5 September 1958, Volume 128, Number 3323

SCIENCE

CURRENT PROBLEMS IN RESEARCH

Solar Spectroscopy

A new vacuum spectrograph at McMath-Hulbert Observatory makes possible greater accuracy in solar spectroscopy.

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It is extremely difficult to find a laboratory source of radiation that is as intense and reliable as the sun. Perhaps this is the reason why the sun has for many years provided the radiant energy for experiments that have been decisive in the development of essential instruments and techniques of modern spectroscopy. At the present state of the art, the compliment is being returned. Measurement and analysis of spectrum photographs are the principal means of studying the sun, and various spectroscopic procedures provide the observations which are the bases for deductions of solar chemical composition and physical conditions of motion, temperature, pressure, density, and electric and magnetic field strengths. Historically, progress in the determination of these elements of solar structure has depended heavily upon the development and perfection of observing apparatus. There follow some examples of the parallel growth of the instruments and of concepts in solar spectroscopy and the description of a new vacuum spectroscope for use in solar studies at the McMath-Hulbert Observatory of the University of Michigan. A brief discussion of some of the unexpected results obtained with this instrument makes clear a need for future improvements in solar astronomical instrumentation.

Genesis of Solar Spectroscopy

Solar spectroscopy began with Isaac Newton's (*1*) summary statement that "the sun's light is a heterogeneous mixture of rays" and that these can be "parted or sorted from one another." Newton drew this conclusion from the results of personal repetitions of experiments, common in his day, with triangular glass prisms and beams of light of narrow cross section.

Newton described one of his first experiments in this way: "In the sun's light let into my darkened chamber through a small round hole in my window shut, I placed a lens. . . . Immediately after the lens I placed a prism, . . . and thereby the round image which the lens alone did cast upon the paper might be drawn out into a long one with parallel sides. . . . Instead of the circular hole . . . 'tis better to substitute an oblong hole shaped like a long parallelogram with its length parallel to the prism. . . . The edges of the prism and lens must be covered with black paper glued on. . . . All light of the sun's beam let into the chamber which is useless and unprofitable to the experiment ought to be intercepted with black paper. . . . It's difficult to get glass prisms fit for this purpose, and therefor I used sometimes prismatic vessels made with pieces of broken looking-glasses, and filled with rainwater. . . ."

Newton's observations with this primitive spectroscope led him to conclude: "Whiteness and all grey colors between white and black, may be compounded of colors, and the whiteness of the sun's light is compounded of all the primary colors mix'd in due proportion."

From the time of the discovery of the colors in the white light of the sun, each improvement in the spectroscope has revealed new features in solar radiation, but progress was rather slow in the years following the publication of Newton's *Opticks* (1704). Almost a century elapsed before the discovery of dark lines intersecting the continuous band of solar spectrum colors was announced by Wollaston (1802) (*2*), in a paper that is considered by many to be the ultimate model of occult description. Wollaston saw only a few of the strongest dark lines interrupting the continuous spectrum, and he seemed to regard them as boundaries separating the seven homogeneal colors urged by Newton as the elemental components of white light.

There is a completely adequate reason for the leisurely rate of advance in spectroscopy and optical science in the 18th century, and the quotation given above from Newton's *Opticks* shows that he was well aware of the cause of the trouble. Although the lenses and prisms in the spectroscopes of Newton and Wollaston were as large as many now in use, the poor quality of the glass prevented the formation of very good optical images. Such technical imperfections often led experimenters to amusingly incorrect generalizations.

This situation was completely changed during the first quarter of the succeeding century. The Swiss glassmaker Guinand (*3*) discovered a method of producing first-quality glass, and reproducible spectroscopic measurements become possible. Under Guinand's tutelage Joseph Fraunhofer mastered the art of making optical glass and, in attempting to perfect his methods of manufacturing scientific instruments, made a detailed study of spectra of flames, of the sun, of the planets, and of a few of the brighter stars. Incidentally he produced both transmission and reflection diffraction gratings, the first measurements of the wavelengths (which can be considered precision designations of color) of solar spectrum lines, a map of the position of 600 dark lines in the sun's spectrum, and the first convincing demonstration that the dark lines in the spectra of astronomical objects were characteristic of the observed object and were not prod-

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ucts of the instruments or methods of observation. Furthermore, Fraunhofer noted an apparent coincidence in wavelength between the dark lines, which he had labelled "D," in the spectrum of the sun and the close pair of yellow lines visible in the spectrum of a candle flame.

Growth of Spectroscopic Concepts

More than thirty additional years of improved observation and measurement, made possible by Fraunhofer's refinements in the art of glassmaking and the construction of scientific optical instruments, were to pass before the recognition of a principle that connected emission and absorption of radiation in light sources. Then, in 1859, just a hundred years ago, G. Kirchoff (*4*) announced the fundamental principle that has made spectroscopic chemical analysis of the sun's atmosphere possible. This relation is: The ratio between the emissive power and the absorptive power is a constant for all bodies at a given temperature. At the time of its announcement, Kirchoff's law completely reoriented research in physics, and its implications for the understanding of the radiation of the stars are still being studied in detail. Kirchoff demonstrated experimentally one of the most important consequences of this statement—namely, a gas which emits a line spectrum also absorbs the lines it emits. He further concluded from direct comparison of emission lines in laboratory sources with the absorption lines in the solar spectrum that at least 21 of the terrestrial chemical elements must also be present on the sun.

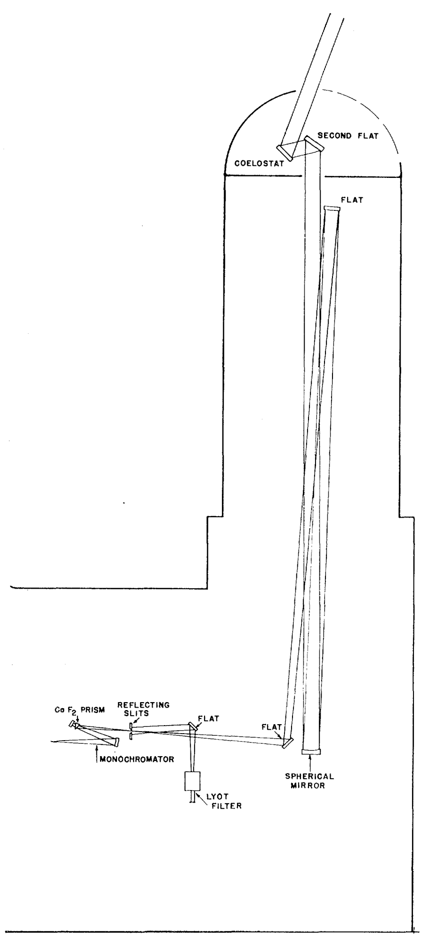


Fig. 1. Diagram of the McGregor solar tower telescope of the McMath-Hulbert Observatory. See Fig. 2 for a diagram of the spectroscope used with this telescope.

But one more fundamental principle was needed to provide a broad base for solar spectroscopic studies. At about the time that Kirchoff and his colleague, Bunsen, were reporting their methods of spectroscopic chemical analysis, a rather puzzling suggestion concerning the spectrum colors was being debated in the scientific journals. Doppler (*5*) suggested that the observed color of a luminous body depended on its state of motion with respect to an observer. Fizeau (*6*) correctly, and independently of Doppler's suggestion, directed attention to a small change in wavelength in the absorption lines in the spectrum that would result if the sun were in motion, which would destroy the nice coincidence predicted by Kirchoff between laboratory emission lines and solar absorption lines. Lockyer verified Fizeau's ideas, in the case of the sun, when he recorded variable distortions, shifts, and broadenings of solar spectrum lines. He recognized these as evidence of motion in the solar gases. "The accompanying changes of refrangibility of the lines in question show that the absorbing material moves upwards and downwards as regards the radiating material and that these motions may be determined with considerable accuracy" (*7*).

After the discovery and verification of Kirchoff's law, and of the Doppler-Fizeau method for the measurement of motion in the line of sight, it soon became apparent that all of the results of laboratory spectroscopy could be applied directly to the study of the chemical and physical constitution of the sun, and solar spectroscopy was well begun.

In the years that followed, a number of instruments were designed especially for the analysis of solar radiation, and experience in their use demonstrated that definitive, quantitative answers to solar spectroscopic problems could be obtained only by the use of highly perfected designs and procedures. Today the best that spectroscopy can give to solar astronomy is not yet quite good enough. The McGregor tower telescope and the vacuum spectroscope of the McMath-Hulbert Observatory (*8*) are representative of attempts to meet these needs. This recently (1955) completed installation embodies a number of improvements that have brought new accuracy and facility to the study of solar structure. Figure 1 is a diagram of the telescope, and Fig. 2 is a diagram of the spectroscope.

Some Features of the McMath-Hulbert Spectroscope

There are four features in the construction of the McMath-Hulbert spectroscope that should be given detailed mention because they may indicate directions toward possible solution of the more persistent problems in solar spectroscopy.

Firstly, wherever possible, mirrors have been used in place of lenses so that the achromatism of the entire system may be as perfect as possible. Perfect achromatism assures correct focusing of invisible radiation, and it is required if all wavelength regions between the cut-off at 0.00029 millimeter by asmospheric ozone and the cut-off at 0.0240 millimeter by water vapor are to be studied without making extensive adjustments for each change of wavelength.

Secondly, the entire spectroscope is sealed inside a vacuum tank, thus eliminating all possibility of image deterioration as a result of air currents flowing around and across the optical parts. A secondary but still very important advantage, that insures uniform and reproducible results, is obtained because the vacuum tank protects the mirrors and gratings from dust and condensation. These considerations are different from those that lead to the construction of large laboratory vacuum spectroscopes. Air is removed from laboratory instruments to obviate absorption of ultraviolet and infrared radiation. In solar spectroscopy the amount of air traversed by a beam of radiation in a spectroscope is trivial in comparison with the long path it must travel through air in order to reach the instrument from the sun.

Thirdly, the dispersing element of the spectroscope is one of the best of the new, modern gratings. It is a plane grating, ruled in an aluminum coating supported by an optically figured, flat Pyrex base. Modern methods of ruling gratings produce very high concentration of the dispersed light in desired spectral regions. Such gratings have been made possible by many years of careful development of techniques and instruments by many gifted scientists, and they represent a remarkable improvement over the prototypes first ruled directly in glass by Fraunhofer. The latest steps toward the perfection of gratings are being taken by Babcock, at Mount Wilson Observatory; Harrison, at Massachusetts Institute of Technology; Richardson, at Bausch and Lomb; Strong, at Johns Hopkins University; and Gerasimov, at the Leningrad Institute for Technical Optics. Babcock ruled the grating of the vacuum spectroscope of the McMath-Hulbert Observatory especially for this instrument in 1954. The Babcock grating is mounted on an electrically driven turntable which can be rotated to permit either photographic or photoelectric registration of any desired spectral region. During the course of photoelectric recording, the grating may be rotated continuously at rates between 1.0 and 0.005 degree per hour to provide a slow drift of the spectrum across the photoelectric exit slit (Fig. 2).

Fourthly, a small prism spectroscope (see "monochromator," Fig. 2) is placed in the beam of radiation before the entrance slit of the main instrument (actually the spectrum produced by this component of the vacuum spectroscope is about one-fortieth as long as the spectrum used by Newton). The prism spectroscope acts as a filter, or monochromator, with adjustable transmission characteristics. With its assistance, most of the incident solar radiation can be excluded from the main instrument and only the portion under investigation admitted. This is a rather erudite way of following Newton's important, and often neglected advice, quoted above: "All light of the sun's beam let into the chamber which is useless and unprofitable to the experiment ought to be intercepted with black paper." Throughout the spectroscope absorbing screens and diaphragms eliminate all possible stray radiation.

Performance of the Instrument

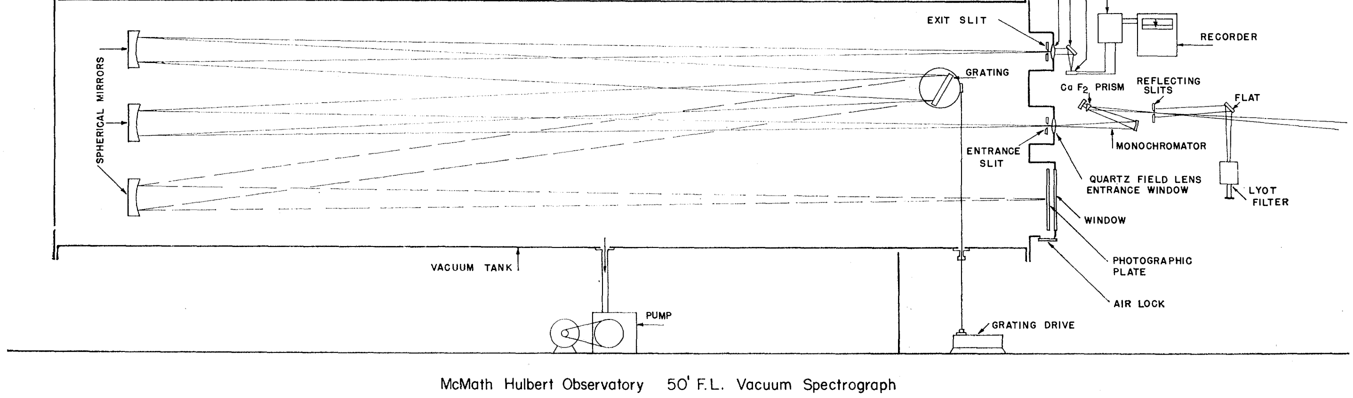
Each of the features of the construction of the McMath-Hulbert vacuum spectroscope listed above contributes in part to the high-contrast, high-resolution performance of the instrument. A spectral image has perfect contrast if test absorption lines, known to be absolutely black, are imaged with no radiation filling in their dark centers. The ratio of the intensity of the background of continuous radiation upon which the black test line is superposed to the intensity of the radiation at the bottom of the line image therefore approaches infinity as a limit, as the image approaches perfection. Since some energy is scattered from all real optical surfaces, perfect contrast can never be achieved, and a contrast ratio greater than 25 is very good indeed. Different measurements of the contrast ratio of the present instrument have been made by several different observers, using different standard lines, and the resulting values of the ratio lie between 25 and 60. The higher values can be obtained only with the most exacting attention to the adjustment of the prism monochromator, so that it admits an extremely small amount of radiation into the larger instrument.

Undoubtedly, much of the credit for this performance should be attributed to the excellence of the Babcock grating, as also should the high resolving power of the instrument. The practical resolving power of a spectroscope is defined as the ratio of the mean wavelength of two lines, just clearly visible separately, to their difference in wavelength. The value of this characteristic of the vacuum spectroscope of the McMath-Hulbert Observatory varies, with the conditions of use of the grating, from 100,000 to more than 1 million and for general observations lies in the range 400,000 to 800,000.

Lines in the Solar Spectrum

If the absorption lines in the solar spectrum had been first observed with spectroscopes as powerful as this, it is doubtful that they would have been called lines. It is evident from a glance at Fig. 3 that in a high-contrast, high-resolution spectroscope, the solar lines look like stacks of bristles, or short streaks.

Figure 3 is a reproduction of the appearance of the first line of the Balmer series of hydrogen, Hα. The smooth, very narrow lines are produced by the water vapor in the earth's atmosphere. The largest variations in the edges of Hα, when the spectrum comes from a quiet part of the sun, occur on the redward side of the line (the right side, in Fig. 3). If these structures are interpreted, following Lockyer, with the aid of Doppler and Fizeau's principle, then they are evidence of the motion of small clouds of gas on the sun, but differences of temperature and density from volume to volume must also play a large part in



McMath Hulbert Observatory 50' F.L. Vacuum Spectrograph

Fig. 2. Diagram of the McMath-Hulbert vacuum spectroscope for solar spectroscopy. See Fig. 1 for a diagram of the solar tower telescope used with the spectroscope.

causing the streaks. Oddly, the observation of the spectrum of an active (but not too active) part of the sun, containing transient features such as sunspots, reveals lines much less "bristly" than the lines from the more quiescent areas. The active regions referred to are called plages, and although they are the part of the sun in which spots and flares and other, often explosive, phenomena burst forth, the relatively smooth lines they produce are evidence that some force, possibly magnetic, restrains the normal motions of the small gas clouds.

The average thickness of the streaks, a measure of some average dimension of the clouds, is about 3500 kilometers on the surface of the sun. At the earth's distance, 3500 kilometers, or slightly more than half of the earth's radius, subtends an angle of about 5 seconds of arc. Bristles on the edges of the "lines" in the solar spectrum are produced both by changes in the total length of the streaks and by shifts of these elemental components structures. There seems to be no evidence at Hα for an underlying uniform dark central core on which the streaks are superposed. The width of the individual streaks, interpreted as motions, has a minimum value of 30 kilometers per second and an upper limit of about 50 kilometers per second. Measurements of the centers of the individual streaks range within plus or minus 16 kilometers per second, with the average shift from the mean position averaging only 0.6 kilometer per second.

The changes in intensity that make the streaks visible can also be measured. Values of the ratio of the difference of intensity from the average value along the spectrum line to the mean value range from 15 to 30 percent. At the edges of the line, these values may go as high as 80 percent. The wider bristles are generally more intense at their centers than the narrow ones. A careful examination of the lines in Figs. 3 to 6 provides strong evidence that the streak-like bristles originate in an outer layer of the sun, the chromosphere. Near the edge of the sun the bristles widen and finally merge without perceptible interruption into the bulge on the edge of the spectrum which is produced in the chromosphere.

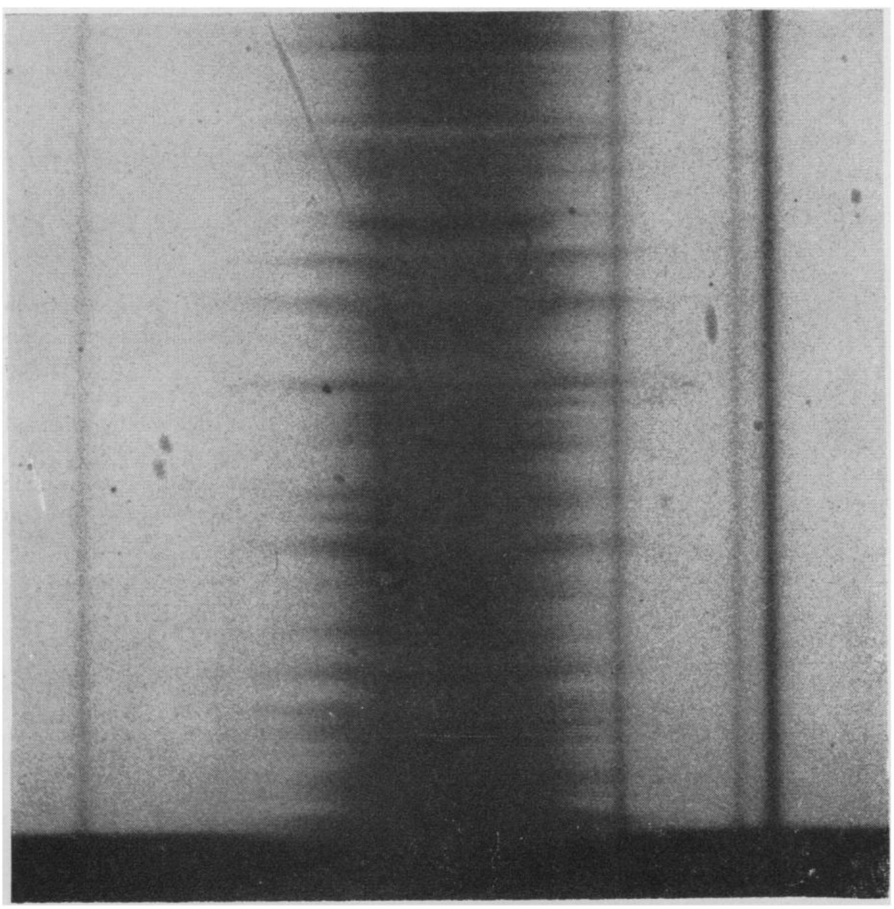


Fig. 3. The solar spectrum line Hα (center vertical band), which appears as a stack of bristles or short streaks. The upper edge of the dark horizontal band at the bottom is the edge of the sun. From left to right, the wavelengths (in angstroms), and identifications of the spectral lines are: 6561.105 (HOH, earth); 6562 (?); 6562 (Hα, sun); 6563.533 (HOH, earth); 6564.075 (HOH, earth); 6564.220 (HOH, earth). Note the bulge at the edge of the sun at the position of the Hα line. This is produced by the chromosphere. A distance of 1 millimeter along the spectral lines is equivalent to 2 seconds of arc on the sun.

Figure 4 shows the second member of the Balmer series of hydrogen Hβ. The Hβ streaks are nearly identical in kind with those of Hα, but there is some evidence of an underlying, uniform, live center. They continue without interruption into the chromospheric bulge at the edge of the sun and, just as in the case of Hα, are doubtless formed chiefly in the outer atmosphere of the sun. Close by Hβ appear a strong line of iron and weaker lines of ionized and neutral chromium, iron, and vanadium. The streaks in the lines of the metals are generally similar to those in the hydrogen lines, from which one concludes that either all of these details of line structure are formed in the same layers of the sun or, if they are formed at different levels, the characteristics of the different regions are closely correlated.

Near the center of the line of ionized calcium, labelled "K" by Fraunhofer (Fig. 5), the streaked structure, which except for somewhat greater coarseness, resembles hydrogen in size and distribution, reaches its most conspicuous development in the entire solar spectrum. The center of the K line is flanked by two bright borders that have been for many years past the subjects of intensive study and the sources of many concepts of the circulation of the sun's upper atmosphere. Nearly always the violet component of the emission (left center in Fig. 5) is the brighter, and this difference in brightness persists to the edge of the sun. It is possible to suppose that the observed asymmetry results from the expansion of hot masses of gas rising through the chromosphere to cooler regions.

If the slit of a spectroscope is illuminated by ordinary sunlight, instead of by the solar image from a well-focused telescope, then the K line has the appearance shown in Fig. 6. All of the streaks and bristles in the line vanish, but the predominant brightness of the violet emission component remains. A measurement of the width of the outer edges of the emission components shows that this quantity is directly related to the sun's intrinsic brightness, just as similarly measured widths of K lines in other stars are related to their brightness (*9*). The observational discovery that the widths of the central emission structures in the K line are connected with stellar brightness provides one of the strongest indications of the fundamental importance of the study of the detailed structure within the solar spectrum lines. Special spectroscopic instruments are required for the recording of this elusive structure with high precision.

Desirable Instrumental Improvements

Observations at the McMath-Hulbert Observatory have shown clearly that the streaks and bristles of the spectral lines revealed by the vacuum solar spectroscope at Lake Angelus give physical data for some of the small structures on the sun. The next great need is an instrument that will make possible spectroscopic observation of the very smallest solar features, structures that in some cases subtend angles no larger than ½ second of arc.

The general lines of construction for the desired improved spectroscope would doubtless be similar to those already tried in the vacuum spectroscope of the McMath-Hulbert Observatory, but with even greater attention paid to the elimination of all parasitic light by the use of more powerful auxiliary monochromators, improvement of all optical surfaces, both reflecting and refracting, and especially the improvement of diffraction gratings. Much of the success of a very large solar spectroscope depends on the production of more perfect and larger diffraction gratings than now exist; to produce them seems to be well within the capabilities of known techniques for ruling gratings.

Specifications for a High-Resolution Observatory

The smallest feature visible in a solar image is determined in large part by the earth's atmosphere. At all observatories, experience shows that the most favorable conditions occur in the early morning hours and at high altitudes. The telescopic image is most tranquil and most clearly defined under these conditions. The image is also much brighter at high altitudes than at sea level. Such considerations indicate that a solar observatory seeking the best possible definition of the image should be located high above sea level and should have an unobstructed eastern horizon.

It may be that in some future time it will be possible to make telescopic solar observations from above the earth's atmosphere, and indeed some important

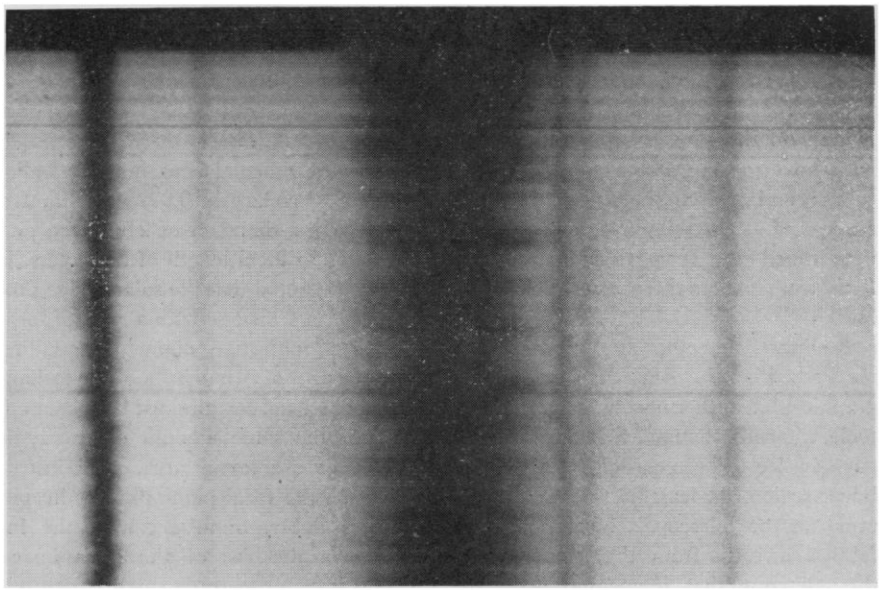
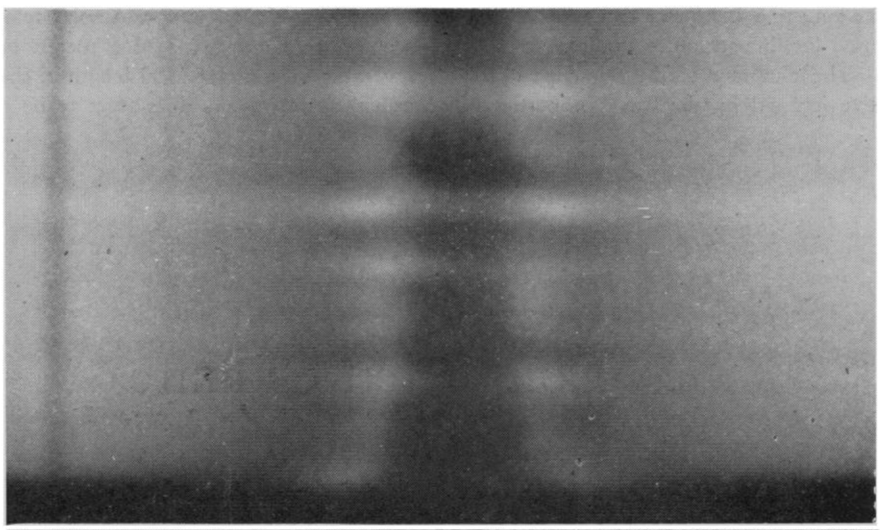


Fig. 4. The solar spectrum line Hβ (center vertical band). The lower edge of the dark horizontal band at the top is the edge of the sun. From left to right, the wavelengths (in angstroms) and identifications of the spectral lines are: 4859.747 (Fe, sun); 4860.220 (Cr^{II}, sun); 4860.992 (Fe^{I}, sun); (?) (Hβ, sun); 4861.849 (Cr^{I}, sun); 4861.953 (?); 4862.551 (Fe^{I}, sun) and 4862.604 (V^{I}, sun). Note that the bristles in the lines of metals correlate with those in the Hβ line. Scale along the lines: 2 millimeters is equivalent to 1 second of arc.



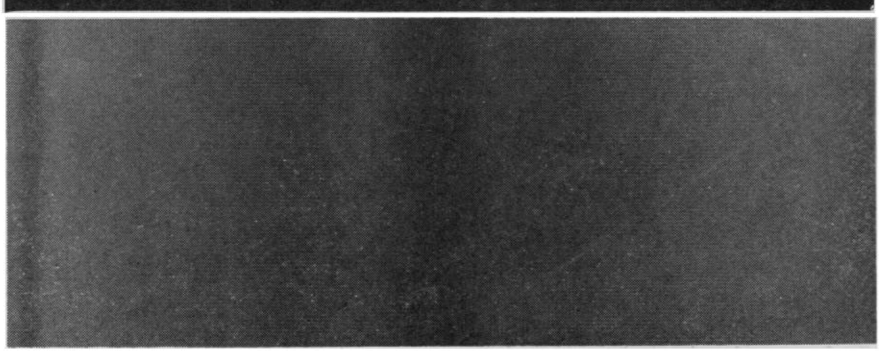


Fig. 5. (Top). The solar spectrum line K, Ca^{II} (center vertical band). The upper edge of the dark horizontal band at the bottom is the edge of the sun. From left to right, the wavelengths (in angstroms) and identifications of the spectral lines are: 3932.638 (Fe^{I}); 3932.916 (Fe^{I}); 3933.532 (K2V) bright line; 3933.683 (K3) dark line; 3933.863 (K2R) bright line. All lines are sun lines. Note the similarity between the line structures in Figs. 3, 4 and 5. Scale along the lines: 2 millimeters is equivalent to 1 second of arc. Fig. 6 (Bottom). The solar spectrum line K made with integrated sunlight. For identification of the lines, see Fig. 5. The bristles are absent; the solar light on the spectroscope slit is not focused into a sharp image.

exploratory observations have already been made. However, the equipment required for precision, quantitative, solar records must be very large and must be guided on the sun for minutes of time with no error larger than a few tenths of a second of arc. The size of the telescope and its associated equipment are determined by geometrical considerations from which there seems to be no escape.

Radiation detectors at present in use for recording the sun, such as photographic plates, thermocouples, and photoelectric cells, demand that the smallest angular size to be recorded must have a linear scale of at least 25 microns (1/40 mm) in the telescope's focal plane. It follows directly from the geometry of the telescope that if measurements of structures only ½ second of arc in size are sought, the equivalent focal length cannot be less than 10.3 meters and preferably should be three or four times this value, if one makes a reasonable provision for ease of observation. Experiments at the McMath-Hulbert Observatory have demonstrated that focal lengths as long as 1 kilometer can be profitably used for fine structure studies.

The diameter of the telescope objective is fixed by the wave properties of radiation and the angular size of the smallest object to be observed. A telescope capable of forming an image of the sun on a scale of ¼ second of arc per 1/40 millimeter, or 10 seconds of arc per millimeter, using infrared radiation of wavelength 0.0025 millimeter, must have a diameter of 2.5 meters and a minimum focal length of 21 meters. It should be noted that the solar image produced by a telescope with a ratio of focal length to objective diameter equalling 21/2.5, or 8.4, is much "too hot to handle." The focal length must be increased, so that the same amount of energy is spread over a larger area, until instruments in the focal plane are not heated uncontrollably. Simultaneously, the increase in the size of the sun's image makes it easier to study small structures.

Conclusion

These are some of the fundamental reasons why a very large telescope is required for significant progress in the study of fine structure on the sun over a broad wavelength range. A solar telescope with an aperture of a meter, or several meters, and a focal length of the order of 100 meters does seem to be a practical possibility. Accompanied by a properly matched spectroscope of modern design, it would constitute a research tool more nearly adequate than any existing instrument for dealing with the questions raised by the presence of the line details shown in Figs. 3–6, and the completely baffling correlation of these formations with the brightness of the sun.

Indeed, a very large telescope for the study of the sun would not only make possible observations of solar fine structure when the earth's atmosphere is "well-behaved," and good definition is possible; even under unfavorable conditions it would enormously extend the attainable precision and productivity in nearly all fields of solar physics now investigated with smaller instruments.

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Controlled-Climate Facilities for Biologists

Readers are asked to consider the feasibility of constructing what the authors term a "biotron."

S. B. Hendricks and F. W. Went

Knowledge of the effects of the environment on the growth and development of plants and animals has come from two different approaches: (i) observations in the field and (ii) laboratory experiments. Field observations are very difficult to interpret because of the complexity and nonreproducibility of the many climatic variables, whereas in laboratory experiments only a single environmental variable can usually be studied. To bridge this gap, it is necessary to have laboratory facilities in which the whole range of climatic variables may be controlled individually so that the interaction of these variables on the organisms can be assessed.

The first facility for the study of plant growth under a wide range of controlled conditions was constructed at California Institute of Technology in Pasadena, in 1948–49. This facility was dubbed a "phytotron" in a humorous moment, but the term was so appropriate that it has endured. The variables under control are chiefly ranges of temperature, light intensities, and cycles of these variables.

The Pasadena phytotron has been fully described elsewhere (*1*), and the results obtained through its use are in the literature. The phytotron has been generally accepted as an experimental tool, comparable to telescopes, particle accelerators, fossil collections, and other tools of science. Interest in such facilities, although it comes predominantly from plant scientists, has also been expressed by others experimenting with animals; thus the concept of a "biotron" developed.

A question naturally arises with regard to a successful experimental tool: How might it be made more widely available? With regard to a biotron, as well as other experimental tools, this is a complex question, involving enthusiasm, needs, effort and cost, the interest of groups of individuals, and the degree to which the community of biologists can afford to support the tool.