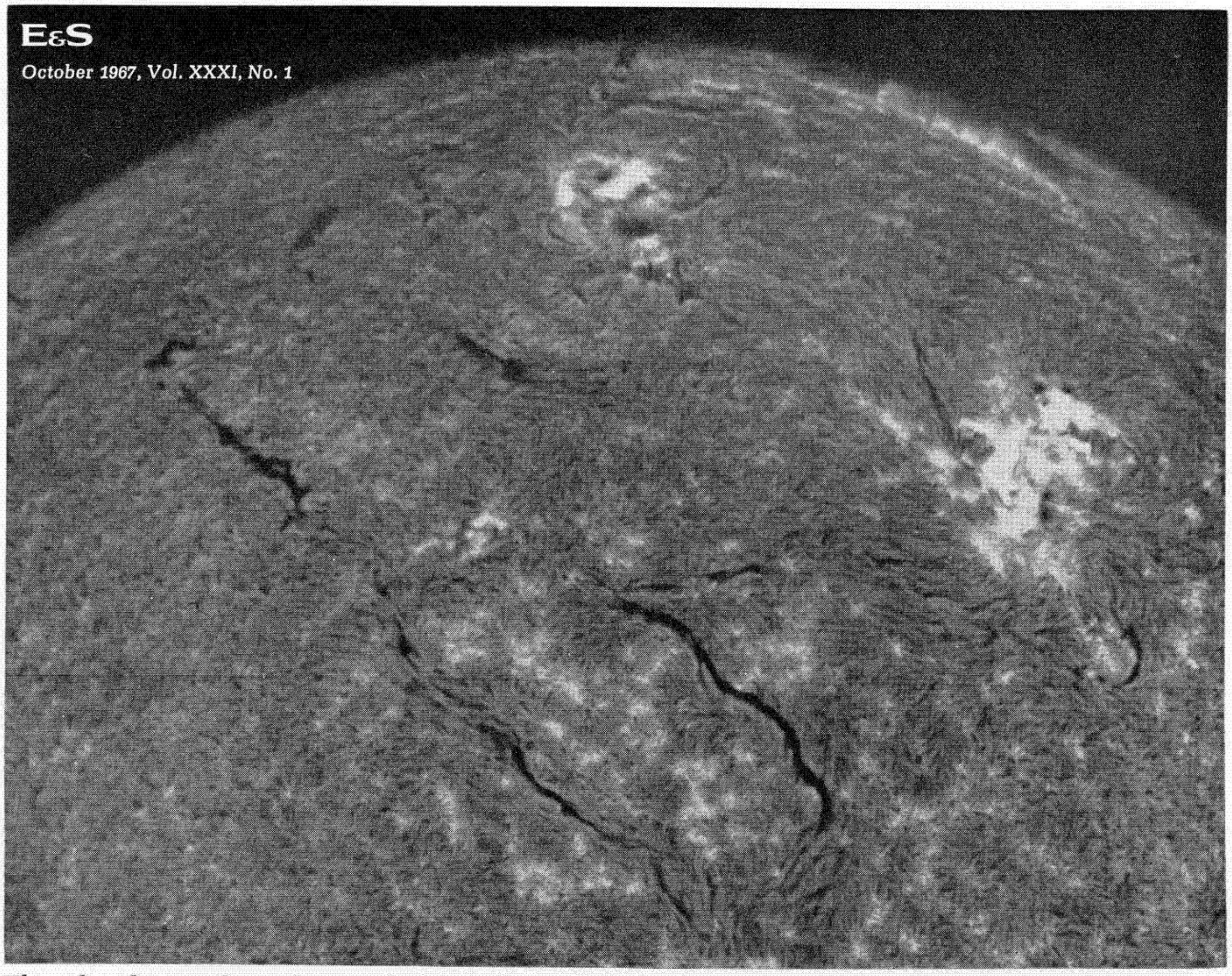


The solar chromosphere photographed in hydrogen light (Hα). The bright areas near the sunspots are plages. The dark filaments are prominences seen against the disk. Note the bright network structure. All bright features in Hα correspond to regions of enhanced light.

THE SOLAR ATMOSPHERE

by Harold Zirin

In the spring of 1966, Harold Zirin, Caltech professor of astrophysics and staff member of the Mount Wilson and Palomar Observatories, was invited to give a lecture for the Voice of America Forum series, "The Earth in Space." His contribution, "The Solar Atmosphere," which appears on the following pages, was one of 30 made by leading U.S. scientists dealing with the body of scientific knowledge about the earth and its cosmic environment. The lectures have now been collected and edited by Hugh Odishaw of the National Academy of Sciences. They will be published in November by Basic Books, Inc., under the title *The Earth in Space*.

Harold Zirin, professor of astrophysics and staff member of the Mount Wilson and Palomar Observatories.

The Solar Atmosphere

As the sun rotates about its axis every 27 days, its surface is constantly changing within a larger, more persistent structure. The surface sloshes back and forth every four minutes, and small granules appear and fade out in eight minutes; sunspots appear, grow, and fade in a few weeks or months, their lifetimes punctuated by the great outbursts we call solar flares. All of this activity rises and falls in the great 11-year sunspot cycle. These are phenomena of the solar atmosphere, but their effects reach out to the earth and beyond it through the solar system.

The sun is so hot that it is completely gaseous, and, therefore, its surface is not hard and sharp like the earth's. In fact, we define the surface of the sun as that level to which we may see in integrated light—the total visible white light. It is the level in the atmosphere at which the density has dropped so low that the gas is transparent. All, or most of, the radiant energy may now stream outward into space. At this boundary, which we call the photosphere, a number of remarkable changes in the behavior of the solar plasma occur.

Because the density drops off sharply and the radiant energy suddenly escapes, convective currents rising from below grow into energetic shock waves. At the same time the gas in the atmosphere sloshes back and forth and up and down just like water in a bathtub. Strong magnetic fields are generated, and these combine with the motions to produce heating of the atmosphere, so that the temperature, which has dropped all the way out from the center of the sun, rises rapidly to 1,000,000° Kelvin.

The tenuous million-degree atmosphere, called the corona, is seen as a halo of pearly light in total eclipses, when the bright light of the surface is blocked out by the moon. The corona reaches out past the earth.

The density at the surface of the sun falls off because the lower layers must bear the weight of the upper layers; they can only do this if the pressure is higher down below. This is called barometric equilibrium. The same phenomenon occurs in the earth's atmosphere; the density decreases quite sharply with height. We can calculate that at the temperature of the sun's surface—6,000°K—the density decreases twenty times at a height of 500 kilometers. When we look at the sun's limb from the earth at a distance of 150 million km, it looks quite sharp to the eye as well as to the telescope. The finest telescopes, under the best conditions, can only resolve objects about 700 km apart on the sun.

If we look at the sun in white light, we at once see several important features. First, the sun is darker near the edges, so the layers we see there must be cooler. Since we cannot see so deeply into the atmosphere when we look slantwise, we conclude that the temperature is still decreasing at the height defined by the edge of the sun. The temperature falls from 6,000°K at the levels which we see at the center of the sun to about 4,500°K near the edge.

The second important feature we see is the granulation, a fine pattern like corn grains about 1,000 km across. These grains cover the entire sun; each grain appears, lives about eight minutes, and breaks up or fades away. The granules appear to represent convective currents carrying heat outward from the interior. If we study carefully the velocities of the gases in the photosphere we find that there is a larger-scale pattern, the supergranulation, which has cells about 30,000 km across, in which the gases flow outward to the edges of the cell. Moreover, the gas at any point in the atmosphere rises and falls rythmically with a period of 250 seconds and a velocity of one-third km a second (1,200 km an hour).

Because of the continual outward flow in the supergranulation cells, magnetic fields accumulate at their edges. At these edges, gas pressure still is greater than the pressure of the magnetic field. But 1,000 km above the granule edges, the gas pressure has decreased by 400 times, and there the magnetic fields, which do not decrease so rapidly with height, restrain and organize the motions of the ionized gases. The result is that when we look at higher levels we see a very strong cellular supergranulation structure.

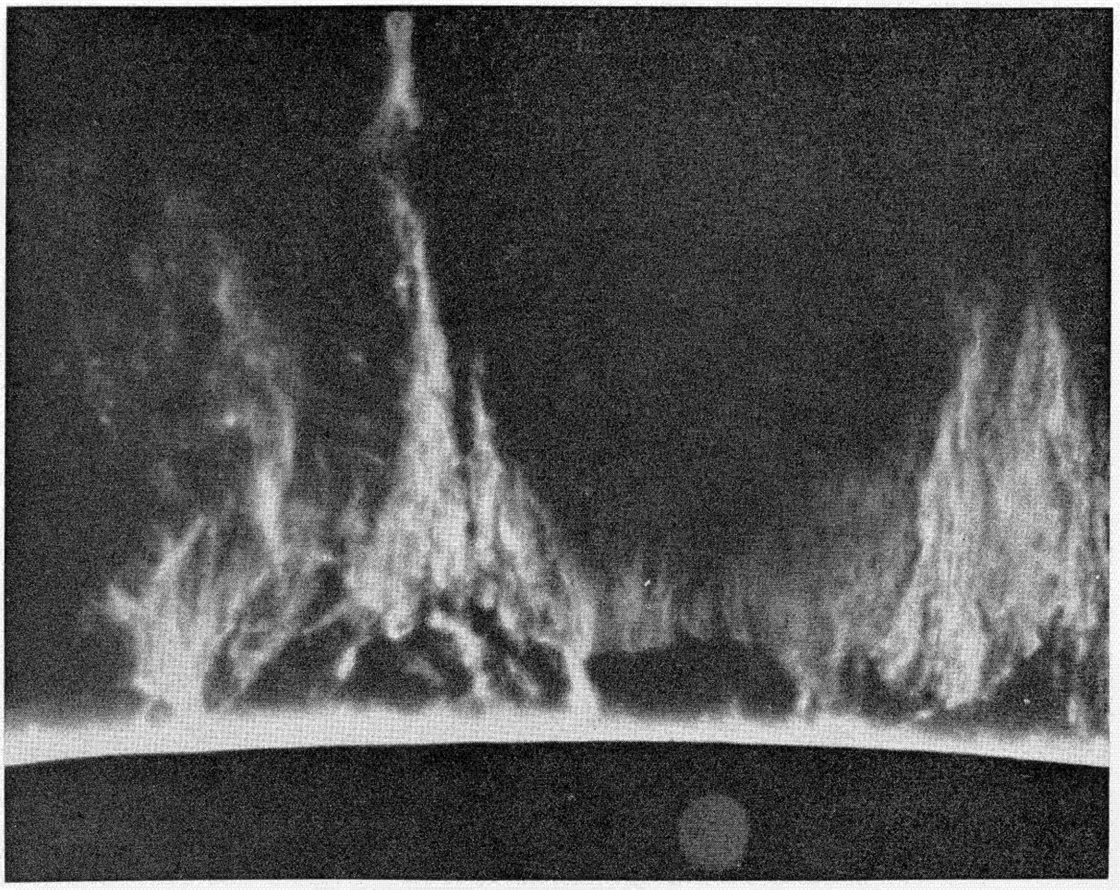
How do we look at higher levels in the atmosphere? These levels are easily accessible to our line of sight, but the gases are quite transparent, so we see right through them, just as we see through our own atmosphere. In order to see the tenuous atmospheric gases, we must use a technique which permits us to look in frequencies absorbed by the gases—for example, the spectrum lines of hydrogen may be used. Another way, much older, is to take advantage of a total eclipse when we can observe the very last crescent of the sun just as the rest of the surface is covered by the moon. At the instant before totality, a bright pink flash of light from the outer edge of the sun is seen; that layer is therefore called the chromosphere.

When we examine the chromosphere in hydrogen or calcium light, we may see the strong supergranulation pattern. The edges of the cells form a network of higher temperature and stronger magnetic fields. If we look carefully we see rapid jets of gas, called spicules, shooting up at the edges of the cells. Their velocity is about 30 km a second, and they rise about 5,500 km above the surface. Although there are not many of them on the disk, when we look at the limb the foreshortening merges them into a forest. It is from these jets that material flows into the corona above, and through them flows the energy that heats the corona.

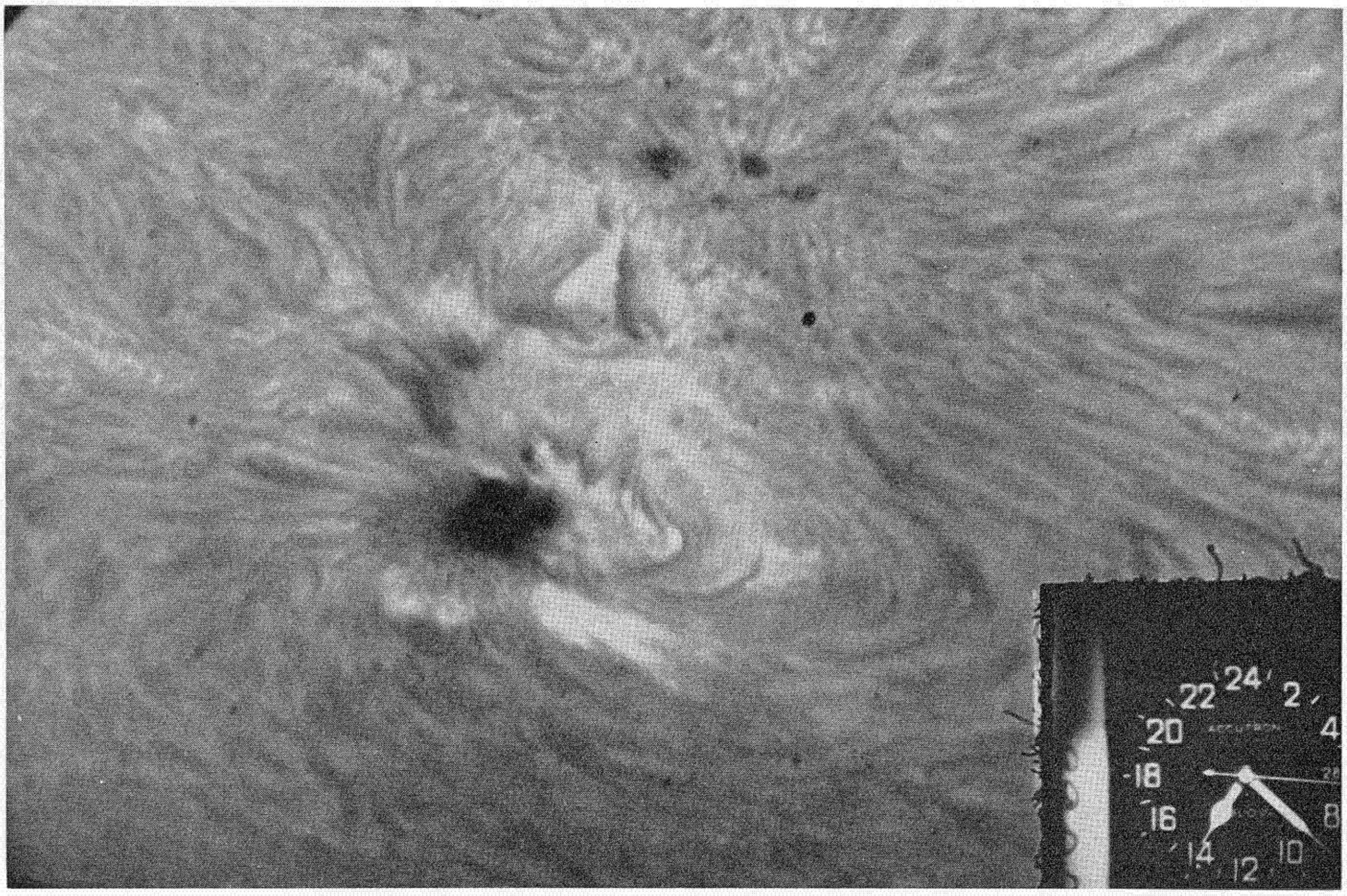
The corona is a very remarkable region. It can be studied only at eclipses, or at high altitudes with coronagraphs that block out the light of the sun itself. The corona is a million times fainter than the disk of the sun, so it is completely lost in a bright and hazy sky.

We know the corona is very hot because of the spectrum lines emitted there. From the radiation we find ionized iron with 13 or more electrons removed, ionized calcium with 14 electrons missing, and so on. Such high ionization can only be produced in very high temperatures. Although the corona is transparent to ordinary light, it is opaque to radio waves longer than five meters, and radio observations confirm its high temperature. We can also show that it produces scintillation in the light of distant radio stars even when they are 90° away in the sky, which proves that the coronal gas extends all the way to the earth.

Because the corona is so hot, it radiates a good



Solar prominence is a region of horizontal magnetic field where material cooling from the corona accumulates and drains downward. Thin layer of chromosphere is seen at edge of occulted sun.



Sunspot photographed in Hα shows the umbra (dark center) as a cup-like depression with bright surging regions around the edge. A small flare squirts out in the direction of the steepest magnetic field gradient.

deal in the ultraviolet. Accordingly, when we observe the ultraviolet spectrum from rockets or satellites, the spectrum is dominated by the lines of the highly ionized coronal atoms. By observing in this region, we can get some information on the corona as it appears on the disk of the sun, rather than just looking at the edge.

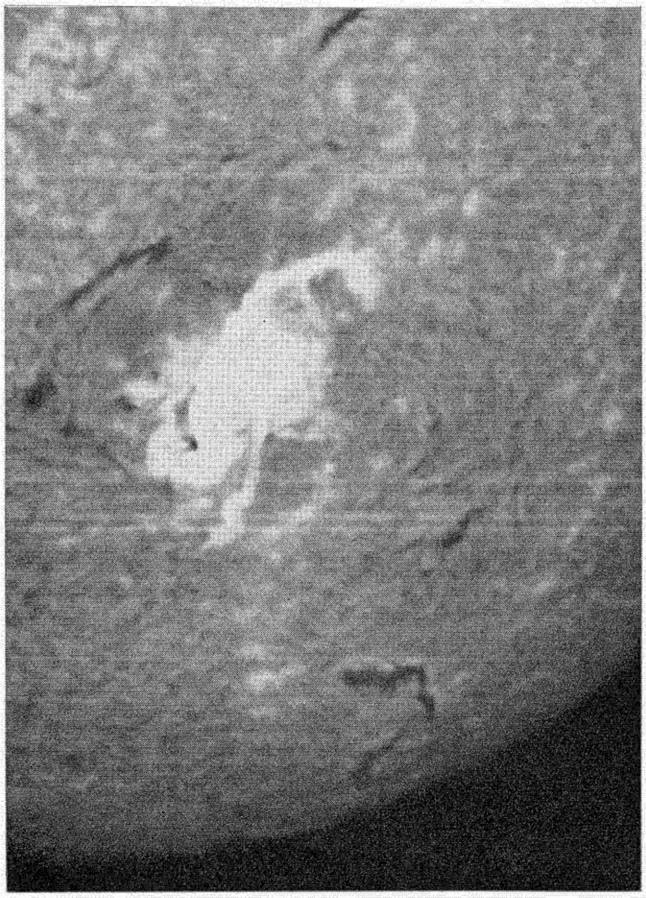
Although the corona is very hot, we often see much cooler clouds, called prominences, above the surface of the sun. These clouds are almost transparent except in hydrogen light, but at that wavelength they are considerably brighter than the corona. They are best seen against the sky with the disk light blocked out. But they may also be seen against the disk of the sun, where they appear dark. This is because they are darker than the disk but brighter than the sky.

When we study the positions of prominences on the sun, we find they are located on the boundary between large magnetic regions of north and south polarity. Magnetic lines of force rise up on one side and come down on the other, and in between the field is horizontal. Since the ionized gas cannot cross the field lines, it is supported above the surface. So the prominences are accumulations of cooled-off coronal material supported against gravity by horizontal magnetic fields. If we make movies of prominences, we may see material slowly moving downward. If the prominence is near a spot group, gas flows down to the spot along arching field lines. Sometimes the magnetic field changes abruptly, and the whole prominence blows out from the sun in a great arch.

I have so far been concerned with the quiet sun and the behavior of the atmosphere when undisturbed by transient activity. But the most exciting occurrences on the face of the sun are the phenomena connected with sunspots.

Sunspots are dark regions on the surface of the sun. They occur in many sizes, from little pores 1,000 km across to giants 100,000 km in diameter that may be seen with the naked eye. They occur between latitudes 5° and 40° in both hemispheres, although in the last ten years there have been very few spots in the southern hemisphere. The number of spots varies cyclically, with 11 years separating successive minima. At the beginning of a cycle small spots appear at high latitudes. As time goes on, the spots grow larger and more numerous, and they also occur closer to the equator. The last spots of a cycle are quite close to the equator.

Sunspots have very strong magnetic fields; their



The eruption of this large solar flare, photographed in 1959, filled the interplanetary space with cosmic rays and wiped out radio communication for days.

field is ten times stronger than an alnico magnet of the best quality, and one can imagine the strength of such a magnet 100,000 km across. The magnetic field is thought to suppress the convection of heat from below and thus make the sunspot cooler than its surroundings, which explains its darkness. Larger spots tend to occur in groups with one polarity on the east side of the group and the other in the west. The polarity of spot groups in the northern and southern hemispheres is opposite. With a new cycle, the polarity of the magnetic field changes, so that it takes two cycles—or a single 22-year full cycle—to come round to the same situation again. No one can explain this remarkable cycle.

Typically, large spot groups last two or three months. Because the sun rotates once in 27 days, we can see large spots come around several times.

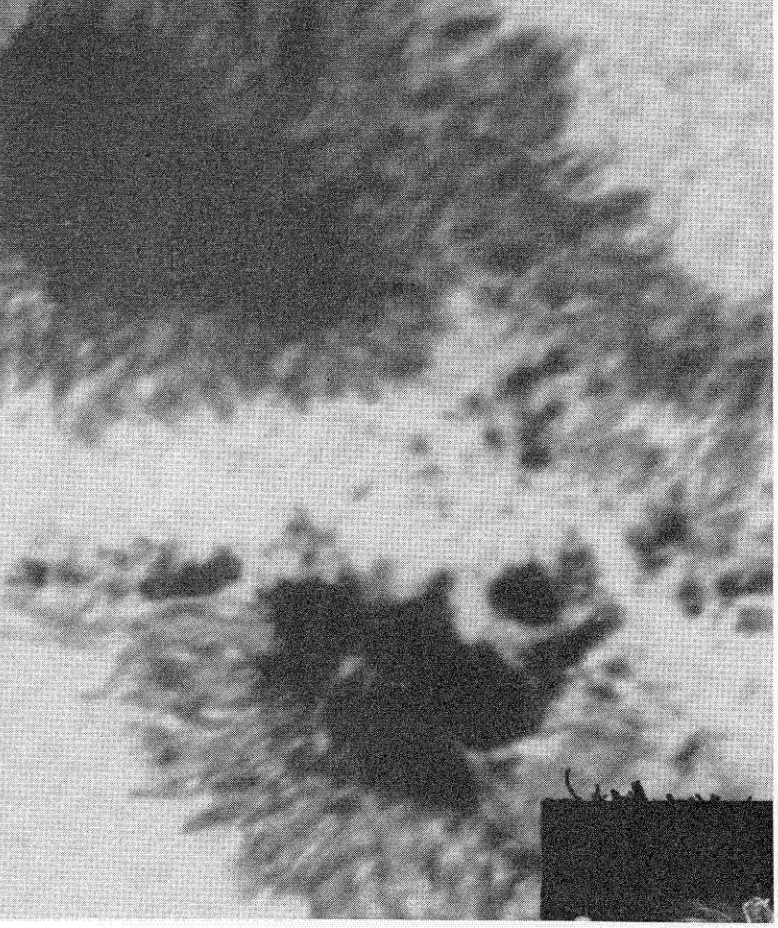
What happens to the sunspot fields when the spots die? The magnetic fields are dragged out by the motions in the surface and spread over the sun. This is helped by the fact that the sun rotates more slowly at higher latitudes, so that fields which drift poleward lag behind and are stretched over the surface. Soon large areas of the surface are covered with weak magnetic fields of one dominant polarity. These fields are marked by long streamers in the corona, and they are even detected in interplanetary fields near the earth.

Every once in a while—sometimes every few hours in particularly active groups—a great outburst of energy occurs in the neighborhood of a sunspot group. This is a solar flare, a truly remarkable phenomenon. Regions tens of thousands of kilometers across will brighten simultaneously in a matter of seconds. Great clouds of matter are thrown out with velocities of 500 to 1,000 km a second. Flares are transparent in ordinary light. Yet if we look in the extreme ultraviolet (the most energetic part of the spectrum), a flare covering 1/1000 of the surface emits more light than all the rest of the sun. Flares are most conveniently seen in the wavelengths of hydrogen light. By limiting ourselves to those wavelengths we reject most of the light of the surface but retain most of the flare emission, making it easily visible.

At the moment of most rapid brightening, energetic pulses of x-rays are emitted that change the earth's ionosphere so that radio signals fade out, and swarms of energetic cosmic rays are emitted that fill interplanetary space. To be sure, the biggest flares that severely disrupt the ionosphere and produce really hazardous cosmic radiation are infrequent—a few a year and only in the biggest spot groups. But even modest sunspot groups will have numerous small flares, each of which produces its own pulses of energy.

Careful observation of flares, particularly by cinematography, shows that they frequently occur in regions having a steep magnetic field gradient and that they are most common in very complex sunspot groups with intertwined regions of different polarity. To explain how flares occur, we must explain how their energy is stored up and then released very rapidly. The underlying sunspot and granulation structure is unchanged by the flare. Although flares have a lot of energy, it is miniscule compared to the enormous thermal energy under the surface of the sun. What makes the flares important is that a great deal of their energy is organized and concentrated in the most energetic part of the spectrum.

If we study the corona above an active sunspot group, we find a relatively dense cloud of hot gas at more than 3,000,000°. Each flare or eruption throws more material upward at high velocities, and these velocities are dissipated in a general heating of the atmosphere. The sunspot magnetic fields extend high above the surface, and often we see graceful loop prominences, which occur as the hot material thrown up by the flare cools, condenses, and



The dark centers in this large pair of sunspots are called umbra—the filamentary periphery, penumbra. Granulation appears on the outside and light bridges can be seen in the umbra.

rains down along the curving magnetic lines of force. The hot gas in these coronal condensations emits a considerable quantity of soft x-rays; in addition, we often find hard x-rays coming from this region. Such radiation is particularly noticeable when a flare occurs just over the edge of the sun, so we see the eruption in the atmosphere even though we don't see the flare itself. The fast-moving electrons produced in the flare are trapped in the atmospheric magnetic fields and radiate their energy in the form of x-rays.

Why do sunspots occur? This question has always fascinated astronomers. Early theories simply considered them as storms on the sun. If we look at atmospheric structure around sunspots in hydrogen light, we see strongly curved configurations, like the curved clouds around a hurricane. We now know that these clouds are elongated because matter is forced to flow along the magnetic lines of force. And we know that the strong magnetic fields in spots suppress motion, so that the spots are rather quiet although the atmosphere above them is very turbulent.

Many theories of the sunspot cycle connect it with the sun's differential rotation—the remarkable fact that the sun rotates faster at the equator than it does at the poles. Some astronomers have conjectured that this unequal rotation winds up the magnetic lines of force, greatly intensifying them, until sunspots break out.

Other astronomers feel that the differential rotation is due to the spots themselves. They suppose that the inside of the sun rotates somewhat more rapidly than the surface, which is slowed by the interaction of atmospheric magnetic fields with the interplanetary medium. The sunspots sink roots from the slowly rotating atmosphere into the interior and speed things up.

But we still don't know how the spots are produced, and we cannot see why they should return so regularly every 11 years.

We passed through a minimum of solar activity in 1964, and a new cycle began, with maximum expected in 1968. Astronomers have developed a variety of new instruments to observe the phenomena of this cycle. We are especially interested in rapid time-sequence observations so that we can observe the evolution of fast-changing phenomena, and in high-resolution observations so we can see exactly what is going on. One important source of information is data from rockets and satellites in regions of the spectrum that do not penetrate our atmosphere, particularly the ultraviolet. In this region we may directly observe the parts of the atmosphere, such as the corona, that are transparent in the visual spectrum. Also, the more energetic ultraviolet light, particularly x-rays, most closely reflects the energetic processes in flares. So we hope, with the further development of satellite and rocket astronomy, that we shall gain new knowledge from a different point of view.

Another way in which we are gaining new knowledge about the sun is by the study of similar activity in other stars. Although the stars are so distant that we cannot see their surfaces (they appear as points), by studying the behavior of certain lines in their spectrum we can determine if they have chromospheres or solar activity. These lines are, of course, the same strong spectrum lines in which we study the solar chromosphere and flares. We can see how often and how strongly these phenomena occur in stars of different ages and sizes, and thus place these phenomena in the proper perspective in the lifetime of a star. On the other side, by studying the phenomena in the sun from the stellar point of view, we may explain to the stellar astronomers the meaning of these barely detectable phenomena, which we only can interpret by looking at the surface of our sun, the only star that we really can see in two-dimensional detail. Thus we use our own star, the sun, to help understand all the other stars of the universe.