the inventor of the micrometer undoubtedly used this method. The modern period of astronomical measurement was thus begun.

As for the telescope itself, it was first improved by the invention of the Keplerian eye-piece and then increased in focal length to overcome the troublesome effects of aberration. Rayleigh has shown that a single lens of 1.7 inch aperture is as good as an achromatic when its focus is 66 feet. Huygens, who worked out the theory of aberration, consequently greatly increased the aperture and focal length of his telescopes. He also devised the Huygenian eye-piece and was rewarded for his efforts by the discovery of the true nature of the rings of Saturn. Three of his objectives, with focal lengths of 122, 170, and 210 feet respectively, are still in the possession of the Royal Society. Telescopes up to 600 feet in length were made in this period, but the difficulty of finding and following the celestial object seriously affected their value. Obviously they could not be carried on equatorial mountings, first described for telescopic purposes in Scheiner's Rosa Ursina, but really not different in principle from the equatorial armilla of Tycho Brahe. An accessory of the highest importance developed at this time was the pendulum clock, devised by Huygens following Galileo's discovery of isochronism.

Two steps taken for the purpose of overcoming chromatic aberration ultimately proved successful. The reflecting telescope, introduced by Gregory and Newton, reached apertures of 4 feet in the hands of
Herschel, and 6 feet in those of Lord Rosse. The invention of the achromatic objective, followed by the production of optical glass in larger and larger disks, made way for the great refractors of the present day. Their high perfection, like that of the modern reflector, is the result of successive advances in the art of the glass maker, the metallurgist, the mechanical engineer, and the optician, and the development of modern machine tools, which Lord Rosse did not possess. Even if the photographic plate had then been perfected, the absence of an accurately driven equatorial mounting would have rendered it useless with his 6-foot reflector. The refinement and precision of the modern meridian circle, with its nearly perfect pivots and beautifully graduated circles, is another result of the improved art of the instrument maker, which is also illustrated in such valuable accessories as the latest types of clocks, the recording chronograph, and the moving wire micrometer.

The first telescopes collected about 80 times as much light as the unaided eye, and this light-gathering power has now been increased to about 200,000 times that of the eye. As the quality of the atmosphere and the optical and mechanical perfection of the best modern instruments are sufficiently good to permit all of this light (barring losses by reflection) to be concentrated and held in a very small image, the gain thus effected is enormous. But the advantages derived from the introduction and improvement of the photographic plate, and the development of many auxiliary instruments and methods, are still more important.

When Newton decomposed sunlight with a prism in 1672, he took the first great step in the initiation of spectroscopy. It was not until 1803, however, that Wollaston, using a narrow slit instead of Newton's wider one, detected the principal dark lines in the solar spectrum, nearly six hundred of which were measured by Fraunhofer in 1814. Their interpretation by Stokes, who in 1852 recognized that the double D line is due to sodium vapor, which absorbs the same radiations that it emits, and later by Kirchhoff and Bunsen, who in 1859 identified many terrestrial elements in the sun, provided the means of determining the chemical composition of celestial objects.

The study of stellar evolution, foreshadowed by Herschel and by Laplace in the nebular hypothesis, was thus rendered possible in the very year of the publication of Darwin's "Origin of Species." This was a tremendous advance, even when only the classification of stellar spectra, at once undertaken by Secchi and Huggins, and the apparent variation of chemical composition with stellar evolutionary progress, are considered. But the chief significance of the adoption of the spectroscope in the observatory lies in the extraordinary versatility of this instrument, and the possibilities it affords of utilizing in astronomy the widest variety of physical and chemical discoveries.

In 1842 Doppler tried to prove that the color of a star depends upon
its velocity. If a star radiated monochromatic light and its velocity were great enough, his conclusion would be correct. Rightly applied with the spectroscope, his principle has given us the means of measuring the motions of gases in the solar atmosphere; the rotation of the sun, planets, and nebulae; the orbital velocity of close double stars discoverable only by this method; and the velocity in the line of sight of various celestial objects.

I wish that time permitted me to dwell on the extraordinary harvest which has resulted from the skilful application of this and other principles of physics, but I can only recall a few of them. The shift toward red or violet of spectral lines by pressure affords a means of measuring the pressure in stellar atmospheres, after other effects have been allowed for. The variation of the relative intensities of lines with temperature gives one clue to stellar temperatures, and has also led indirectly to Adams’ beautiful method of deriving absolute magnitudes and parallaxes from stellar spectra. Reduced to a sound scientific basis through the recent advances of physics, the study of line intensities has also become one of our most powerful guides, not only to the nature of stars, but to the structure of the atom itself. The shift of the maximum of intensity in the spectrum as a function of the temperature, the influence of magnetic and electric fields on radiation, the phenomena of polarization, of anomalous dispersion, and of optical resonance are also among the numerous discoveries of the physicist which the astronomer has already utilized, with important positive or negative results.

In addition to the spectroscope, the astronomer has derived from the physical laboratory a long line of other valuable instruments. The photometer, now powerfully supplemented and largely displaced by photographic methods, has given us the magnitudes of tens of thousands of stars. The thermopile and the bolometer have led to remarkable advances in our knowledge of the infra-red spectrum, precise measures of the varying intensity of the solar radiation, the determination of the heat radiation of stars as faint as the thirteenth magnitude, and even to studies of the energy spectra of some of the brighter stars. The photo-electric cell has yielded stellar photometric measures of surprising precision. The radiometer, which gave the first actual measure of the pressure of radiation, now known to play such a dominant part in the massive stars, has recently provided the means of detecting the last wave-lengths missing in the long range from the gamma rays of radium to radio waves 20,000 meters in length. The interferometer, springing from Young’s famous interference experiment of more than a century ago, has served for scores of brilliant successes, recently culminating in the determination of the angular diameters of giant stars.

Without attempting to enumerate more of the astronomer’s long list of debts to the physicist and chemist, let us look for a moment at the increase in the precision of measurement effected by instrumental ad-
vances. The star places of the Greek were given to the nearest 10' of arc, one-third the diameter of the moon. Tycho succeeded in reducing the probable error of a single measure of the distance between two neighboring stars to 57". In double star observations the probable errors of the best micrometric measures are about 0'.1. In modern photographic parallax determination the probable error is about 0".005 to 0".010. With the interferometer, the probable error of a single measure of the separation of the components of Capella is 0".001. The diameter of Arcturus, 0".019, can be similarly measured with a probable error of about the same amount.

The advantages to be gained by the early utilization of the rapid progress of the physicist and chemist are obvious. Almost any discovery may help us directly or indirectly. We are interested in new organic dyes because they may improve the sensitiveness of our plates in various regions, especially in the infra-red, a most promising field for future research. We earnestly hope for a reduction in the size of the grain of the most rapid photographic plates, which would be equivalent to a marked increase in the aperture of our telescopes. We keenly watch for the appearance of new alloys, perhaps suitable for telescope mirrors or for the special needs of optical gratings; progress in the manufacture of optical glass; the production of large masses of clear fused quartz for prisms or mirrors—every technical advance, in fact, that we can learn to utilize. And we are equally anxious to benefit by the constant improvement of high tension transformers, electric furnaces, vacuum tubes, electromagnets, and the many other devices on which we depend for the imitation and interpretation of celestial phenomena.

These illustrations of the increasing possibilities of instrumental development have not been enumerated in strict chronological sequence, but a glance at this partial list will show how rapidly the opportunities of the astronomer have multiplied in recent years. Another point should be noted: the obvious change is not always the most important one, and the greatest advances may come from the recognition of possibilities that are not immediately apparent. Hence the astronomer cannot watch too intently the progress of related sciences, and especially the numerous devices and methods which are constantly arising in various fields. Such beautiful new instruments as the X-ray spectrograph or the mass spectrograph of Aston, while perhaps not directly applicable in astronomy, may contain hints, and also yield results, which can be used to advantage.

Such considerations will help to explain the somewhat unorthodox equipment and policy of the Mount Wilson Observatory. We have tried from the outset, with the valuable co-operation of our Research Associates, to utilize some of the more obvious possibilities offered by the progress of physics and chemistry, and to gain such advantages as laboratory conditions and methods place at our disposal. Hence the
design of the Snow and tower telescopes, equipped for solar research; the coudé principle and constant temperature laboratories of the 60-inch and 100-inch reflectors, arranged for the photography of stellar spectra under high dispersion and for investigations like those with the thermopile and bolometer on stellar radiation and energy spectra; the exceptional care taken to secure smooth rotation of the 100-inch dome, in order to diminish the vibration of the high dispersion stellar spectrograph (soon to be mounted on its pier) during exposures continued for several nights; the construction of the ruling machine, one of the prime purposes of which is to permit such experiments as have just rendered possible the concentration of most of the incident light in any desired order of spectrum; the development of the stellar interferometer, first in conjunction with the 100-inch telescope and now as a separate instrument. Hence the provision of machine and optical shops adequate for a wide range of constructional work and a physical laboratory in which to conduct researches required for the interpretation of celestial phenomena. Hence also our close co-operation with the California Institute of Technology, the recent growth of which as a research institution is so advantageous to the observatory.

Looking ahead, and speculating on the possibilities of future instruments, it may be mentioned that comparative tests of the 60-inch and 100-inch telescopes promise well for larger apertures. Their practicability, so far as this depends upon atmospheric limitations, can be fairly well tested by observations of the united star images given by the two mirrors of a stellar interferometer at increasing separations. The production of large mirror disks is another problem. Fused quartz mirrors, if they can be made of sufficient dimensions, will be extremely valuable for solar telescopes and large reflectors because of their low co-efficient of expansion, but for moderate apertures pyrex glass has already proved a fairly effective substitute. As for the stellar interferometer, I believe it will ultimately attain apertures of 100 feet or more, possibly in some fixed form, with accurately controlled coelostats. Fixed telescopes and spectrographs for solar work, whether horizontal or vertical, can be shortened if desirable by the use of telephoto lenses or by combinations of mirrors. Both the ultra-violet and the less refrangible part of solar and stellar spectra deserve more consideration than they have received, and here especially improvements in the photographic process, as well as in prisms and reflecting surfaces for the ultra-violet, are greatly to be desired. No increase in the resolving power of the grating is required for astronomical purposes, but more light, obtainable from greater area of ruled surface, with concentration in a single order, is still needed for various purposes.

I shall not attempt in this paper to deal with less obvious possibilities, or to discuss particular problems. Let me conclude with the reminder that if instruments are important, "the man at the eye-end" is more important by far. In the Hindu treatise Siddhanta Siromani, the