Recent Progress in Solar Physics

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Abstract. A number of significant recent advances in solar physics are reviewed. New kinds of observations made during the present sunspot cycle, which began in 1954, have emphasized still further the apparent complexity of solar phenomena and the need of nonequilibrium theoretical treatments. Among the new developments discussed are solar cosmic rays and high-energy particles, flares and prominences, coronal condensations, solar magnetic fields, and solar radio noise emission. Theoretical analyses of the conditions of the solar atmosphere as a hot plasma, and as a gaseous ensemble exhibiting gross departures from thermodynamic equilibrium, are discussed. New work on atomic collisional parameters is also reviewed. The article concludes with a synopsis of certain major unsolved problems of the solar atmosphere.

INTRODUCTION

Solar physics is growing at an explosive rate. We try, in this review article, to summarize advances of the past few years that seem to us most significant.

The stimulating impact of the IGY is immediately apparent. It is particularly fortunate that the IGY coincided with an extraordinary peak of solar activity. On Christmas day of 1957 the Wolf sunspot number reached the highest value yet recorded. It is probable that no higher sunspot activity level has occurred since Galileo first began observations in 1611.

The outstanding individual events of solar activity of recent years have produced terrestrial effects which, thanks to the IGY, have been examined with unprecedented detail. The February 23, 1956, cosmic-ray flare, a precursor of the IGY activity to follow, brought the largest increase in cosmic-ray neutron activity yet observed at the surface of the earth. The Climax neutron monitors, for example, reached a level of about 40 times normal. The night of February 10–11, 1958, produced an aurora of extraordinary proportions, accompanied by severe radio and telegraphic disturbances and earth currents of unusual magnitude. August 22, 1958, produced a flare late in the afternoon in the Soviet Union, also observed early in the day over the United States, that initiated spectacular solar radio noise outbursts at a wide range of frequencies. The radio source apparently extended high into the solar atmosphere and occupied a volume of space roughly comparable with the sun itself.

The outstanding activity continued into the International Geophysical Cooperation 1959. For example, May 12–13 produced a brilliant aurora and strong proton radiation into the terrestrial polar cap. At the top of the atmosphere over Minnesota the proton flux reached 1000 times the normal cosmic-ray values. The great peak of flare activity of July 13–16, 1959, also produced strong proton emission and was accompanied by the largest Forbush-type decrease of cosmic-ray intensities yet detected. Solar activity in August and November of 1959 generated powerful long-wave solar radio noise.

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emissions of unusual nature for which excellent radiospectroscopic observations exist.

Intensively observed events like these, coupled with the numerous rocket and satellite observations of the ionosphere, the Van Allen belts, and interplanetary space, have vastly enriched the source materials for sound theoretical advances in astrophysics. It is no surprise that solar physics proceeds at an enormously accelerated pace.

**Observational Highlights**

Observational techniques in solar physics have improved enormously in recent years; the work with rockets and satellites has contributed importantly to this development. Moreover, the older means of observation, such as coronagraphs, spectroheliographs, and magnetographs, have been substantially improved, and these more conventional techniques have been more widely employed.

**IGY solar activity patrols.** The hundred-odd solar stations of the IGY have cooperated in providing unprecedented coverage in solar phenomena since the beginning of IGY. Some thirty flare patrol stations spread in all longi-
Fig. 2. Intensity recorded by the University of Chicago neutron pile at High Altitude Observatory, Climax, Colorado (elevation 11,300 feet). Graph, courtesy of Professor John Simpson.

tudes have kept the sun in virtually unbroken \text{H}_\alpha scrutiny since June 1957. These stations have photographed the sun on standard films to standard scale at intervals not exceeding 3 minutes. For the first time in history, a continuous solar motion picture covering the 24-hour-per-day activity of the sun is being assembled for a 2-week period during the IGY. An international committee headed by H. J. Smith, of the United States, and including J. Rösch, M. N. Gnevyshev, and R. Giovanelli, of France, Russia, and Australia, respectively, is overseeing this task. This intensive coverage will enable us to understand more clearly the interrelation of the various solar phenomena.

There has also been a considerable increase

Fig. 3. Sacramento Peak Observatory \text{H}_\alpha photograph of complex loop prominences made with 15-inch coronagraph. Courtesy of Dr. R. B. Dunn.
in the number of nonpatrol-type instruments, such as coronographs, large solar spectrographs, and high-resolution magnetographs. The work with these instruments is crucial to understanding the physics of the sun.

Researches on prominences and the chromosphere with coronographs. The Lyot coronagraph, because of its low light-scattering properties, is an excellent instrument for investigating solar-limb phenomena. Coronagraphs have evolved from routine survey instruments, with which only the red and green coronal lines were observed, to instruments that can cover a broad range of spectrum either by taking rapid series of spectra at different foci or by using achromatic first objectives. With such instruments the relative intensities of a number of coronal lines can be studied, as well as interesting faint lines in the spectra of prominences, many of which are no brighter than coronal lines and thus are accessible only to coronographs.

R. C. Dunn at Sacramento Peak has obtained outstanding monochromatic photographs with a high-resolution coronagraph of 15-inch aperture in studies of the fine structure of prominences and chromosphere. Photometric details of spicules and the statistics of occurrence of spicules have been examined with considerable detail. The same instrument has also revealed that the internal filamentation of large quiescent prominences seems sharp down to the resolution of the telescope (about 0.5 second of arc). It is remarkable, too, that both active and quiescent prominences, when viewed under high resolution, seem to show a marked tendency to divide into tiny threadlike filaments, which are probably the result of confinement of prominence gases along magnetic lines of force. We still do not know how fine the filaments are; the observations provide only an upper limit. Any theory of prominences, to be considered successful, must explain this fine structure.

Observations (by Zirin and Tandberg-Hanssen) with the coronagraph-spectrograph at Climax have shown that prominences fall into two distinct spectroscopic classes. The long-lived filaments, even when they erupt (disparitions brusques), show the same spectrum as the chromosphere at 1500 km height; they appear to have kinetic temperatures of approximately 10,000°K. Loop prominences, flares, surges, and other short-lived prominences representative of high solar activity show a much 'hotter' spectrum. For example, atoms and ions with low ionization potential, as Ti II, Fe I, and Fe II, are weakened as compared with lines of neutral helium, which has a high ionization potential. Moreover, the ionized-He line, 4686 A, is greatly enhanced. The following typical line ratios may be given: in cool prominences (Sr II 4077 A)/(He I 4026 A) ~ 1; in hot prominences, the ratio is about 1/7. In cool prominences, (He I 4713 A)/(He II 4686 A) ~ 5; in hot prominences, ~1/2. The fact that the spectra divide sharply, with few intermediates, suggests that there are two distinct temperatures at which the material is thermally stable. The existence of discrete temperature 'plateaus' was predicted by Athay and Thomas [1956] and has been substantiated by Zirker [1960]. The kinetic temperatures of the hotter 'plateaus,' however, are difficult to determine experimentally because the Doppler profiles are confused by considerable motion in these prominences. They must be at least 30,000°K and perhaps as much as 100,000°K.

The observed similarity of the spectrum of tightly looped active-region prominences to that of flares is not surprising. Many workers, over the years, have noted that flares seen in projection at the limb often have the form of loops [Waldmeier, 1958; Zirin, 1959]. Of course, some flares appear as erupting forms of outgoing material; the picture is not simple.

Athay has made successful observations of the chromospheric spicule spectrum in Hα, Hβ, Dα (He I), and the K line (Ca II) with the Climax coronagraph. The extreme breadth of the spicule line profiles contrasts sharply with the narrow profiles of quiescent prominences. The line widths must be interpreted as being due to kinetic temperatures of the order of 50,000°K.

A difficult problem for students of the solar atmosphere is to explain the occurrence of the He II 4686 A line (excitation potential 48 volts) in places where it ought not to be, namely quiescent prominences and the low chromosphere. To be sure, the line is very weak in these places, but it ought not to appear at all. Explanations of its appearance as being due to ionization by coronal radiation all seem to fail quantitatively. A clue is given by the fact that
the line width of 4686 Å in quiescent prominences appears to be twice as great as that of the other spectrum lines. In such regions we probably do not have a homogeneous kinetic temperature but sharp temperature gradients.

Coronal motion pictures. Great advances have been made in the study of the solar corona in recent years. At the Sacramento Peak Observatory routine movies have been made of the corona in the light of λ5303 through a high-quality birefringent filter and coronagraph system developed by R. B. Dunn. Two years of observations have revealed many unsuspected features. On several occasions structures in the corona, usually fairly low arches over active regions, have been seen to disrupt violently with a whiplike motion, which has led to the designation of such events as 'whips.'

Other active regions have been found to develop series of 'flashing loops' which appear as the illumination, at successively greater heights, of curved loops overlying strongly active centers, particularly after strong flare activity. These loops are shaped like the trajectories of the pronounced 'loop prominences' often found over extremely active regions. After a sudden start of activity, they seem to be illuminated, with no apparent motion of material, at successively greater heights with the passage of time. The coronal motions suggest changing regions of excitation rather than actual matter motion of gas. In this respect the coronal motions are unlike the motions of prominences.

Regular corona patrols are now being carried out in all regions of pronounced activity. From region to region, great structural differences appear. Sometimes tightly closed loops are seen, resembling prominence trajectories found above such regions; sometimes 'open' structures are observed diverging outward above active centers, also a characteristic of prominence trajectories of certain active regions.

Since these loops and open structures presumably map out the magnetic field above the spot groups, it may be that the corpuscular emission from the two types differs significantly, and the chances for magnetic disturbances from one or the other may also differ. One thing is certain: the old concept of the corona as a homogeneous medium in hydrostatic equilibrium is a gross oversimplification.

Coronal spectrum measurement. From measurements of the intensities and profiles of coronal lines in specific coronal regions, Billings and Cooper [1957] have concluded, however, that average values of scale heights do correspond to the temperatures found from profile measurements, and so it is possible to consider the structural features in the monochromatic corona as perturbations of the hydrostatic equilibrium corona. They have made some progress in determining the nature of the perturbing influence. By assuming that the coronal region is in equilibrium between pressure, gravitational, and magnetic forces, they have been able, with some uncertainties, to map the direction of the magnetic field, obtaining in one case a very plausible map that resembles prominence structures in the region. In the same coronal region, the distribution of line widths suggested a very definite oscillatory pattern which might be interpreted as a hydromagnetic wave [Billings, 1959].

Eclipse research. The number of large and elaborate eclipse expeditions in 1952, 1954, 1955, 1958, and 1959 has been notable. The Khartoum eclipse of 1952 yielded valuable results. The ItAO-Sacramento Peak-Harvard expedition obtained splendid flash spectra which greatly extended our knowledge of the solar chromosphere, and the French-Egyptian expedition headed by Lyot discovered a number of new coronal lines, though its success was marred by the tragic death of Lyot. The 1954 eclipse was clear for many teams, and good observations were made. It was particularly interesting because it occurred at the minimum of the solar cycle. The 1955 eclipse, which was favorable because of a very long period of totality, was clouded out, but 1958 saw a number of successful expeditions to the South Pacific. Elaborate Sacramento Peak-HAO expeditions were clouded out in 1958 and 1959. Nevertheless, rocket investigations made by the Naval Research Laboratory group at the 1958 expedition were highly successful, as were accurate coronal polarization studies made from Africa by Ney and colleagues at the October 1959 eclipse.

Solar magnetic field measurement. Marked progress has been made in the study of solar magnetic fields. The Babcocks, at Mount Wilson Observatory, have developed automatic scan-
ning instruments (magnetographs) designed to make longitudinal-component magnetic-field-intensity measurements at low field intensities over the entire sun and to provide representations on a convenient scale. The technique utilizes measurement of the wings of certain absorption lines in the solar spectrum that are sensitive to the Zeeman effect. Maps are produced showing fields as low as 1 gauss. One striking result has been the occasional appearance of low-latitude magnetic fields of only one polarity, covering large regions. The same technique can be applied to high-resolution studies of strong fields in active regions by using lines of lower magnetic sensitivity and smaller scanning apertures.

The Babcocks' work has given valuable information about the existence of a weak general solar field, but the situation is still somewhat confused. A change of the polarity of the general field in recent years has been revealed in a remarkable study by Babcock [1959]. The south polar field reversed in mid-1957, and the north polar field in November 1958. The sun's general field is now parallel to that of the earth, the opposite of the situation in 1953–1957. For over a year, during the highest activity, opposite rotation poles of the sun thus had the same magnetic polarity. The existence of a large general field (>5 gauss at the poles) has been ruled out, at least for the half-dozen years thus far carefully studied.

The technique of the Babcocks has been extended by A. Severny and his colleagues in the Soviet Union, who have used high spatial resolution and have studied a number of active regions at the tower telescope of the Crimean Astrophysical Observatory. They conclude that there is a tendency for flares to occur in steep magnetic field gradients where the field passes through 'neutral points.' Similar active region field mapping has also been carried out by J. W. Evans, of the Sacramento Peak Observatory, using different techniques and obtaining results that are somewhat different, though they are still provisional. Work on the fine structure of photospheric fields has also been done by H. von Klüber at Cambridge. Howard, Cragg, and Babcock [1959] at Mount Wilson Observatory, in some preliminary studies of photospheric magnetic fields in active regions before and after flares, have found no important changes attributable to the flares.

The latest development in this field is the work of Leighton [1959], at Mount Wilson Observatory, who takes spectroheliograms in the wing of a Zeeman-sensitive line, splits the two states of polarization, and superposes positive and negative pictures so that magnetic fields are shown by deviation from a uniform gray image. This method allows a picture of the whole region to be taken at one time. Leighton finds that the resultant pictures look very much like K-line (Ca II) spectroheliograms—regions of enhanced field occur over the same regions as calcium plages. This result is of great theoretical importance.

Research with high-resolution spectrographs. High-resolution spectrographs coupled with large magnification solar telescopes have produced a wealth of new information about the solar photosphere and chromosphere. McMath and colleagues, for example, have combined the McGregor tower telescope of the McMath-Hulbert Observatory with a new vacuum spectrograph to obtain spectra of the solar disk that reveal the presence of a fine network of Doppler shifts in the Fraunhofer lines originating in the photosphere [McMath, Mohler, and Pierce, 1955]. Study of the line profiles, velocity behavior, and magnetic field structure of this fine-scale photospheric structure is under way at the McMath-Hulbert Observatory, aided by a new high-resolution isophotometer [Mohler and Pierce, 1957]. These disk studies, like the prominence and chromosphere work of Dunn, open up a new area of small-scale phenomena.

The large spectrographs have brought renewed interest in the 'bombs' seen in Hα and first described many years ago by Ellerman; the small chromospheric details, very similar to Ellerman's bombs, which Severny [1957] has named 'moustaches,' have been accorded great attention observationally. These moustaches are very small bright points which produce extremely wide (~10 Å) emission in the Hα line. The most puzzling feature found by Severny is that the moustaches show the much narrower Hα absorption line superimposed upon them, so that they must originate at a level below that corresponding to the center of Hα. Flares, on the other hand, show no such Hα absorption.
Severny believes that the flares are a mass of many small moustaches except that perhaps in flares the overlying layers have been blown away.

Flare spectrum observations have also been made over an extraordinarily large wavelength range, from 3900 to 7200 A, by Jefferies, Smith, and Smith [1959]. They utilized an echelle spectrograph and made single exposures simultaneously, revealing a large number of emission lines of a large disk flare of September 18, 1957. Their analysis reveals the complexity of the flare phenomenon and the variations of excitation conditions with depth in the solar atmosphere, and yet this complex phenomenon occurs often and usually with exactly the same structure.

Balloon solar astronomy. Another new way to study the photosphere has been pioneered by Schwarzschild, who has flown a 12-inch telescope to 80,000 feet altitude, in a balloon, with controls to point it accurately and focus it properly to obtain photographs of granulation. The pictures so obtained are significantly better than those that have been obtained on the ground. They reveal the remarkable structural details of the granulations, which range from 300 to 1800 km in diameter, often appear to be polygonal, and resemble the structures found for 'nonstationary' convection in the laboratory [Schwarzschild, 1959]. It is clear from these experiments that Schwarzschild's method is limited principally by telescopic resolution, and results should improve as better apparatus is flown. Figure 4 shows granules and a sunspot group photographed by Schwarzschild and colleagues in August 1959.

The solar constant. A great deal of interest has been centered recently in the constancy of the solar constant. A new 'planetary method' has given improved results. Its advantages are that the sun's radiation output is measured by comparison of the reflection from the surface of a planet with the background of stars of known brightness in the angular vicinity of the planet in the sky. Because the method is differential and is compared with the stars, the absorption and scatter in the terrestrial atmosphere drop out of the calculations.

Observations taken between 1954 and 1958 by Johnson and Iriarte [1959], of the Lowell Observatory, suggest that a 2.5 per cent increase in the solar radiation has occurred over this time in the violet end of the spectrum where the observations were made. If it was attributed to a change of the temperature of the solar surface, the corresponding increase in the 'solar constant' would be about 2 per cent. The results must still be viewed with caution, however, since they are in conflict with the redetermination of the 'old-method' values of the solar constant from Smithsonian measures by Sterne and Dieter [1958]. These calculations suggest that no variations as large as 0.3 per cent have occurred over the period 1923 to 1952, since there is no fluctuation of so large a value common to the various Smithsonian stations involved in the determination.

Solar radio astronomy. Radio astronomy has provided an enormous volume of new observational data. Particularly outstanding has been the superposition of interferometric and swept frequency methods by Wild, Sheridan, and Trent [1959], of Sydney. These workers have shown that velocities hitherto inferred from the frequency change of the radiation are actual motions of the radiating source. The application of radio-frequency polarimeters has also made great strides, giving testimony to the role of solar atmospheric magnetic fields. Swept frequency solar radio noise patrols, such as that operated by A. Maxwell at the Radio Astronomy Station of Harvard College Observatory in Texas, have made important contributions to the discovery and systematic classification of solar radio phenomena.

The classification of radio noise bursts originally made by Wild has been extended as shown in Table I, adapted from Denisse.

The mechanisms of the production of solar radio noise are still not established. Plasma oscillations seem a likely source of type II and type III bursts. A traveling disturbance is supposed to excite the local plasma frequency of the corona as it travels outward. Synchrotron radiation appears to be the only possible source of the continuum radiations, but no adequate theory has been proposed.

On the other hand, much of the slowly varying solar radiation has been adequately explained by thermal radiation, either by the quiet sun or by active regions in the corona. The so-
called microcondensations at higher frequencies may be due to hot loop prominences forming above the sunspots.

Radio astronomy has also enabled us to investigate the outer corona by studying occultations of the Crab nebula by the outer corona of the sun at meter wavelength. Observations have been made by many workers, including Vitkevich, Hewish, Slee, Boischot, and Denisse. The results are somewhat puzzling in detail, but there is no doubt that the corona extends out to at least 20 solar radii and shows irregularities capable of scattering and even focusing the Crab nebula radio radiation passing through it.

Flare-geomagnetic storm relationships. Much interest has centered lately on the radio properties of flares producing geomagnetic effects. H. Dodson Prince and colleagues at the McMath-Hulbert Observatory and the sun-earth relationships group of the National Bureau of Standards have devoted particular attention to this field [see, for example, Dodson and Hedesman, 1958.] If a solar flare has major burst activity at its earliest phases, well before the radio noise activity that generally accompanies the peak of flare, there appears to be a considerably heightened probability of a sudden-commencement geomagnetic disturbance 1 to 3 days later. Important work on these relations has also been done by Mustel and colleagues in the Soviet
**TABLE 1. Classification of Radio Noise Bursts**

<table>
<thead>
<tr>
<th>Burst Type</th>
<th>Time Duration</th>
<th>Size</th>
<th>Polarization</th>
<th>Wavelengths</th>
<th>Associated Phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Tenths of seconds</td>
<td>?</td>
<td>Circular</td>
<td>Bursts are at meter wavelengths, but associated centers often emit weak continua.</td>
<td>Associated with 'R centers' which are in corona and roughly overlie active regions.</td>
</tr>
<tr>
<td>II</td>
<td>Minutes</td>
<td>?</td>
<td>Usually not strongly polarized</td>
<td>Centimeters to tens of meters: sweep in frequency at (\sim \text{Ma/s}^2)</td>
<td>Exhibit harmonics are associated with flares; are moving sources of (\sim 500 \text{ km/sec in corona; perhaps associated with magnetic storm producing solar corpuscles.} )</td>
</tr>
<tr>
<td>III</td>
<td>Seconds</td>
<td>Irregular</td>
<td>Meters to tens of meters sweep in frequency at (\sim 100 \text{ Mc/s}^2)</td>
<td>Associated with early stages of flares; are probably sources moving at substantial fraction of speed of light; perhaps associated with high-speed proton showers at earth.</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Minutes to hours</td>
<td>(\sim 10^4) km</td>
<td>Often circularly polarized</td>
<td>Continuum from centimeters to tens of meters</td>
<td>Associated with very strong flares, starts (\sim 15 \text{ min after flash phase; perhaps associated with synchrotron emission and cosmic-ray generation; sources sometimes displace in atmosphere at speeds of 100–1000 km/sec; often associated with type II bursts.} )</td>
</tr>
<tr>
<td>V</td>
<td>Minutes</td>
<td>(\sim 50,000) km</td>
<td>Variable</td>
<td>Broad-band continua but enhanced at centimeter wavelengths</td>
<td>Ascending sources of speeds (\sim 3000 \text{ km/sec; often follow type III bursts.} )</td>
</tr>
</tbody>
</table>

There are also other types of solar radio emissions: radio noise storms, slowly varying emissions, U bursts, inverted bursts, etc.

Union and by Sinno and associates in Japan [Sinno and Hakura, 1958]. We must admit, however, that it is still not possible to predict geomagnetic and ionospheric storm occurrences with a large measure of reliability from solar observations alone, except for certain storms of very large, radio-noisy flares.

**Rocket solar research.** Finally, we come to the important observational advances produced by rocket research. The most fundamental ones are the extensions of our knowledge of the ultraviolet solar spectrum down to the 50-A region. Detailed and well-analyzed spectra have been obtained down to about 100 A. Prominent are the resonance lines of Mg II and Si II and the strong absorption doublet of Al I leading to autoionization. The observed spectrum to the short-wave side of 1500 A is dominated by Lyman \(\alpha\), which, according to the excellent observations of the Naval Research Laboratory group under Tousey, appears to be quite broad (\(\sim 0.7 \text{ A}\) and to have a broad self-reversal within which appears a very sharp absorption feature of still greater depth [Purcell and Tousey,
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The resonance lines of He I and II (576 and 304 Å) are also strong, and it has been suggested by Rense that the Lyman α-like helium line at 304 Å may deliver to the terrestrial atmosphere energies of the order of several ergs per square centimeter per second, equaling the energy of Lyman α.

In addition, the resonance lines of higher stages of ionization of abundant light elements are seen, such as O VI, Si III, and C III. These lines presumably originate in the upper solar atmosphere. Because there still is atmospheric absorption present and, further, very few f values are known here, little quantitative analysis is possible, but rapid advances will be made in the next two years.

Viotti and Rense [1959], at the University of Colorado, have obtained rocket spectra of more than 100 solar lines between 1216 and 83.9 Å. These spectra are still under analysis for identification of the many lines present. This region and the one bordering it are of great interest because they include resonance lines of atoms known to be present in the corona. In principle we should soon be able to observe the corona directly against the disk.

Of great interest are the monochromatic photographs of the sun in Lyman α. A crude picture was obtained by Rense’s group in 1957, and a very fine one by Tousey’s group in 1959 [Tousey, 1959]. The picture looks very much like a Ca II spectroheliogram, except that more bright area is seen. It is probably very similar also to a map of Fe XIV coronal line emission and to a map of the regions of the solar photosphere of magnetic field greater than 5 gauss. These facts, if fully confirmed in future work, are of obvious relevance to the theory of active region energy balance.

Important rocket observations have been made by Friedman, Chubb, Kupperian, and co-workers at the Naval Research Laboratory on the soft X-ray flux. Rocket measurements at the October 1958 eclipse showed that the flux of 50-Å X rays continued during totality but the Lyman-α flux disappeared. This finding directly establishes a fact predicted by most coronal theories, namely that the 50-Å radiation comes from the multimillion-degree-temperature regions of the corona well above the solar limb.

The Naval Research Laboratory group has also obtained interesting results on X-ray emission from flares. Despite the difficulty of bringing a rocket to altitude at the precise time of the flare, they have made rocket observations during several flares, the data showing strong enhancement of X rays in the 2- to 10-Å region [Friedman, 1959]. Unfortunately, no conclusive data on Lyman α were obtained. The origin of these X rays is probably nonthermal; the highest stage of ionization observed in the corona is Ca XV, with 814 ev, which produces the yellow line at 5694 Å; at 4 × 10⁶ degrees this produces recombination X rays up to perhaps 2000 ev, or down to 6 Å in wavelength. However, calculation shows the probable flux from a typical coronal condensation to be about 10⁴ lower than the fluxes of 10⁻⁴ erg/cm²/sec observed.

Further, the relation of the flare to the corona has not yet been clearly delineated. At least one large flare was accompanied by the collapse and dissipation of a previously existing coronal condensation [Zirin, 1959]; it could well be that the collapse increases the coronal radiation. In another well-observed case [Waldmeier, 1958], however, little yellow line was observed near a huge flare.

The effect of the X-ray emission in producing SID’s is not obvious. On several occasions the Naval Research Laboratory group observed large X-ray fluxes when no D-layer absorption was apparent, or when the absorption was far past its peak. The role of Lyman α in producing the fadeout has not been fully investigated. Satellite observations are badly needed.

Observation of solar particle emission. The University of Minnesota group headed by Ney and Winckler and Anderson of the State University of Iowa have made a series of remarkable observations of fast protons (100 Mev) occurring after some large flares. The production of these high-energy particles appears to be relatively common, whereas large cosmic-ray production is rare. Clearly, large nonthermal effects must be going on in flares, which accelerate particles that ultimately impinge on the high terrestrial atmosphere. Of course, it is much easier for some hydromagnetic processes to accelerate particles to the Mev range than to the bev cosmic-ray range, but our knowledge of the physics of flares does not explain the detailed mechanism for either.
ANALYTICAL AND THEORETICAL RESULTS

There is a remarkable array of new observational solar data. Important progress has been made toward its interpretation, particularly as regards theories of the nonequilibrium solar atmosphere, in hydromagnetic interpretations of solar corpuscular emission, and in theories of solar radio noise generation.

Theory of a solar atmosphere not in thermodynamic equilibrium. Some of the most important advances have centered in methods that treat the solar atmosphere as a gas outside thermodynamic equilibrium. Since the solar atmosphere is transparent, it is not a hohlraum, and the radiation field is specified by a temperature much different from the kinetic temperature of the medium. Thus the population of atomic states cannot be calculated by means of the Saha equation, but the equilibrium rates of many atomic processes must be laboriously calculated. This procedure was introduced in 1937 by Menzel and others [1945] in a series of papers on physical processes in gaseous nebulae. This approach was not applied to the sun until somewhat later by a number of workers, including Thomas, Athay, Giovanelli, and Jefferies. Although it seems clear that this is the appropriate way to attack the problem, extensive research has revealed the magnitude of the difficulties involved. For example, early treatments of the formation of absorption and emission lines considered the lines as coming essentially from one height in the solar atmosphere and assumed that their structure could be specified by one line-broadening formula. Now attention is directed to the solution of the equation

\[ I(\nu) = \int_0^\infty S_\nu(\tau) e^{-\tau} \, d\tau \]

where \( I \) is the emergent intensity at frequency \( \nu \), \( \tau \) is the 'optical depth,' and \( S \) the so-called 'source function,' which gives the amount of energy contributed by each element \( d\tau \). If we had thermodynamic equilibrium, \( S \) would equal \( B_\nu \), the Planck function. Since we generally do not, \( S \) may have any value less than \( B_\nu \). In particular, it may vary considerably with wavelength across a single spectral line. In the center of an absorption line we do not 'see' nearly so deeply into the sun's atmosphere as in the wings. The main contribution to the integral over \( S \) will come from different regions, and \( S \) will be different in these. Investigations of these problems have been very difficult, but they have already explained a number of phenomena. A major stumbling block is lack of information on transition probabilities and atomic cross sections for the atoms of the atmosphere.

In the field of the chromosphere, application of nonthermodynamic equilibrium methods (often referred to as 'non-LTE' methods) has led to various models by different workers, all of which try to fit the eclipse data. At this point it is difficult to say which fits the data best. It is certain that the chromosphere below 1500 km is cool (<10,000°K), and the chromosphere above 5000 km hot (>30,000°K). As was mentioned above, there is some evidence for the existence of temperature plateaus at specific temperature values in the solar atmosphere (for example, in the work of Athay and Thomas [1956]) with clearly different temperature regimes prevailing at different positions and heights in the atmosphere. But there is no clear agreement about the validity of the different two-temperature or even three-temperature models that have been proposed.

Studies of coronal physics. In the corona the situation is somewhat simpler, as all lines except the resonance lines, which means all lines that fall in the now-observable region of the spectrum, are optically thin, making interpretation easier. Atomic cross sections, which are not well known, represent a major difficulty.

Recent work has resolved the discrepancies between temperatures deduced from Doppler broadening and temperatures deduced from ionization theory based on observation of the line intensities corresponding to different stages of ionization of iron. The former method gave 2,000,000°K; the latter, 700,000°K. Further, the ionization theory predicted that only a few stages of ionization should be seen at once; normally all the stages from Fe X to Fe XV can be detected simultaneously. The ionization cross sections that led to discrepant ionization-theory temperatures were classical ones given by J. J. Thomson in 1909. A recent quantum-mechanical calculation by Schwartz and Zirin [1959] showed that the cross sections are less than one-tenth those given by the Thomson formula. The
reason is that the incident electron is highly accelerated by the large charge of Fe XIV and spends little time near the nucleus, and so matrix elements are very small indeed. The temperature obtained from the ionization theory is now 1,500,000°, in agreement with Doppler measurements. And a broad range of ionization is now possible, so that the different lines appearing simultaneously can be explained. More refined work on these coronal cross sections is needed, however.

A milestone in solar research was the definite identification of the yellow coronal line, λ5694, as the *P₁ → *P₂ transition in Ca XV. This identification had originally been suggested by Edlén in 1942, but doubt had been cast on it for several reasons: (1) its ionization potential of 814 ev was extremely high, whereas some arguments suggested that the regions emitting it should be cooler than the adjacent regions; (2) Waldmeier had discovered another line near by at 5446 A which had similar characteristics but was fainter by a factor of 6 than the yellow line, rather than the 50 to 100 per cent intensity predicted for the *P₁ → *P₂ transition if it was Ca XV; and (3) the theoreticians could not predict wavelengths that could be considered consistent with the observed ones. These difficulties were resolved by several developments. Pecker, Billings, and Roberts [1954] showed that the 5446-A line coincided with a Fraunhofer line in the sky background; when this was allowed for, the intensities of the yellow lines came out appropriately close together. Further, they showed that comparison of the profile of the yellow line in an active region with that of the red and green lines of Fe indicated an element of atomic weight 40. Finally, Rohrlich [1956] and Layzer [1954] recalculated the predicted wavelength, including configuration interaction, and got wavelengths for the two Ca XV lines satisfactorily closer to the observed values.

The Chapman conduction corona. An interesting suggestion was recently made by Chapman [1957], who calculated a spherically symmetric, no-magnetic-field model of the corona heated by conduction. He obtained a corona of very great extent, with temperature of around 2,000,000° K at the earth. He argued that the existence of such a 'supercorona' would account for thermal gradients in the F layer of the ionosphere. The most difficult problem in this model is the heat loss through radiation by heavy atoms in forbidden lines and through collisions with interplanetary dust. It is rather probable, however, when all ionizing mechanisms are considered, that the interplanetary medium is a region in which hydrogen is completely ionized, and at a temperature of at least 10,000°K, though it is not certain that conduction in the corona plays a major role in this heat supply. Convection in the solar atmosphere. The problem of convection in the solar atmosphere, long the object of intensive research, has not come very much nearer solution in recent years and remains one of the key problems. No theory of the heat transport in the unstable 'hydrogen convective zone' just below the surface has been advanced except one based on the Prandtl mixing length. That theory is very sensitive to the mixing length, which happens to be unknown, and it also faces other objections. Without a better theory it is impossible to make a satisfactory model of the solar interior or reasonable theories for heating of the chromosphere and corona. It is further difficult to understand the connection between photospheric granulation and subsurface convection, particularly in view of the recent observations of granulation, or to see how we can explain the cooling of the sunspots by suppression of convection by magnetic fields, as some authors have suggested, when regions of enhanced corona and plage activity coincide with regions of strengthened magnetic fields.

Cosmic rays from the sun. Solar magnetic fields and their relation to observed nonthermal phenomena are of great interest, but the efforts at explanation are still speculative. A great deal of work has been done on propagation of auroral particles and cosmic rays. The February 23, 1956, flare and associated cosmic-ray increase was peculiar in that, although the initial particles came directly from the sun, later on the particle flux was isotropic. Parker has postulated from this that the solar magnetic field is
stretched out radially by corpuscular emission but becomes irregular beyond the earth. The irregularity reflects the cosmic rays back and produces an isotropic flux. The problem of where the magnetic field of a rotating body stops rotating with it is important. Presumably this point is the same as that at which the atmosphere also no longer shares the rotation.

**Thermal processes in prominences.** Some work has been done on the possibility that prominences are formed by condensation from the solar corona under the influence of the magnetic field; also, many workers have given attention to problems of the heating and cooling of flare material and to maintenance of the corona against ‘drainage’ by prominences if the condensation process actually goes on. Coronal material is unstable against cooling, so that, as was first pointed out by Kiepenheuer, the more it cools, the more it radiates. But problems arise because it radiates so slowly that prominences would take very long to form. Investigations have been made by Lüst and Zirin [1960] and by Kleczek [1957] on possible means of increasing the radiation and the rate of prominence formation. The answer probably lies in compression by magnetic fields. It is a very interesting fact that the yellow line often appears high above the sun near the point where the loops are forming, and we have several rather definite observations showing that the yellow line first appears as the loop starts to condense. This phenomenon is also accompanied by increased continuum emission (high density). It therefore looks as though a compression starts the process going and incidentally lets us see the yellow line either because of the temperature rise or the density increase or both.

**Principal Unsolved Problems**

The unsolved problems could be a long list, but we shall confine ourselves to those having the greatest interest and the best prospect of solution. For example, a very important problem is the cause of the solar cycle, but most people think that progress waits on better knowledge of the origin of sunspots themselves. Further, there is a host of problems in allied fields whose solution will greatly advance solar physics, for example, better atomic cross sections, a sound and applicable theory of turbulence, a better knowledge of hydromagnetics and of plasma physics.

First in importance is the problem of observing and describing the atmospheric magnetic fields of the sun. These fields undoubtedly control prominence and flare formation and many other solar processes. Certainly they are also responsible for the guidance, acceleration, and general control of the solar particle emission, including cosmic rays, and the particles that replenish the Van Allen belts. It has recently been discovered that after many solar flares strong proton emission is detected in the high terrestrial atmosphere within the polar cap. These particles travel with perhaps half the velocity of light from sun to earth. The nature of their ejection from the sun and guidance by magnetic fields in the solar atmosphere is crucial. It seems probable that studies of prominence motion fields, coronal structure, and polarization of radio noise are the most promising modes of attack on this problem, although there are other possibilities.

The second important problem is study of the distribution of photospheric magnetic fields and the relationship of such fields to solar flares. Small fractional charges in the energy contained in the magnetic field of an active region could easily explain the entire output of a solar flare, including its radiational and corpuscular emission. Consequently observational and theoretical studies in this area are of highest importance.

A great deal of further work is necessary to explain in detail the acceleration of cosmic rays, the generation of solar γ rays, and the processes involved in the proposed synchrotron radiation in the sun. Extraordinary incidents like the August 22, 1958, and August 22–24, 1959, solar radio noise outbursts, with their large size and strong continuous emission, deserve particular attention. A theory of the mechanism, to be satisfactory, must explain the enormous increases of continuous radio noise emission, the polarization of the radio noise, and the large observed sizes and heights of the radio-noise sources. It also seems clear that γ rays are sometimes generated in such events, as in the August 22, 1958, incident, and that high-speed protons are frequently ejected.

There still remains the resolution of the question of the relative roles played by coronal X
rays and by ultraviolet radiation in producing the radio fadeouts associated with large flares. Straightforward observations from an artificial satellite seem to be called for. It was heartbreaking that the July 16, 1959, satellite firing was unsuccessful, because it contained the necessary experiments to solve this question and was followed in a few hours by an extremely large and geoaactive solar flare. Consequently, an early repeat, and success, are highly to be desired.

Another problem related to solar atmospheric magnetic fields is the close relation of coronal, prominence, and plage activity. The fact that a magnetogram resembles a K-line spectroheliogram, which in turn resembles a coronal green-line map as well as a Lyman-α spectroheliogram, is intriguing. One would think that the magnetic field comes first, since it is hard to picture a coronal condensation producing a magnetic field. Presumably the explanation will bring with it the answer to the whole question of coronal heating, a highly important unsolved problem of solar physics.

The understanding of temperature plateaus and the multitemperature chromospheric structure should be a key to our solution of several problems of the solar atmosphere; it is intriguing that a cloud of gas suspended high above the atmosphere, as in a quiescent prominence, shows much the same spectrum as the low chromosphere. It is further interesting that when a huge surge emerges from the chromosphere it already has the hot spectrum corresponding to >30,000°K. Progress in understanding these phenomena should be highly rewarding.

The equatorial acceleration of the sun's rotation is a problem that has thus far defied solution, and it deserves more specific attention than it is now getting. As Plaskett [1959] has suggested, it may involve a solar thermal gradient 'wind,' but further observational and theoretical studies are needed for confirmation.

Before we can expect to answer the problems of particle production in flares we need much better knowledge of the physical conditions of the flares themselves. The appearance of flares observed in the center of the Hα line and in the wings is still a virtually unexplored field. Yet unnamed solar features that show up on spectroheliograms taken in the wings of strong absorption lines [Mohler and Dodson, 1958] (also unpublished communication) deserve further attention.

Also of high priority is the problem of the flare-corona relationship. It is known that enhancements of the corona, especially of the yellow line, are associated with flares, but it is not definitely known whether the enhancement precedes the flare, as seems more probable, or follows it. To answer this question will necessitate long vigils at the coronagraph, waiting for lucky circumstances. We still know little about the fine structure and the vertical structure of flares. All this is research that requires patient work on the ground with large-scale coronographs capable of giving us large images with very low scattered light.

We have only touched on a few of the many problems of today. Although their number seems to be increasing rapidly, we should be comforted by the thought that we have made great advances in recent years, have solved many difficult problems, and can see pathways of progress for many other solar enigmas which today seem far less mysterious and disconnected than they did 10 to 20 years ago. This is an optimistic omen for the coming decade.

References


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