

Largest solar prominence ever photographed

ASTROPHYSICISTS WATCH

by Donald H. Menzel and Catherine B. Wyatt

High in the Colorado Rockies at an altitude where some fliers put on oxygen masks, observers keep daily watch on the sun with a special type of instrument. The High Altitude Observatory of Harvard University and University of Colorado, the highest permanent astronomical laboratory in the world, houses a very new type of solar telescope, the coronagraph. The coronagraph, as its name implies, records the corona, the faint outer envelope of the solar atmosphere which makes an eclipse of the sun a spectacle of awesome beauty.

The scientist regards the phenomenon of an eclipse as an opportunity to pierce the veil of mystery surrounding the sun. The solar chromosphere, the prominences and the corona—features that become strikingly visible during total eclipse—are of vast

importance to our understanding of the physical processes in the sun and of the effects of solar variation upon the earth itself.

The Sun

Before describing how this new instrument aids astrophysical research, we should like to recapitulate briefly what we now know of the sun, a hot ball of gas, nearly a million miles in diameter and 93 million miles distant from the earth. It derives its tremendous heat from atomic energy, probably by a process that converts hydrogen into helium. Carbon atoms act as a catalyst in the reaction. The energy thus produced in the center of the sun, in a single second, exceeds that of ten billion atomic



High Altitude Observatory

THE SUN

bombs. The mass converted into energy during this interval is approximately three million tons.

Our studies of the solar surface enable us to determine the physical conditions in the solar depths, where the temperature is $25,000,000^{\circ}$ centigrade. The surface of the sun presents many interesting and important phenomena. The most obvious, if not the most spectacular, of solar features are the well known sunspots. The shining surface, of photosphere, has a temperature of approximately 6000° C.; the spots are about 2000° cooler and hence appear dark by contrast. The number of spots fluctuates from year to year, in cyclic fashion, with successive maxima spaced approximately eleven years apart. Spots also vary in position on the disk. They are almost never found between the poles of the

The coronagraph, with an artificial moon that permits observations of the sun as though it were in eclipse, is providing a rapid accumulation of data which are raising more questions than they have answered.



The High Altitude Observatory. This view is looking eastward from Climax toward the Observatory.

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Three government agencies have contributed to the coronagraph work. The Office of Naval Research and the National Bureau of Standards have supported the High Altitude Observatory of Harvard University and University of Colorado, at Climax. The Air Forces has contributed mainly from a site in southern New Mexico. Parts of this article have appeared previously in Leaflets Nos. 139 and 206 of the Astronomical Society of the Pacific. The illustrations have appeared in *Sky and Telescope Magazine* and *Our Sun* by D. H. Menzel, Blakiston Company.

sun and latitude 35° . Most of them lie in the equatorial belt and, as a given sunspot cycle progresses, newly formed spots tend to approach the equator. Sunspots possess powerful magnetic fields. The total electric current, whose source is not known, required to produce the magnetism is of the order of ten million million amperes.

Photographs of the disk of the sun, taken with specialized filters or equivalent instruments, show that the regions surrounding the spots are disturbed and turbulent. The entire solar atmosphere is in rapid motion. Millions of explosive jets, with lives ranging from two to fifteen minutes, appear on the solar surface. Their activity is most pronounced in polar zones, where the jets, known technically as spicules, are most nearly radial. A jet will generally have a cross section of from one hundred thousand to one million square miles and may extend to heights of 10,000 miles or more. The jets appear to move with supersonic speeds.

The so-called solar prominences are great clouds of luminous gas, which occasionally rise to very great altitudes above the surface of the sun. Some of these prominences have extended more than a solar diameter above the surface. Spectra of the prominences indicate that the temperatures are far higher than the value of 6000° assigned to the shining surface. The temperatures necessary to explain the observed degree of excitation of the atoms range from $15,000$ to $30,000^\circ$ C. There are numerous varieties of prominences, which differ from one another mainly in size and activity. Occasionally we observe brilliant flares whose intensity may alter markedly in the space of one minute or less.

Above the spicules and, to some extent, intermingling with the rest of the solar atmosphere, we find the corona. This portion of the solar atmosphere is tenuous, faint in luminosity, and extends to great heights above the surface. Its spectrum consists mainly of the lines of iron, calcium, and nickel atoms that have lost up to half of their normal complement of electrons. This characteristic is indicative of an extremely high temperature, of the order of $1,000,000^\circ$ C.

From large observatories such as the Mount Wilson and McMath-Hulbert in this country, from college observatories, and an organized association of amateurs, spectroscopic, photographic, and visual observations of the "surface" features are collecting. Only through long and continuous record of these

variable phenomena can we understand the mechanisms by which they are produced and their interrelation with each other and with the solar corona.

The Coronagraph

Until the invention of the coronagraph in 1931 by the French astronomer, Dr. B. Lyot, astronomers were forced to make their observations of the corona only at times of total solar eclipse. With this limitation, information concerning the physical state of the corona accumulated very slowly. On the average, only some two minutes and fifty seconds per year are available to an astronomer for eclipse observations. Eclipse paths often lie over oceans or remote and inaccessible areas. Weather often intervenes to spoil plans that have required months of preparation and long travel. It is understandable why astronomers have long dreamed of the possibility of observing the corona without benefit of the moon and why Lyot's achievement, after a century of unsuccessful attempts, is considered outstanding in the history of experimental astronomy.

The coronagraph is a type of telescope that produces an artificial eclipse of the sun, by means of appropriate screens that mask out the bright solar image. The residual light from the sun's corona and the prominences jutting out from the solar limb may be sent into several varieties of auxiliary equipment. Studies of motions of solar prominences, with color filters and with motion-picture technique, are also possible. These pictures, projected on the screen, exhibit graphically the majesty and magnitude of the enormous storms occurring in the solar atmosphere.

The corona is one of the most difficult photographic subjects in existence. Its brilliance is about half a million times less than that of the sun and just about equal to that of the full moon which we can see and readily photograph in the daytime as long as its does not lie in the neighborhood of the sun. The trouble with the corona is that it lies so close to the sun. The minutest stray light in the telescope will drown the coronal image. Every source of unwanted light must be eliminated.

In the telescope itself, to eliminate inter-lens reflections, we employ a simple one-piece lens, like an enlarged spectacle lens. The glass must be of highest quality and polish, free of scratches, bubbles, "sleeks," or striae, which would introduce scattered light into the optical system. An objective of this type would be practically useless for ordinary astro-

nomical photography because the various colors come to focus at different distances and one cannot get a sharp picture of a star. Nevertheless, by photographing in light of a single color, we can obtain a clear record. But we must refocus each time we move to another color. The lens must be entirely dust-free, because each tiny imperfection scatters light profusely and shines like a brilliant star. A few grains of dust will send far more extraneous light to the plate than will the entire coronal image.

At the main focus of the coronagraph, a metal disk blots out the sun and a second lens, well behind the disk, re-images the surrounding sky, with any projecting solar formations, upon the photographic plate or film. The edge of the objective lens also produces scattered light. To eliminate this additional source of scattering, we introduce a third lens just behind the occulting disk. This so-called "field lens" images the main objective upon the camera lens, so that we can now block out the edges with a diaphragm. Additional disks introduced at appropriate spots in the optical system cut out other reflections that come to a focus.

Even with all these precautions, we should still fail if we operated the coronagraph in an average location. The ordinary sky is not clear blue. Dust, smoke, and other contaminations throw a milky screen over the heavens. The intensity of this whitish light increases to a brilliant glare in the neighborhood of the sun. From most locations, the scattered light is many times brighter than the corona and obliterates any trace of the faint solar features we desire to study.

Sky conditions, therefore, dictate that coronagraphs should be located at fairly high altitudes in regions where frequent precipitation cleanses the air of accumulated contamination. A dust-free atmosphere is dark blue, with no appreciable increase of intensity up to the edge of the solar disk. The five existing coronagraph stations are so located: Meudon maintains one on the Pic du Midi in the Pyrenees; Zurich has established one in the Alps; two German observatories exist, one at Wendelstein peak and the other at Kanzel; and the High Altitude Observatory is at Climax, Colorado at an altitude 11,500 feet above sea level. Harvard is now establishing a new station in southern New Mexico.

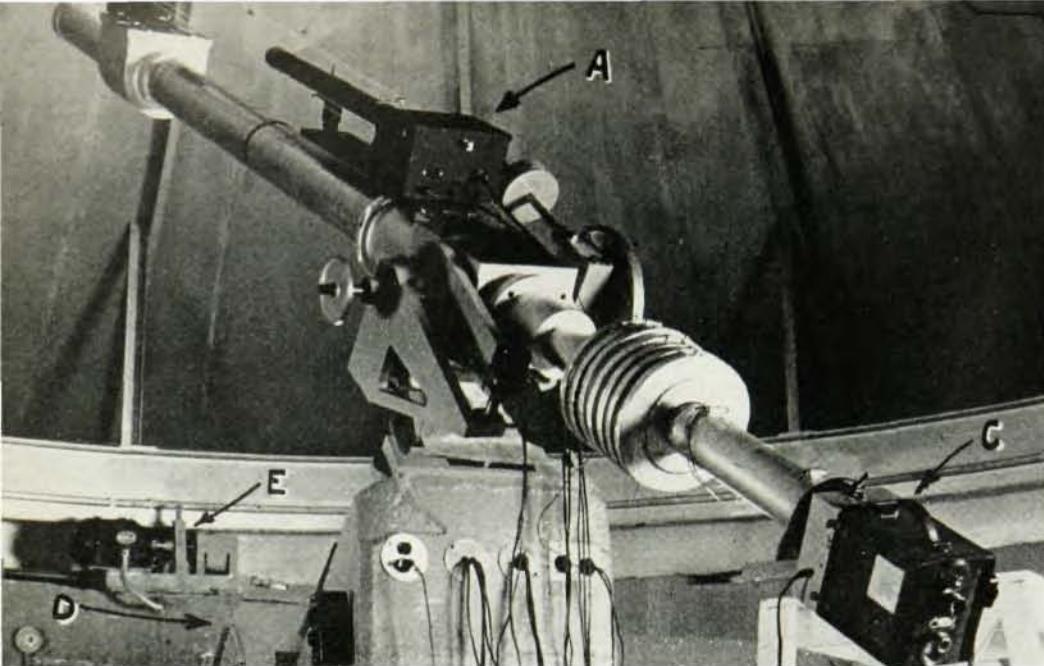
The present Climax coronagraph, built in 1940, was originally intended to be a pilot instrument for preliminary study of methods, techniques, and test-

ing. It is equipped with a camera for direct photography of the corona prominences and a spectrograph for recording of their spectra. A monochromatic filter is a necessary accessory for any coronagraph. Lyot first described the types commonly employed; he and John W. Evans have independently developed certain improvements. These instruments are multiple deacker sandwiches of quartz (or calcite) with various polarizing elements between. Properly made, such a device will transmit certain narrow regions of the spectrum centered around the interesting coronal and prominence radiations.



MARCH 1950

*Solar surface with large sunspot group
Mt. Wilson Observatory*



The coronagraph, showing the photoelectric guider at A and the guider lens at B. At C is the 35 mm motion-picture camera. Part of the spectrograph shows at D. At E is one of the two motor-driven wheels used to rotate the observatory roof.

A filter transmitting the red (H alpha) line of hydrogen will act as effectively as a spectroheliograph in the recording of prominences, with the additional advantage of possessing no moving parts. The McMath-Hulbert Observatory was the first to obtain motion pictures of prominences, with the spectroheliograph. The accumulated records of prominence motions contain extremely important information concerning these phenomena.

Early Results

The motions of streamers are slow and relatively uniform in speed. At least, the speeds are less than one would expect for material moving in the powerful gravitational field of the sun. This result confirms earlier work by Pettit. But the motions are not always uniform; changes of velocity are not instantaneous and the relationship between initial and final velocities is not usually simple. Dr. Helen Dodson, of the McMath-Hulbert observatory, has recently shown that surges appear to be subject directly to the gravitational forces.

Records of prominences made at Climax over the past few years provide useful data from which we shall be able to study the statistics of their distribution and brightness at different solar latitudes. One fact emerging from this survey is that Pettit's classification of prominences according to form (quiescent, tornado, coronal, surge, eruptive, etc.) is primarily descriptive of the instantaneous appearance of the object. One type may rapidly transform to another in the course of development.

Interesting as prominences are, however, the true aim of coronagraphic work is study of the still fainter corona detail. In spectrographic recording and in direct photography Lyot again was the pioneer. During the war, the recording of the spectrum of the corona took precedence over all other work at Climax. These daily records of the intensity of the green and red coronal emissions at various points around the disk furnished the armed forces with important information for the prediction of radio communications conditions. Other factors than the corona enter into the forecasts, such as solar data from other observatories and magnetic and ionospheric records. But the coronal measures proved extremely useful.

We still do not fully understand the physical connection between the sun and the ionosphere though we know that the electrified layers of the atmosphere arise from action of ultraviolet light from the sun. Changes in solar activity undoubtedly result in large variations of the output of ultraviolet radiation. The corona, by virtue of its high excitation and million-degree temperature, must be responsible for a large portion of the ultraviolet energy output by the sun.

The Climax records show that the corona is reasonably stable and rotates with the sun. W. O. Roberts, superintendent of the Observatory, has shown this result conclusively from the fact that a bright coronal patch on the east limb will appear on the west about thirteen days later. Apparently, the variability of the ionosphere arises at least in part from the nonuniformity of coronal brightness around the

sun. When an excited coronal region shows on the east limb, an ionospheric disturbance is to be expected from three to five days later, even though the sun may be devoid of spots or other obviously disturbed regions.

As direct coronal photography is developed we may expect to learn more and more about the corona and its relationship to the earth, radio, magnetic storms, and aurora. We have taken a few such photographs at Climax, but anticipate a great expansion of this program with new and larger equipment now in the process of development. The most successful motion picture records of the corona are those obtained by Lyot. He finds that, although the coronal formations often display prominence-like features, the motions are small. The changes appear to be fluctuations of intensity rather than motions of matter. They resemble the pulsating flashes of the aurora borealis more than they do the sharply defined motions of prominences. Records at Climax confirm Lyot's conclusions, for the spectral lines are rarely displaced by large velocity effects.

This result is somewhat surprising, for some of us had been supposing that certain prominence formations were merely coronal streamers that had cooled from $1,000,000^{\circ}$ to a mere $25,000^{\circ}$ or so. But it appears that much more work is required to determine the relationship between corona and prominences.

One phenomenon, discovered by Dr. Roberts during the war and mentioned briefly earlier, is of special interest. He found that there are myriads of tiny prominences, "spicules" he called them, which go to form the solar chromosphere. The existence of these objects had been known previously, but Dr.

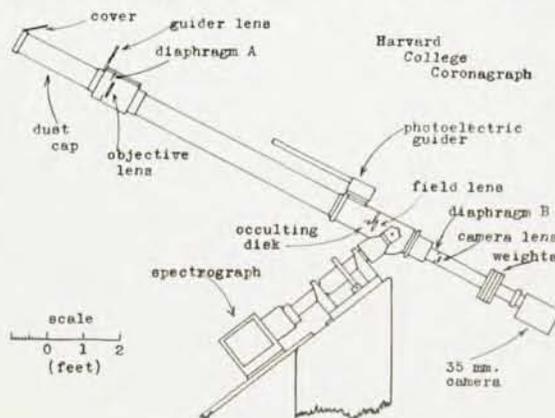
Roberts found them to be short-lived indeed. They first appear as bubbles on the solar limb. A minute or two later the bubble bursts, ejecting a dart of luminous gas. Lifetimes range from a couple of minutes to twelve or fifteen minutes. In these spicules, whose appearance at the solar poles differs from that near the equator, we may possibly find a direct connection between the ordinary granulation of the disk and the fine streamers of the corona.

Another fact that seems to be emerging from recent studies of prominences is the universal filamentary character of the gases that comprise them. A bright prominence that appears quite uniform in intensity under low magnification will, under higher power, show as a complicated network of interlacing threads. One result of further studies of this phenomenon will be the revision of our concept of densities and pressures in the prominences.

Problems

The astrophysical problems presented by these records, and the analogous ones obtained with the McMath-Hulbert spectroheliograph in Michigan, are many. We see the prominences, great clouds of luminous gas, suspended as if by magic, ten thousand miles or more above the solar surface. From projections in the clouds great streams of incandescent matter fall downward in graceful arcs. Some prominences are in obvious rotation. Others look like hazy patches of expanding mist. An occasional jet rockets up from the underlying layers. How is this material suspended? Since the prevailing motion is downward, how did most of the material rise in the first place? Certainly, what comes down must

Sunlight is scattered into the image from the following sources: diffraction of light from the edges of the objective-lens cell; reflection from the second face of the objective lens to the first and then a second reflection back into the image; and diffraction around dust particles on (and imperfections of) the objective lens. Any one of three sources is enough, usually, to render an ordinary telescope useless for coronal photography. The first two may be eliminated completely and simply. The third may be reduced by employing the very highest skill in making the telescope objective and in cleaning it. Diffraction at the edges of the objective lens can be eliminated by placing a diaphragm A with a sharp edge in front of the objective, and by means of the field lens focusing an image of this diaphragm (thus focusing the diffracted light) on diaphragm B, just in front of the camera lens. If diaphragm B is slightly smaller than the image of the diaphragm A, all scattered light from the first source will be eliminated. By proper design of the objective, its multiple reflections can be brought to a point at diaphragm B and eliminated completely by a small screen in the center of B. The objective lens images the sun on the occulting disk, and the camera lens in turn images this artificial eclipse at the 35-mm camera film. A mirror may direct the image into the spectrograph.



have gone up! Why is solar gravitation so annulled or weakened that the motions are usually slow and uniform, rather than sharply accelerated? Do electrical and magnetic fields or the pressure of solar radiation play any role in prominence dynamics? How do sunspots come into the picture? Finally, and most important of all, what is the underlying cause of solar activity and the well known eleven-year periodicity in its magnitude?

The character of the prominence motions strongly suggests that magnetic fields are the controlling factor. Indeed, for the slower moving prominences, we suspect that the ionized gas clouds follow along the lines of magnetic force. But if the gas moves rapidly, it may carry the lines of magnetic force along, twisting and tangling them like a skein of yarn. Which effect predominates depends on whether the kinetic energy does or does not exceed the magnetic energy per unit volume.

The existence of a general magnetic field on the sun is somewhat in doubt, the evidence not being absolutely definite on this point, but there are combination coronal and prominence effects that do suggest a cooperative action of the general field with the specific fields of various spots. Prominence matter, for example, may condense from the hot corona, via a duct or tunnel that joins the two magnetic fields. The problem is extremely complicated, but it resembles that familiar to many physicists who have studied regions forbidden to electrified particles moving in a magnetic field. Störmer studied the problem for terrestrial aurorae; Lemaitre and Vallarta investigated it for cosmic rays.

And, with respect to cosmic rays, the possibility that the sun may be the source is not to be lightly dismissed. Variations in the solar magnetic fields

may cause marked accelerations of electrons—a sort of betatron effect, first discussed by Swann. Cosmic rays might be formed by any one of several processes associated with such variation.

Flares are among the more interesting and exciting of solar phenomena. These brilliant bursts, which show predominantly in the red line of hydrogen, must also emit huge blasts of ultraviolet (Lyman alpha) radiation. This light, striking the earth's atmosphere, causes ionospheric and associated magnetic disturbances. We have generally regarded the flare as the source of such ions. However, the charged clouds may have originated in the polar spicules, with part of the gas condensing (via a magnetic tunnel) to form a flare, with the remainder (guided by the solar magnetic field) going into space. Still more recent studies by Menzel indicate that the sheer mass of accumulated coronal material may cause the semi-flexible lines of magnetic force to collapse. A sunspot may result from such collapse.

The coronagraph is proving itself to be a very powerful tool for solar study. Although its uses, to date, have been largely confined to recording of prominences and corona, there are other problems to which it may well be put. Any region of the sun that appears darker than the rest of the surface, like spots or the areas between the bright granules, may contain a certain amount of atmospheric or instrumental scattered light upon its surface. This extraneous light reduces the contrast and measures of the dark areas may be in error as a result. Coronagraphic techniques, applied in such cases, may give information of great value.

The coronagraph, which permits regular observation of these faint solar features, is certainly superior to the total eclipse for most problems though up to now coronagraphic records refer primarily to the bright inner portions of the corona, and we have to rely upon eclipses for knowledge of the form and spectrum of the outer layers.

Except for special investigations, the coronagraph stands supreme. The astronomer who, in the course of his lifetime, could observe as many as twenty solar eclipses, all clear, would be fortunate indeed. He would have little more than one hour of eclipsed sun in an entire lifetime for study of the sun's outer appendages. The coronagraph enables astronomers to become Methuselahs, from the viewpoint of solar eclipses.



A highly enlarged portion of a spectrograph plate showing the well known "green line" of the coronal spectrum. The coronal line shows lighter than the background. The dark lines are the lines of the spectrum of ordinary sunlight coming from the bright face of the sun. All the lines are curved because a curved spectrograph slit was used to follow the edge of the sun's image closely.