The Solar Flare Recorder of the Sacramento Peak Station of the Harvard College Observatory[1]

John W. Evans
High Altitude Observatory of Harvard University and *the University of Colorado, Boulder*

SOLAR FLARES seem possessed of a peculiar and fascinating perversity. The more we learn about them, the harder they are to understand, and the sharper the appetite for more information becomes. Briefly, a flare is a small area in the solar chromosphere in which several lines of the solar spectrum suddenly flash out in emission. Although the Hα line of hydrogen and the H and K lines of ionized calcium are the brightest, the emission is usually not quite sufficient to fill in completely their normal Fraunhofer absorption contours. Thus, the total light output constitutes a very tiny enhancement of the normal brightness of the solar surface, and the flares are quite invisible without special instruments. Typical flares rise to maximum brightness in a few minutes and then gradually die out over a period of half an hour or so. They occur in or near sunspot groups and are comparable with the spots in size. Small flares are the most numerous, and the frequency diminishes steadily with increasing area. They appear at a rate that varies with the sunspot cycle and runs at about one every eight hours in our present mid-position on the downward curve.

In spite of their feeble light emission, the flares are apparently very powerful sources of far ultraviolet and corpuscular radiations, which are strong enough to produce large-scale changes in the terrestrial ionosphere at a distance of 1.5×10^7 km. They also emit radio noise with an intensity 10^4 times that of the normal sun at some frequencies, and of certain components of cosmic rays. The reconciliation of the small light output of flares with the obviously enormous output of other forms of energy is a major theoretical problem.

At present we lack quantitative statistical information on the simple flare characteristics of brightness, size, and position, and on their association with geophysical phenomena. The data we have comes almost entirely from the valiant efforts of a group of visual observers all over the world, working cooperatively through the International Astronomical Union to keep the sun under constant surveillance for the detection of flares and for estimates of their characteristics. This effort is immensely worth while and has led to important results. However, visual observation of such rapidly changing objects has troublesome shortcomings, not the least of which is the requirement that the observer must endure many hours of tedium for the brief excitement of each flare discovery. The estimates simply classify the flares into four groups of "importance," a combination of area and brightness. Systematic personal differences between the estimates of individual observers introduce decided inhomogeneities into even this rough classification.

The Mount Wilson Observatory has run an automatic flare camera since 1936, photographically recording the sun in the light of the K line with a spectroheliograph at intervals of three to five minutes. The flare discoveries from this program, like those of the visual observers, are published by the I.A.U. in terms of time, position, and importance.

As a first step toward improving the statistical data, the High Altitude Observatory, with the Harvard College Observatory, has initiated a photographic flare patrol. The entire disk of the sun is recorded in the light of Hα on 35-mm. film at intervals of one minute whenever the sun is shining. This one instrument does not, of course, achieve anything like complete coverage, because of cloudy weather and nighttime interruptions. Five or six such instruments distributed fairly evenly in longitude would probably be required to detect substantially all the flares on the visible hemisphere of the sun above the detection threshold. R. G. Giovanelli, of the Commonwealth Scientific and Industrial Research Organization at Sydney, Australia, is constructing a second photographic flare recorder, which will be located in a very favorable longitude relation to our own. It is to be hoped that others will join this effort.

Although invisible in a simple telescope, the flares can be observed with a monochromator that transmits a very narrow band of the spectrum centered on one of their emission lines. The solar continuum is thus eliminated, and the flares and other features of the chromosphere stand out in brilliant contrast. Traditionally, the spectroheliograph and spectrohelioscope have been used for this purpose. They are scanning monochromators, which build up an image, slit-width by slit-width, on a photographic plate or (by very rapid scanning) in an eyepiece for visual observation. In 1942, however, a birefringent filter built by the author was installed in the coronagraph at the Climax, Colorado, station of the High Altitude Observatory (of the Harvard College Observatory, at the time) for

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making motion pictures of prominences. They, like the flares, can be observed only with the aid of some form of monochromator. The resulting photographs were of the highest quality, both in definition and in contrast. Since the birefringent filter is very much simpler, more compact, and less expensive than the spectroheliograph, it is gradually coming into more general use for solar observation, and we decided to use it in the flare recorder. Because it is the most vital single element, a brief description of its characteristics is necessary. For a full discussion of the birefringent filter the reader is referred to the literature (*1, 2*).

In its simplest form the birefringent filter consists of a multiple sandwich with alternate layers of Polaroid film and plates of some birefringent crystal. Quartz, calcite, and ammonium dihydrogen phosphate (abbreviated ADH hereafter) have been used successfully. The crystal plates are cut with their optic axes parallel to the surfaces and mounted with the axes at 45° to the vibration planes of the polarizers (which are all parallel). In traversing a crystal layer the ordinary and extraordinary waves travel at different velocities, and, on emerging, they interfere. The transmission of a single crystal mounted thus between polarizers is

$$\tau = \cos^2 \pi n,$$

where

$$n = \frac{d}{\lambda}\mu.$$

Here τ is the transmission, d the thickness of the crystal plate, μ the difference between the ordinary and extraordinary refractive indices, and λ the wavelength.

Neglecting the comparatively slight variation of μ with wavelength, we find that τ is a periodic function of the wavelength. Let curve (*a*) of Fig. 1 represent the transmission of the thickest element of a birefringent filter over a short length of spectrum. The second element is half as thick and has transmission curve (*b*). The third element is again half as thick, with transmission curve (*c*). The combined transmission of the three elements is

$$\tau = \cos^2 \pi n_1, \cos^2 \pi \frac{n_1}{2}, \cos^2 \pi \frac{n_1}{4}.$$

It is represented by curve (*d*), which is characteristic of the birefringent filter. It consists of a series of sharp transmission bands spaced at wide intervals along the spectrum. The ratio of band separation to effective band width is approximately 2^k in a filter of k birefringent elements. As an example, the Climax filter has six elements of quartz, with thicknesses in powers of ½. The thickest element has $d = 51.381$ mm, and $n = 704$ at Hα. The effective width of the transmission band is 4.2 A with side bands spaced at about 270 A at each side. The band separation is sufficient to enable us to cut off all the transmission bands of wavelengths shorter than Hα by means of a glass filter. The longer wavelength bands are comparatively harmless, since the sensitivity of the eye and of appropriately selected photographic material falls off very sharply in this region. The efficacy of this filter in showing the normally invisible prominences is shown in Fig. 2.

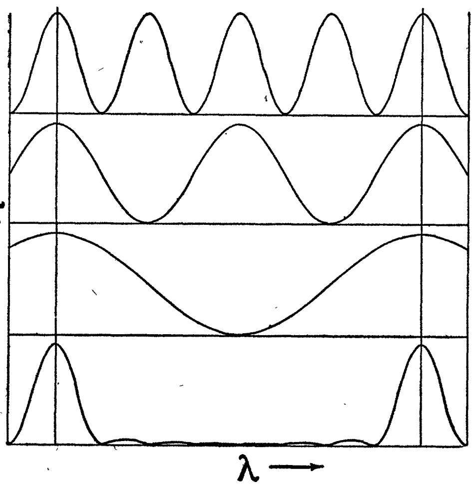

Fig. 1. Transmission curves of birefringent elements.

This simple form of monochromator, like any rose, is not without its thorns. The wavelength of the transmission bands is a function of the direction in which light traverses the filter and of the temperature of the birefringent elements.

Let λ (φ, θ) be the wavelength of the transmission band for light at an angle φ (in air) to the instrumental axis, in azimuth θ, measured from the crystal optic axis. Then, approximately

$$\delta\lambda = \lambda(\varphi, \theta) - \lambda(0, 0) = \lambda \frac{\varphi^2}{2\omega}\left(\frac{\cos^2\theta}{\varepsilon} - \frac{\sin^2\theta}{\omega}\right).$$

Although the filter works equally well in collimated or convergent light, the maximum permissible value of φ is restricted by the maximum tolerable value of $\delta\lambda$. In the Climax filter, φ max = 0.025 radion. Since it is placed in convergent light, the beam traversing the filter is limited to f/20. Although this is not a severe restriction, it must not be neglected in designing the optical system.

The temperature variation of the wavelength of a transmission band varies widely with the crystal used. In the neighborhod of Hα, $\frac{\Delta\lambda}{\Delta\tau}$ is − 0.7 for quartz, − 0.4 for calcite, and − 7.0 for ADH, in units of A/degrees centigrade. The temperature of the filter must therefore be controlled. The control of an ADH filter is inherently far more difficult than that of a filter of quartz or calcite.

Another limitation of the simple birefringent filter not shared by the spectroheliograph is that the wavelengths of the transmission bands are fixed, except for the fine adjustment obtained by changing the temperature.

More complicated forms of the birefringent filter are theoretically and practically possible, in which the maximum value of φ is greatly increased, and the

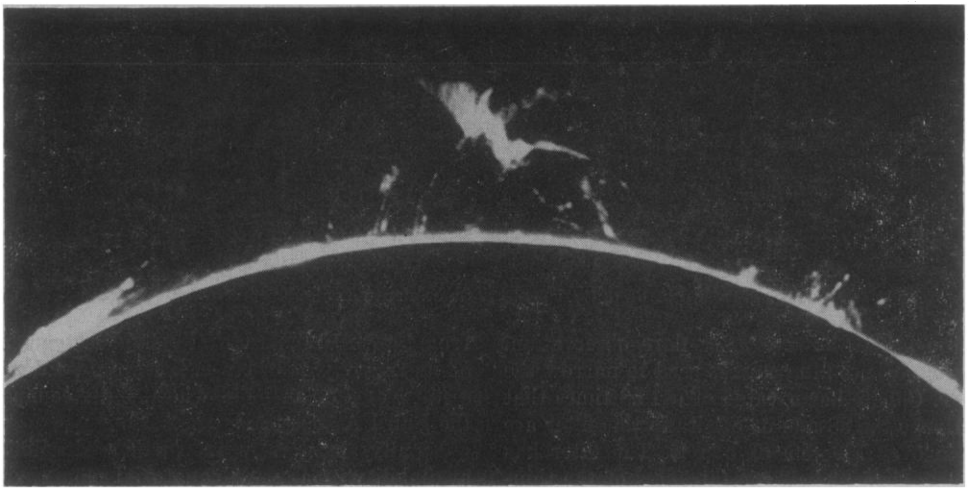

FIG. 2. Solar prominence photographed through a birefringent filter.

wavelengths of the transmission bands can be adjusted to any desired values. Such a filter of quartz and calcite has been designed to be used with the 16-inch coronagraphs now being constructed for the Climax station of the High Altitude Observatory under a contract with the Office of Naval Research, and for the Sacramento Peak station of the Harvard College Observatory, in New Mexico, under a contract with the Geophysics Research Division, Air Force Cambridge Research Center.

Experience with temperature-sensitive ADH filters has led to a general impression that the temperature cannot be controlled with sufficient accuracy to stabilize the wavelength of a really sharp transmission band. The difficulty can be overcome by a thermostat which senses the wavelength directly, instead of sensing the temperature at some point outside the birefringent elements. This device should be especially effective in a filter of adjustable wavelength, since the center of the band can be instantly corrected by the λ control. A control of this type is planned for the large filter mentioned above. In any case the problem is far less acute in quartz and calcite filters than with ADH.

With this rather lengthy introduction, the description of the essentially very simple flare recorder is largely done. The permanent instrument now in operation at Sacramento Peak was preceded by an experimental "breadboard" model built for use in our Boulder, Colorado, laboratory to assess the effectiveness of the birefringent filter for our purpose and to eliminate the inevitable "bugs."

The telescope for the Boulder instrument consists of a polar heliostat mirror feeding an achromatic lens of 16 cm aperture and 300 cm focal length. The light from the lens enters the laboratory through a glass window and is reflected horizontally to the west to form a stationary solar image, 28 mm in diameter. This is followed by a filter and camera unit shown in the diagram of Fig. 3.

Preceding the filter is a field lens with the primary objective at its focal point. Its function is to collimate light from the entrance aperture. Thus, the axis of the diverging cone originating at each point in the image traverses the filter parallel to the instrumental axis, and the maximum value of φ is held to the smallest possible value. It was necessary to restrict φ further by placing a 6-cm diaphragm over the objective. A second field lens follows the filter to form an image of the entrance aperture on the camera lens. The camera lens in turn forms a 17-mm image of the sun in the film gate of a modified Fairchild radar recording camera, through a separate rotating-sector shutter from a Mercury Univex camera. The film transport and shutter winding are performed by electric motors actuated in the proper cycle by a timer. The whole arrangement was constructed rather hastily and has given occasional trouble in routine operation.

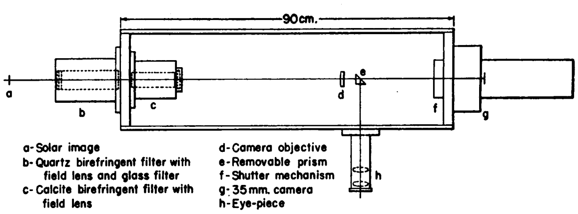

FIG. 3. Optical system of the Boulder experimental flare recorder.

Between the camera lens and shutter is a prism which can be rotated into or out of the beam. When in position, it reflects the solar image into an eyepiece for visual observation between exposures, and a buzzer warns the observer eight seconds before an exposure is due.

The filter is made in two units with independent temperature controls. The first unit is of quartz, 50 mm in aperture. It is a duplicate of the Climax filter, with a 4.2 A transmission band. Such a band width is nearly optimum for prominence observation, where the ratio between the Hα emission and the neighboring continuum is perhaps 100 times as great as that for monochromatic features against the disk of the

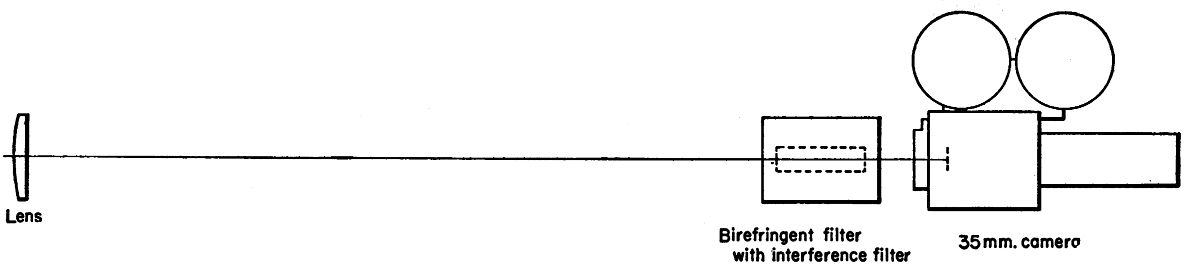

FIG. 1. Diagram of optical system, Sacramento Peak flare recorder.

sun. It is too broad, however, for flare observation. Hence a second calcite filter unit is used to narrow the band further. Calcite has a value of μ 18.8 times that of quartz. Hence the 38 mm of calcite in this filter are equivalent to over 700 mm of quartz. The filter has a single quartz element half the thickness of the thinnest element in the first unit, and three elements of calcite, giving sharp bands 4.2 A apart. The two thickest elements of calcite are split, and the quartz and remaining calcite elements are sandwiched between the halves of the thicker elements. This is the first operating example of the split element construction (*2*), which requires only half as many polarizers as the simple filter. The two filter units together transmit a band 0.52 A wide at Hα, with side bands 540 A on either side.

The temperature of the calcite unit was naturally the most critical, and had to be controlled to about ± 0.1 degree C. This was accomplished by mounting the elements between two thick glass ends in a massive aluminum shell. A thermsistor in a well in the aluminum controls the current to a heater wire wound on the shell through an electronic bridge. In the neighborhood of the operating temperature (about 38°) the variation of the heater current is approximately proportional to the temperature deviation. The control has been entirely satisfactory and free of trouble.

Unfortunately, the only calcite available when the filter was constructed was inhomogeneous in birefringence. As a result the calcite unit has appreciable "leaks" outside the principal band, which vary considerably over the field and seriously reduce the contrast of chromospheric features. In spite of this defect, the flares are shown brilliantly, and the preliminary flare recorder was pressed into routine service, monitoring the sun from Boulder for nine months, while the permanent recorder was gestating. During this interval 252 flares were recorded.

The final flare recorder now in operation at Sacramento Peak is notably simpler than the preliminary model. Construction of the eyepiece–shutter–camera complex was completely avoided by the purchase of an Acme motion-picture camera. This beautiful machine has a built-in reflex mirror to send light into an eyepiece and is designed to take single exposures of widely adjustable duration on impulse from a simple timer. The registration accuracy is of the order of 0.0003 inch.

The original plan was to transfer the two-unit filter from the "breadboard" to the final instrument. In view of its faulty performance, however, we decided to use a filter of 1.25 A band width, built commercially by the Baird Associates.

Finally, matters were further simplified by the availability of a stable equatorial mounting at Sacramento Peak, capable of holding the whole instrument. This mounting, which already carried a prominence motion-picture telescope, was explicitly designed to carry simultaneously a variety of solar instruments. It is a rigid 10-foot spar of steel, 12 inches square, mounted equatorially, and accurately guided on the sun by a photoelectrically controlled servomechanism. Mounted on this platform, the flare recorder points directly at the sun, and reflecting surfaces are unnecessary.

Fig. 4 shows the optical system. The objective is a single plano-convex lens of 12 cm aperture and 183 cm focal length. It was made in our optical shop and figured to remove spherical aberration in the red. In use it had to be stopped down to 7 cm to fit the

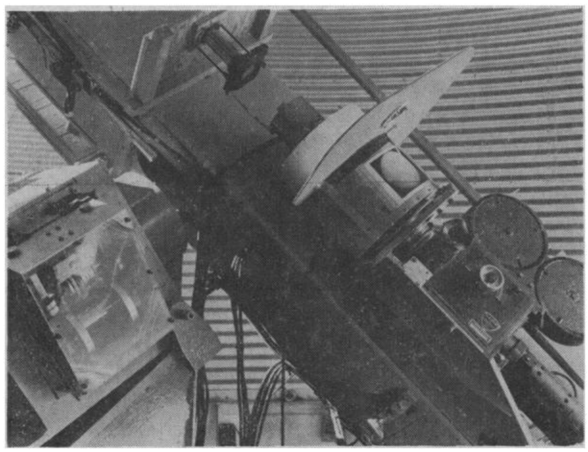

FIG. 5. Photo showing optical system, Sacramento Peak flare recorder.

φ-tolerance of the filter. The camera receives the primary image, rather than a secondary image, as in the Boulder instrument. An auxiliary removable lens swings in front of the filter to form an image of a small record plate on the film (Fig. 5). The record plate is simply a sheet of plastic on which observation information (date, time, and state of the sky) can be written. It is placed in a frame between the objective and the filter and photographed by sunlight. Fig. 6 shows the flare recorder assembled on the 10-foot spar.

In our efforts to simplify the instrument we were only partially successful in evading the law of the conservation of difficulty. We did have a change of diet, however. When the filter was first set up, the transmission band wandered around through several angstroms on either side of Hα, in spite of the very elegant electronic temperature control. The Baird Associates gave us their vigorous cooperation in tracking down the main source of trouble and reducing the uncontrolled wavelength shifts to a usable value. To a large degree the difficulty lay in a minor detail of construction, which can be simply corrected in future instruments.

The Baird filter is made of crystals of quartz and ADH. It is therefore very sensitive to temperature variations. To provide a small controllable adjustment of the wavelength of the transmission band in the filter, so as to follow radial velocity shifts of various chromospheric features, the thickest ADH elements

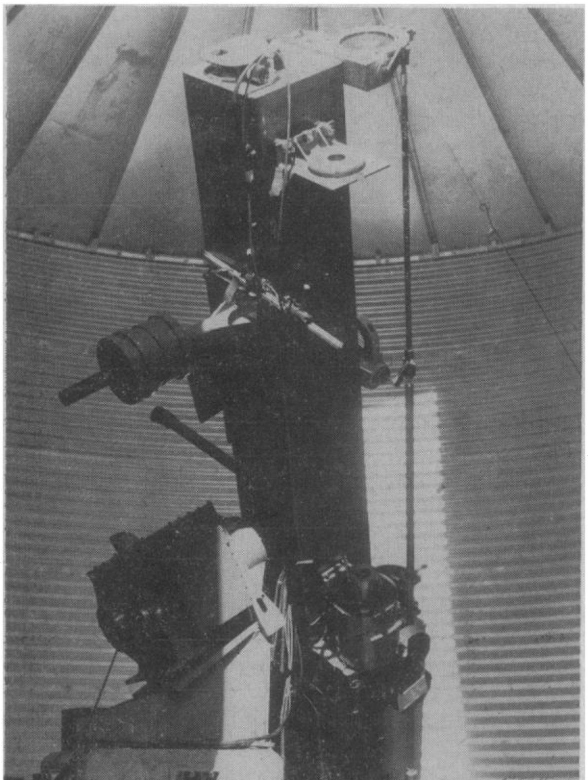

FIG. 6. Sacramento Peak flare recorder mounted on the 10-foot spar.

were mounted with quarter wave plates in rotating rings. Unfortunately, one of these was mounted at the entrance end of the filter, where it received a relatively intense beam of sunlight, without the benefit of the

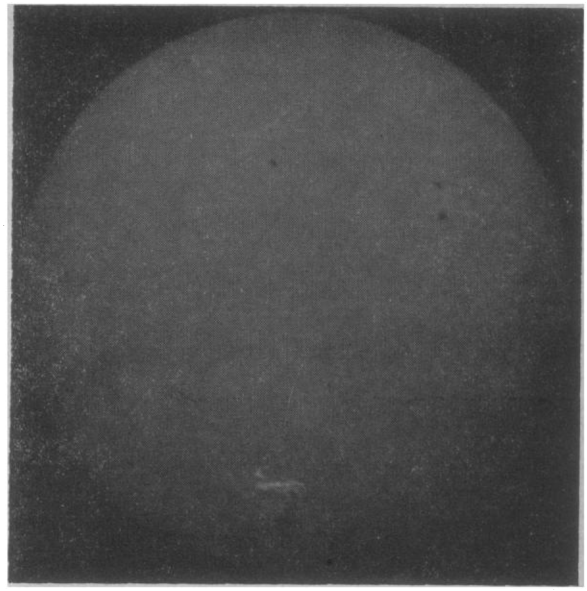

FIG. 7. Typical solar flare photographed with the flare recorder.

attenuating filter action of the thinner elements. Matters were further complicated by the presence of an absorption band in ADH at 1.5 μ. Preceding the birefringent filter is a high-efficiency interference filter for isolating the Hα band. This filter, however, is rather transparent at 1.5 μ. The electronic control, therefore, was quite unable to cope with the solar heating of this exposed element. The permanent cure is obviously (in hindsight) to mount both rotating elements at the exit end of the filter. However, a fairly satisfactory reduction of the wanderings of the transmission band was achieved by inserting a water cell in front of the filter. Although it still requires an occasional adjustment of the rotating elements to stay centered on Hα, the filter is giving a good performance and is otherwise an ideal monochromator for our purpose.

The Sacramento Peak flare patrol has been in regular operation since March 1951. By the first of September 252 flares had been recorded. A sample of one of the 35 mm frames with a typical flare is shown in Fig. 7.

The routine of operation of the flare patrol at Boulder and Sacramento Peak is as follows. The recorder runs during each day whenever the sun is free of clouds, taking exposures at one-minute intervals. At the end of the day the film is processed and dries overnight. It is examined for flares the next morning. The position and area of each flare discovered are measured; the brightness is estimated; and the times of discovery, maximum brightness, and ending are noted. This information is sent immediately in a coded telegram to the National Bureau of Standards. There it is used in combination with other data for studies of solar-terrestrial effects.

The most glaring weakness of this program at present is the lack of a quantitative measurement of flare brightness—perhaps the most important single parameter. Plans are being made for photometric standardization of the films and for measurement with a contour densitometer similar to that described by Babcock (*3*). A "breadboard" of the densitometer is approaching the try-out stage, but the work goes slowly because of the pressure of other commitments. We do not expect to have any real brightness measurements, therefore, for some months.

The 504 flares observed so far already constitute a small but homogeneous statistical sample, and several interesting discoveries have emerged from preliminary studies. Space is lacking to discuss them here, but they do justify our efforts in building the flare recorder, and our hope that we may see eventually a whole chain of these instruments stretched around the world to keep a record of all the flares on the visible hemisphere of the sun.

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Technical Papers

Salt Hypertrophy in Succulent Dune Plants

Steve G. Boyce

Division of Biological Sciences,
North Carolina State College of Agriculture and Engineering, Raleigh

Early German investigators (*1*) were the first to recognize that "many plants produce on the shore more succulent leaves than they do when grown inland, while the leaves of *Salsola Kali, Halogeton sativus,* and others, are thinner when the plants are grown upon a soil without salt, than is usual on plants growing on saline ground." Succulence of plants growing on saline soils has been attributed to the absorption of salts by the roots and their subsequent concentration in the mesophyll tissue, resulting in salt-induced hypertrophy (*2–4*). However, no previous investigation has satisfactorily explained the type of succulence found in dune plants near the strand.

Iva imbricata Walt. exhibits the typical succulent nature of plants found on coastal dunes. The leaves on the windward side of the plants toward the ocean are thick and succulent, whereas those on the leeward side of the same plant are thin, less succulent, and frequently coriaceous. The margins of leaves turned toward the ocean are thicker and more succulent than the leeward margin of the same leaves, and the tips of the leaves are more fleshy than the bases.

Succulence in dune plants has been considered to be a consequence of the more xeric habitat (*5*), of excessive transpiration (*6*), and of the salinity of the substratum (*7, 8*). Salinity of the substratum can be disregarded, since it has been shown that dune sands contain very little soluble salts (*9*). However, none of these proposals explains why leaves of an individual plant exhibit different degrees of succulence.

Previous studies on the coast have shown that droplets of sea water are ejected into the air by the bursting bubbles of the ocean; that these particles, concentrated by evaporation, are transported inland by winds and deposited on the coastal vegetation; and that the resultant killing of leaves and twigs by this concentration of salt is responsible for the zonation and spray form of the plants (*10–13*).

During a study of the coastal vegetation of Brunswick County, N. C., the author investigated the relation of salt spray to succulence. Succulent and nonsucculent leaves on the same plant of *Iva* were collected, the surface washed in distilled water, and 5 disks of equal area were punched from each leaf with a small rubber stopper punch. Each group of 5 disks was then macerated and titrated with $AgNO_3$ for halides. The 5 disks of the succulent leaves contained an average of 16.8 mg of Cl compared with an average of 4.5 mg of Cl in the disks of the nonsucculent leaves. (The titration data are expressed in terms of mg of Cl since the other halides make up such a small part of the salts of the ocean.)

The quantity of salt deposited on the different leaves was estimated with the use of oiled glass slides (*14*). Slides were exposed for 30 sec at different positions in an *Iva* shrub located on the top of the foredunes. The number and diameter of the deposited droplets were immediately determined with a microscope, which was protected from spray by a plastic cover. The average wind velocity from the ocean was 31 km/hr. The slides exposed on the windward side of the shrub caught an average of 1,900 droplets/cm^2/min, which averaged 51 μ in diameter. Slides exposed on the leeward side caught an average of 490 droplets/cm^2/min, which averaged 22 μ in diameter. Slides exposed at different positions in the shrub caught an intermediate concentration of droplets, both in number and in diameter. Obviously, the leaves on the windward side of the plant are receiving a much higher concentration of salt than the leaves on the leeward side.

Anatomical studies of the succulent and nonsucculent leaves showed a striking difference in the size of the cells. Table 1 shows this difference in *Iva*. The nonchlorenchymous parenchyma showed the greatest swelling, and the chlorenchyma and epidermal cells showed an intermediate swelling. The stomata showed