Ultraviolet Solar Images from Space

An orbiting observatory has obtained valuable new data on the three-dimensional structure of the sun's atmosphere.

Leo Goldberg, Robert W. Noyes, William H. Parkinson
Edmond M. Reeves, George L. Withbroe

Astronomers and physicists have long been fascinated by the outer atmosphere of our nearest stellar neighbor, the sun. The solar atmosphere is the site of important physical processes not easily duplicated in the laboratory. For instance, the density is so low that the scale length for the interaction of radiation with matter is larger than the size of any conceivable laboratory experiment. In the solar atmosphere there also occur hydromagnetic waves and shocks with length scales larger than the earth itself. Not only are these processes interesting in their own right, but some of them, such as solar flares, have important practical consequences. Events occurring in the solar atmosphere give insight into analogous, and often much more violent, events in other stellar atmospheres; some of these (for example, mass loss from stars, similar to that which occurs on a much reduced scale in the solar wind) have important consequences for their evolution.

It is not surprising, then, that aside from the earth itself, the sun is probably the most thoroughly studied of all astronomical objects. As a result, considerable is known about its surface structure and dynamics. Much of this information has been gained by the use of the spectroheliograph, a device invented by George Ellery Hale in 1892, which allows monochromatic images of the sun to be obtained. By selecting for observation wavelengths at which the solar atmosphere is more or less opaque, the structure can be explored over a limited height range in the solar atmosphere. For example, at the wavelength of 3933 angstroms, in the center of the very strong resonance absorption line of Ca^{+}, it is possible to see to a level perhaps 3000 kilometers higher than the "white light" surface, known as the photosphere. The appearance of the sun is enormously different at these two levels (Fig. 1).

Intermediate levels may be explored by making spectroheliograms in lines of intermediate opacity, but it is impossible to make spectroheliograms at higher levels by traditional methods, for the resonance line of Ca^{+}, along with the Balmer alpha line of hydrogen at 6563 angstroms, are the most opaque lines in the part of the solar spectrum that is accessible to ground-based observation. Therefore, much of observational solar astronomy has to do with understanding this well-observed region extending a few thousand kilometers above the photosphere, loosely known as the chromosphere. In the low chromosphere, the temperature declines to a minimum value of perhaps 4500° Kelvin, then gradually rises to several times that at the top. At this point, the temperature rises, probably quite suddenly, to the order of 10^6 degrees Kelvin, in the corona (Fig. 2). In the region of the transition to the corona, and in the corona itself, many interesting phenomena take place.

In visible light, the emission from the hot and very tenuous corona cannot be seen in front of the disk, because it is swamped by the light of the photosphere. Much is known of the overall structure of the corona from observations of its extension above the limb, made in eclipse when the moon blots out the bright photospheric radiation (or by the use of a coronagraph at an appropriate high-altitude site, in which an occulting disk artificially occults the solar image). However, because the corona is then viewed edge on, little spatial resolution is obtained.

One way to achieve spatial resolution in the corona is to make spectroheliograms in the far ultraviolet, from above the earth's atmosphere. Most of the emission lines from the coronal transition zone and the corona fall below 1500 angstroms; for that reason alone the spectrum in the far ultraviolet is highly significant. But, in addition, the radiation of the photosphere (which looks approximately like a blackbody at 6000° Kelvin) is very weak in the far ultraviolet, so it is easy to observe the coronal emission lines in front of the solar disk, with good spatial resolution. Finally, by looking at the emission from ions of various stages of ionization, good height resolution can also be obtained. At temperatures of several tens of thousands of degrees, only the outer electrons are stripped from an atom, which produces low stages of ionization. The process continues to remove electrons from the ion as the temperature increases, and so progressively higher stages of ionization are produced. Each stage of ionization corresponds to a particular temperature range and each ion has its own characteristic spectrum different from all other stages of ionization of its own and other elements. The rapid variation of temperature with height means that an atom in a given stage of ionization will be formed, and hence radiate, only over a small range of heights in the solar atmosphere.

Accordingly, about 10 years ago, we began the design of an ultraviolet spectroheliograph, which could produce solar images of high spectral purity in the wavelength region from 300 to 1400 angstroms. This instrument was launched in the orbiting solar observatory OSO-IV in October 1967 (*1*) (Fig. 3). The upper portion of the satellite is referred to as the sail, and carries the two main solar instruments which are directed toward the sun at all times. The sail also carries an array

The authors are with the Solar Satellite Project of Harvard College Observatory. Leo Goldberg, the principal investigator, is chairman of the department of astronomy at Harvard and director of the Observatory. Robert Noyes is an astrophysicist at Smithsonian Astrophysical Observatory and lecturer at Harvard. William Parkinson and Edmond Reeves are senior research associates at the Observatory, and George Withbroe is research fellow at Harvard College Observatory.

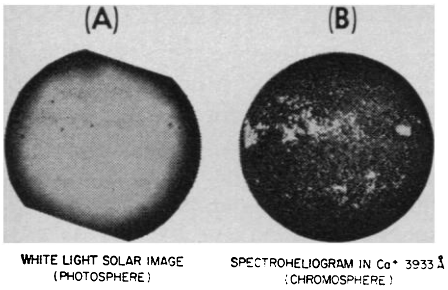

Fig. 1. (A) The solar surface in white light. Sunspots, the darkening toward the limb, and the faint appearance of chromospheric emission near the limb are salient features. (B) The solar chromosphere in the light of Ca^+ 3933 angstroms. Bright emitting areas are active regions and correspond to areas of enhanced magnetic field (*4*). [Courtesy Sacramento Peak Observatory]

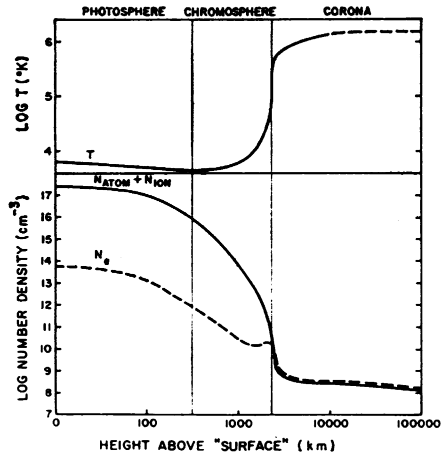

Fig. 2. Approximate distribution with height of temperature, density, and electron density in the solar atmosphere.

of energy-producing solar cells which charge the satellite batteries, operate the scientific instruments, and power spacecraft systems such as tape recorders and transmitters. The lower portion of the satellite, called the wheel, rotates once every 2 seconds and contributes gyroscopic stabilization. The wheel contains both the spacecraft systems and a variety of solar and stellar experiments which scan their targets once per revolution. The three arms contain high-pressure nitrogen gas which is used in small jets to control course orientation of the satellite and the rate of rotation of the wheel. The Harvard spectrometer is located in the sail instrument assembly (shown to the left of center in Fig. 3). Figure 4 presents an optical layout of the instrument. Parallel light rays from the sun enter through the aperture (*A*) (Fig. 4, left), travel the length of the instrument and strike the 4-centimeter aperture platinum-coated collecting mirror, which images the sun on the entrance slit of the spectrometer portion of the instrument. The entrance slit limits the field of view of the spectrometer to a 1 arc minute square on the solar disk (Fig. 4, right). Light from that 1-minute region on the sun passes through the entrance slit; the light strikes the grating (*G*) and is dispersed into its component wavelengths, which are then imaged and detected by a windowless photomultiplier behind the exit slit. The photomultiplier has a tungsten photocathode that is insensitive to the photospheric spectrum at longer wavelengths; the associated electronic circuitry allows it to detect and count individual photons. To scan the spectrum, the grating is rotated about an off-axis point to keep the spectrum in focus as it moves past the detector. The output from the electronics is recorded on a tape recorder aboard the satellite, which can be commanded to play back to receiving ground stations.

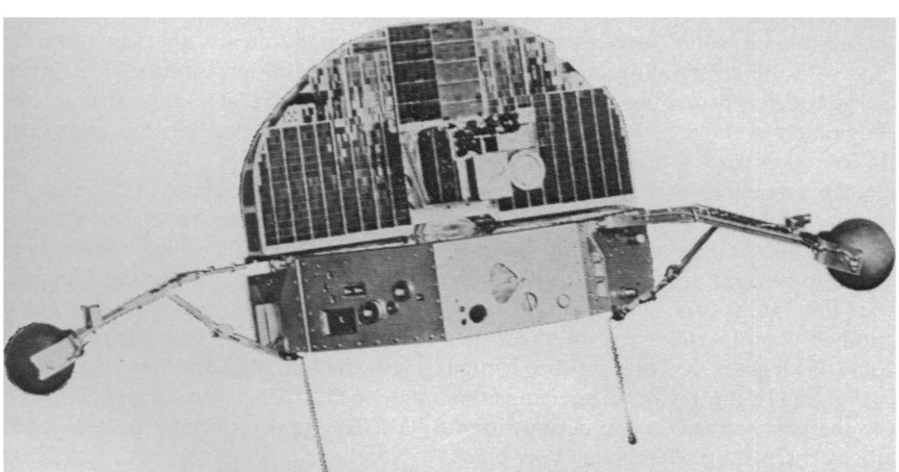

Fig. 3. The orbiting solar observatory OSO-IV; the diameter of the body of the satellite is about 4 feet (1.2 meters).

One complete scan of the spectrum from 300 to 1400 angstroms takes about 25 minutes.

The most important feature of the instrument is its ability to obtain spectroheliograms of the sun at any wavelength within the range of the spectrometer. The grating may be commanded to stop at any desired position, by use of the zero-order reflection as a wavelength reference. This position is chosen to make the light of the desired emission line fall continuously on the photomultiplier detector. The upper portion of the satellite is then commanded into a raster mode (Fig. 4, right) which allows the entrance aperture to scan over the solar disk and record point-by-point the intensity distribution of the sun in that emission line. The intensities measured from each point in the pattern can then be used to reconstruct the spectroheliogram of the sun from the data played back to the ground.

In order to select from among the hundreds of emission lines in the observable wavelength range, a special communications net was set up in which data from the entire orbit could be played back to the ground from the satellite tape recorders and transmitted directly to Goddard Space Flight Center at Greenbelt, Maryland, and into a computer. The computer selected out the Harvard data, scaled it, and transmitted numerical reconstructions of the spectroheliograms to the Harvard College Observatory in Cambridge, Massachusetts. This process took approximately 20 to 30 minutes. The experimenters at Harvard College Observatory could thus evaluate the data in near real-time, and send any corrective commands or changes in the observing program back down the data link; these commands were then transmitted to the satellite on its next pass over a ground station. Approximately, six consecutive orbits 90 minutes apart could be used in this way to sample the data coming from the orbiting solar observatory satellite and to devise the most meaningful program consistent with the state of activity on the sun at that time. This "quick-look" capability added immeasurably to the success of the Harvard instrument.

A little more than 5 weeks after the satellite had been successfully launched, an electronic failure in the detection system of the instrument occurred and terminated the useful life of the instrument. However, during the useful lifetime, more than 100 spectral scans

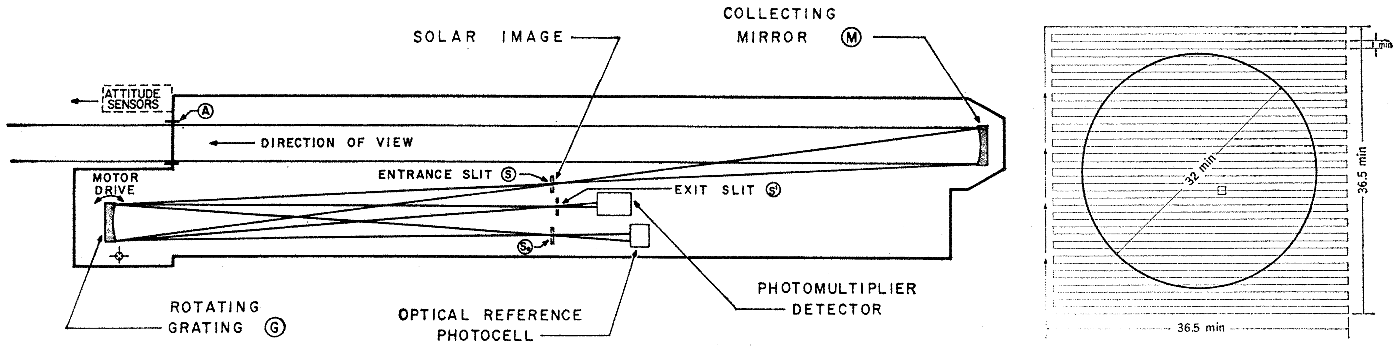

Fig. 4. (Left) Optical layout of the Harvard spectrometer aboard OSO-IV. (Right) Raster scanning pattern of the Harvard spectrometer over the solar disk. The small square represents the size of the square entrance aperture of the spectrometer.

of the spectrum from the center of the sun were obtained, together with over 4000 ultraviolet images in 52 different wavelengths distributed over a wide range of temperatures and heights in the solar atmosphere. Most of the emission lines represented have never before been observed with spatial resolution on the solar disk.

Figure 5 shows the spectrum of the center of the disk as observed by the Harvard spectrometer. Most of the strong emission lines are identified below the spectrum. The majority of the lines are emitted by the abundant elements H, He, C, N, O, Ne, Mg, Si, S, and Fe in various stages of ionization, from neutral (I) to 15 times ionized (XVI).

Above the spectrum is a quasi-photographic representation of four of the spectroheliograms, in lines which vary in temperature of formation from 10,000 to 2,500,000 degrees Kelvin. In height of formation they vary from a few thousand kilometers above the visible surface to several tens of thousands of kilometers above the surface. The increased emission above the limb in Mg X and Si XII is quite evident; indeed it overfills the field of view of the spacecraft. The spectroheliograms were obtained within 6 hours of each

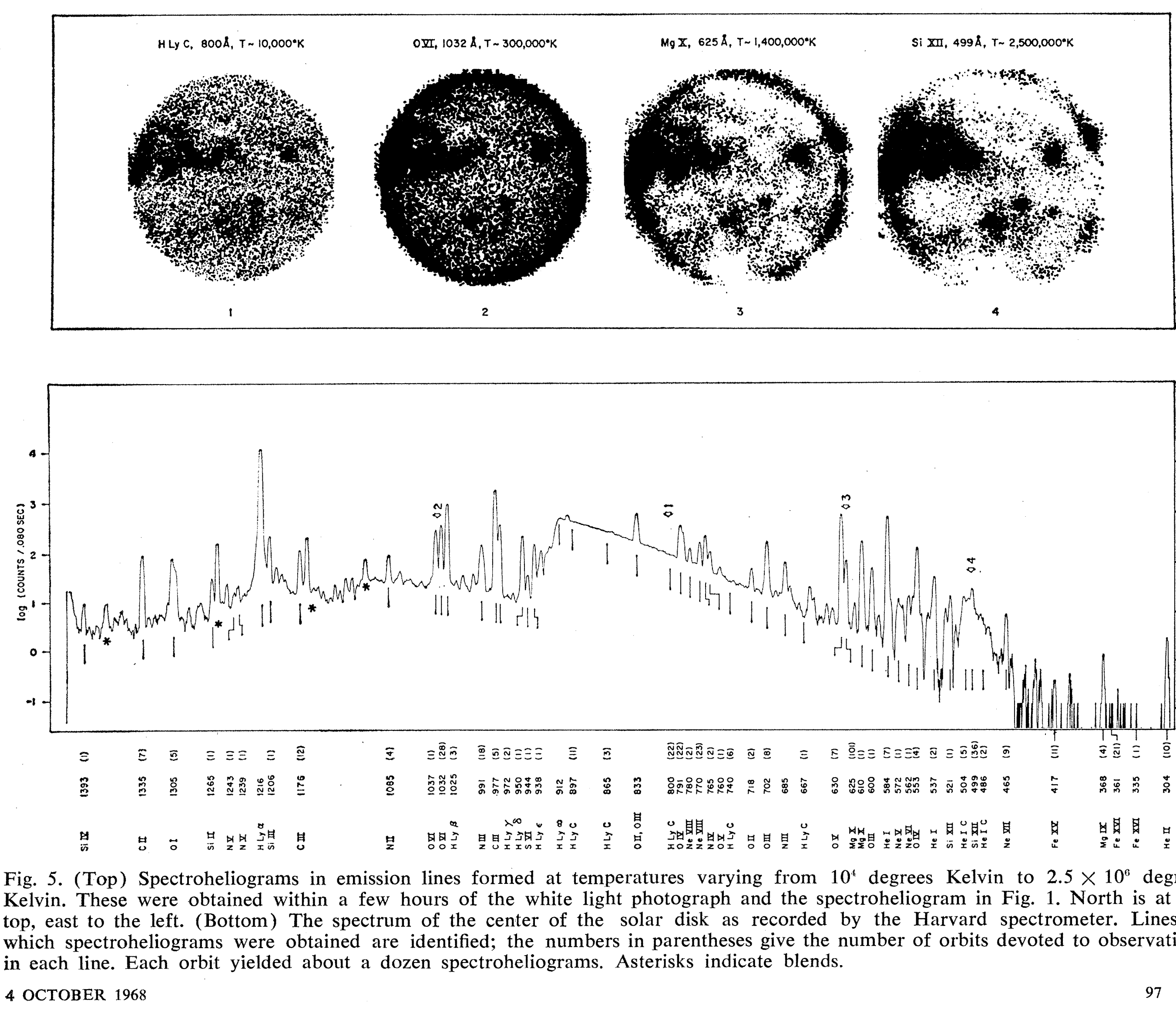

Fig. 5. (Top) Spectroheliograms in emission lines formed at temperatures varying from 10^4 degrees Kelvin to 2.5×10^6 degrees Kelvin. These were obtained within a few hours of the white light photograph and the spectroheliogram in Fig. 1. North is at the top, east to the left. (Bottom) The spectrum of the center of the solar disk as recorded by the Harvard spectrometer. Lines in which spectroheliograms were obtained are identified; the numbers in parentheses give the number of orbits devoted to observations in each line. Each orbit yielded about a dozen spectroheliograms. Asterisks indicate blends.

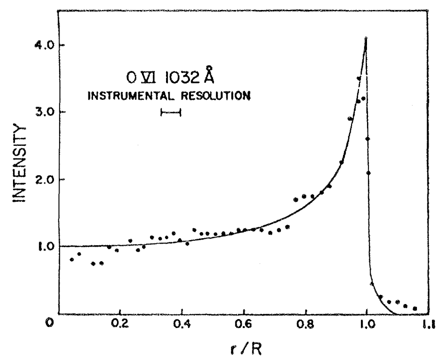

Fig. 6. Variation of intensity in the line of O VI; filled circles indicate variation from center to limb of the mean intensity of the quiet sun obtained from one spectroheliogram by averaging all points which lay at a given distance *r* from the center of the disk and were not in active regions. Solid line traces the theoretical prediction of the limb brightening expected from a model of the corona (*2*) with a sharp transition zone. The curve has not been corrected for the instrumental resolution function, whose half-width is indicated.

other and within 12 hours of the illustrations in Fig. 1, so direct comparisons are meaningful.

Active regions are visible as bright emitting areas concentrated in zones north and south of the equator; these may be seen in all four of the spectroheliograms in Fig. 5. The brightness of the active regions relative to the quiet sun increases markedly in the corona. The active regions coincide in position with the large patches of emission visible on ground-based spectroheliograms in the Ca^{+} line, and are seen in Fig. 1 (right). Unfortunately the spatial resolution is insufficient to resolve the smaller scale emission network visible all over the image in Fig. 1, right. Nevertheless, the rather modest resolution of our data still permits a wide variety of studies of the upper chromosphere and corona. As examples of some of the areas of study opened up by these data, we describe, below, two broad analysis programs being undertaken and then list briefly several other promising lines of attack.

Structure of the Quiet Corona

The intensity of solar emission lines from the quiet corona at the center of the solar disk, as obtained from spectra, such as that in Fig. 5, already provides significant information about the state of the quiet corona. The theory of emission of coronal resonance lines is reasonably straightforward. Because the coronal radiation field is very dilute, excitation of coronal ions occurs mainly by collisions of electrons with ions in their ground state. Since two particles are involved, the emission per unit volume is proportional to the square of the density. In addition, of course, ions of the appropriate degree of ionization must be present. As indicated above, the equations of ionization equilibrium predict that a given ionization stage occurs in a rather narrow temperature range centered about an optimum temperature for that ion. The steeper the temperature gradient in the atmosphere, the smaller the volume of coronal material within the appropriate temperature range. Thus the total observed emission, that is, the product of emission per unit volume and the volume able to radiate, measures the product of the square of the density and the inverse temperature gradient (*2, 3*). The major uncertainties are in the rates of the atomic processes involved (that is, rates for collisional excitation and ionization, autoionization, and dielectronic recombination) and the abundance of the elements in the corona.

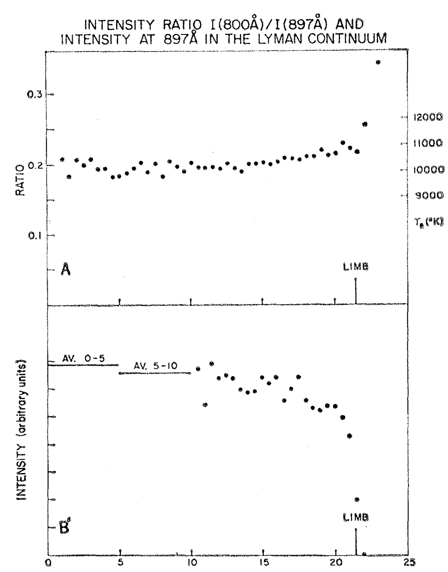

Fig. 7. (A) Center-to-limb variation of the ratio of two points in the Lyman continuum; the increase of the ratio toward the limb shows that the temperature rises with height in the chromosphere. (B) Center-to-limb variation of the intensity near the head of the Lyman continuum. The decrease toward the limb shows that the amount of absorption per unit emission increases with height.

Studies of spectra of the integrated emission from the entire sun have shown (*2, 3*) that the transition zone from the temperature of 10^5 to 10^6 degrees Kelvin is very sharp, occurring in only a few thousand kilometers. The new data allow refinement of these calculations considerably, for the quiet center of the sun can be isolated from the disturbing influence of active regions, which probably have a much different structure. In addition, we can get valuable checks on the model from the center-to-limb behavior of the emission intensity. Figure 6 shows, for example, the variation of intensity in the line O VI (1032 angstroms). The bright ring at the limb seen in spectroheliograms of that line (Fig. 5) is evident in the plotted data. These studies should provide a definitive description of the run of temperature and density in the quiet corona.

Structure of Upper Chromosphere

The emission from the upper chromosphere is somewhat more difficult to interpret in terms of atmospheric structure, because in most chromospheric emission lines there is considerable self-absorption at the rather high densities in the chromosphere. The consequent problems of radiative transfer in the chromosphere are formidable even under drastic simplifying assumptions, such as structural homogeneity or lack of motions in the atmosphere.

One hopeful approach is to study the hydrogen Lyman continuum, the dominant feature in the spectrum of Fig. 5. The analysis of the Lyman continuum is somewhat simplified because the emission is by recombination of free electrons and protons which are at a well-defined kinetic temperature. In addition, spectroheliograms obtained at different wavelengths in the continuum may be compared to check for self-consistency in chromospheric models.

For instance, the ratio of intensities of corresponding points of two spectroheliograms obtained at different wavelengths in the continuum measures the slope of the continuum at each point; this in turn may be related to the slope of the Planck function at the temperature characteristic of the recombining electrons and protons. The temperature deduced from the slope is about 10,000° Kelvin, and increases toward the limb (Fig. 7A). Because near the limb the emission emerges along a slant path, it must originate at a higher level; hence we conclude that the temperature increases outward, as we expect.

Since the temperature is known to be about 10,000° Kelvin from the slope of the continuum, the absolute flux of the continuum can be predicted if it is emitting like a blackbody at that temperature. The observed flux is less than this value by nearly three orders of magnitude. One possible explanation might be that the emission occurs in unresolved small clumps, with no emission in between, but such inhomogeneities probably do not reduce the emission by a factor of 1000. Another possible resolution of the discrepancy is provided by calculation of the equilibrium population of atomic energy levels in a low density plasma such as the chromosphere. Near the top of the chromosphere the ionization rate of hydrogen by collisions and photoionization is so low that the ground state of neutral hydrogen becomes considerably overpopulated relative to the population of free protons and electrons. Roughly speaking, this increases the absorption, but does not change the emission rate, and thus the net intensity observed at the earth is decreased.

The overpopulation effects are predicted to increase with height, and thus we might expect to see a decrease in intensity as we look to higher layers near the limb, even though the temperature is higher in these layers. That this is indeed the case can be seen in Fig. 7B.

From the empirical run with depth of the amount of overpopulation we may deduce the run with depth of the electron density; this together with the temperature found from the slope of the continuum should yield a fairly complete description of the structure of the quiet chromosphere.

Other Projects

Other projects will be carried out with the data described in this article.

Structure and evolution of active regions. Techniques similar to those described above can be applied to active regions in order to learn how their physical properties differ from those of the quiet chromosphere and corona. Data obtained on time scales varying from a few minutes to several weeks can also be examined to study the evolution of active regions. Comparison with ground-based measurements of the solar magnetic field show that the excellent correlation between magnetic fields and enhanced emission, already observed in the low chromosphere (*4*), extends throughout the corona. Out in the corona, however, the enhancement of active regions relative to the quiet corona increases markedly (Fig. 5), reaching a factor of as much as 50 or 100 in lines such as Si XII or Fe XVI. Analogous enhancements in active regions are observed in the white-light corona and in the radio region, although not as large. Hopefully, the new data will contribute significantly to the ultimate goal of understanding how active regions are formed and, in particular, what role the magnetic fields play in their formation.

Abundances in the corona. As mentioned earlier, one of the uncertainties in the theory of the spectrum of the quiet corona is the abundance of the elements. Indeed, there are some indications of apparent abundance anomalies, in that heavy elements, such as iron, seem to be an order of magnitude overabundant in the corona relative to the photosphere (*5*). Because until now all ultraviolet data have included the entire flux from the sun, including both active and quiet regions, the ultraviolet results have been ambiguous (*2, 3*). However, the new data will go far toward resolving these ambiguities.

Flares. During the 5 weeks of operation of the Harvard College Observatory experiment, over 100 solar flares were recorded, including several major flares. Enhancements of up to a factor of 30 in some lines were observed to occur within a few minutes. Unfortunately, the time resolution of 5 minutes, imposed by the raster period of the Orbiting Solar Observatory-IV spacecraft, is rather low for flare studies. A new instrument is being prepared for flight on the Orbiting Solar Observatory-G spacecraft in 1969, and it will have twice the spatial resolution and ten times the time resolution. This will enable the development of flares in ultraviolet lines to be observed at the rate of one spectroheliogram every 30 seconds, and with a spatial resolution of about 30 arc sec or 2000 kilometers.

Although we are still a long way from the kind of resolution obtainable from the ground, that too will come eventually. In the meantime, there is an enormous amount of information waiting to be extracted from this brand new type of data.

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