Solar Radiation in the Far Ultraviolet and some Related Geophysical Phenomena

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ABSTRACT. It has been known for a long time that apart from the visible and heat radiations of photospheric origin there are other radiations which emanate from the sun and produce notable effects on the earth's atmosphere and on the surface of our planet. Some of these effects, such as the annual means of geomagnetic variations, the frequencies of polar lights, the variations in the brightness of the night sky, the water levels of the different lakes and inland seas, the thickness of the annual rings of trees etc., exhibit a remarkable parallelism with sunspot activity. The object of the present article is not to deal with all these various effects ; we shall restrict our considerations mainly to the effects of solar ultraviolet radiation on the outer atmosphere of the earth and on the variations of the geomagnetic field, our principal aim being to derive, from available terrestrial observations, conclusions regarding the nature and the intensity of the ultraviolet radiation emanating from the sun in so far as they seem justifiable on the basis of theoretical considerations and plausible hypotheses.

1. Methods of studying solar ultraviolet

Because of the absorption by ozone at altitudes approximately between 20 km and 50 km in the earth's atmosphere it is impossible at the earth's surface to study directly the spectra of astronomical bodies at wavelengths shorter than about 2900 Å. Nevertheless, solar ultraviolet radiation in the interval 2900 Å can be studied by the following methods—

I. Direct measurement in the upper atmosphere
II. Indirect determination through effects on bodies of the solar system
III. Indirect determination through effects on the ionosphere
IV. Indirect determination from the spectrum of the night sky
V. Indirect determination from geomagnetic field variations

2. Direct measurement in the upper atmosphere

Although in the past some attempts have been made to study the far ultraviolet solar spectrum by means of spectrographs carried into the upper atmosphere by sounding balloons, it has not been possible to reach heights above the ozone layer. One of the most spectacular scientific advances in the years following World War II has been the application of the German V2 rocket and the U. S. Aerobee and Viking rockets to the exploration of the extreme ultraviolet spectrum of the sun. In these remarkable experiments both slitless spectrographs and spectrographs with slits have been used and various ingenious devices have been employed for admitting sunlight into the spectrographs during the flights of the rockets. The dispersing members of the spectrographs have been 15,000 line-per-inch concave gratings of 40 or 50 cm radius of curvature. In this way some very fine photographs of the solar ultraviolet spectrum down to 1900Å have been secured and analysed by Hopfield, Clearman, Oberly, Durand, Tousey, Johnson and others. Below 1900 Å it had not been possible until the end of 1952 to observe the solar spectrum by spectroscopic methods, because of the difficulties of giving long exposures during rocket flights. In

December 1952 the region 1200—2600 Å of the solar spectrum was, however, photographed from an Aerobee rocket (Rense 1953); and on this spectrogram the Lα line (1216Å of hydrogen was clearly visible as an emission line with a width of 1-2 Å and intensity of 0.1-0.5 erg cm^{-2} sec^{-1}.

On the other hand, by the use of thermoluminescent phosphors and ultraviolet photon counters Watanabe, Friedman, Lichtman and Byram (1951) have been able to study the extreme ultraviolet wavelengths in sunlight down to 910 Å, below which nitrogen and oxygen absorption becomes strong at the altitudes of observation. Even the emission of soft X-rays (λ = about 8 Å) by the sun has been detected first by Burnight (1949) through the use of photographic plates exposed through beryllium windows. This important discovery has been confirmed later by Burnight (1952), Friedman, Lichtman and Byram (1951) with the help of photon counters and by means of thermoluminescent phosphors flown by Tousey, Purcell and Watanabe (1951). In all probability this constitutes only a small part of the X-ray spectrum of the sun.

The most characteristic feature of the solar spectrum below 3000 Å which emerges from these rocket observations is the great number of unresolved blends of the multiples of FeI and FeII. Another noteworthy feature is the occurrence of the strong absorption lines of MgII at 2802.7 and 2795 Å which cover a range considerably greater than 50Å. This doublet is scarcely resolved, but the position of each line is marked by intense central emissions analogous to the H_2 and K_2 emissions of CaII, which are striking features of the H and K lines in the accessible part of the solar spectrum, particularly over and around spots. Like the H_2 and K_2 lines these emission components of the MgII doublet are probably emitted by a high-temperature region high in the chromosphere even in the absence of any unusual activity. As far as can be judged from the rocket observations available up to 1953 the intensity of the solar spectrum in the interval λ3400—λ2200 falls increasingly below the 6000°K curve. Below 2200 Å there are no measurements, but at 2200 Å the intensity has approximately the value corresponding to 4900°K. But the energy density between 1050 and 910Å as estimated from phosphors flown with rockets is between 10 and 100 times as great as that of black radiation at 6000°K.

3. Indirect determination through effects on bodies of the solar system

The direct measurements, which have become possible through the tremendous developments in rocket propulsion in recent years, provide unquestionably the most convincing information we yet have on the ultraviolet spectrum of the sun ; but up till now this information is rather fragmentary and it is by no means certain that further work will not bring about far-reaching changes in our knowledge of the hitherto inaccessible part of the solar spectrum. In the present state of affairs, indirect determinations of the solar ultraviolet spectrum have not, therefore, lost their importance. One such interesting indirect method is the study of the effects of solar ultraviolet radiation on the bodies of the solar system other than the earth. For many years now efforts have been made to correlate the variations in the brightness of planets and satellites with the solar constant, notably by Guthnick (1918), Bernheimer (1924), Stebbins (1927) and others. A recent analysis by Becker (1949) indicates that the brightness of Saturn and Uranus shows minima, the most pronounced of these minima coinciding with the minima of solar activity. As all the planetary bodies concerned in these studies have atmospheres it is not possible to say precisely what part the solar ultraviolet plays in the observed correlations. Recent observations made with a coronagraph by Lyot and Dollfus (1949) have however, shown that the moon is completely devoid of an atmosphere; at any rate, density of the lunar atmosphere at the surface must be less than 10^{-8} of that of the earth. The solid surface of the moon must, therefore, be exposed to the ultraviolet radiation from the sun, and any real variations in the luminescence of the lunar surface might be attributed to excitation by variable solar ultraviolet radiation. As a matter of fact, Link (1951) has found from an analysis of the photoelectric measures of the brightness of the moon's surface by Rougier that there exists a correlation between the variations in the brightness of the moon and the variations of the solar constant. It may be noted in this context that according to Abbot (1942) a small increase in the solar constant may involve a large increase in the solar ultraviolet; in fact, Abbot estimates that the ratio of the increase in ultraviolet intensity to the increase in solar constant is about 6 at 3500Å.

Variations in the brightness of comets have also been attributed by some astronomers to variations in the intensity of solar ultraviolet radiation. In the case of some comets, whose orbits have small eccentricity such as the Schwassmann-Wachmann comet 1925-II, one would expect the brightness to be sensibly constant. But Van Biesbroeck (1934) found that the Schwassmann-Wachmann comet showed sudden increases of brightness by as much as 5 magnitudes. Richter (1941, 1949) attributes these sudden increases in brightness to solar flares which are known to produce large increases in the ultraviolet output as well as increases in corpuscular emission. It is impossible to decide whether the observed sudden increases in the brightness of comets are due solely to increases in the solar ultraviolet wave radiation or to solar corpuscular streams or to both. But some astronomers (Richter, Beyer) who have studied a number of comets from this point of view seem to incline to the view that it is rather the ultraviolet wave radiation which is responsible for the observed effects.

The many attempts that have been made so far to study indirectly the ultraviolet spectrum of the sun through its effects on the members of the solar system other than the earth, suggestive though they undoubtedly are, cannot at present be said to have led to conclusive or positive results.

4. Indirect determination through effects on the ionosphere

One of the most fruitful indirect methods of deducing the nature of the far ultraviolet spectrum of the sun is based on the detailed study of the terrestrial ionosphere. It is now well established that in the middle and equatorial latitudes the ionized layers, D, E, F_1 and F_2 of the earth's outer atmosphere which are detected by radioelectric soundings are produced essentially by the action of an ultraviolet wave radiation from the sun. The ionizing action of the solar corpuscular radiation is restricted to the polar caps of the earth, although the corpuscular radiation does affect the ionosphere in the lower latitudes indirectly through the disturbances it produces in the geomagnetic field in the upper atmosphere. Even though it has been impossible until very recently to study directly the sun's ultraviolet wave radiation reaching the outermost layers of the earth's atmosphere, it has been possible to determine the state of ionization and dissociation, the temperature and even to some extent the chemical composition of these layers through physical experiments, and from these to deduce fairly reliable conclusions concerning the nature and the intensity of solar ultraviolet radiation.

The ionosphere is characterised by the number N of electrified particles—electrons and ions —per unit volume. The number N can be measured by means of electromagnetic waves which can be reflected by a given ionospheric layer. According to the echo method due to Breit and Tuve a radio transmitter sends up a short wave-train and a receiver in the immediate neighbourhood receives the echo from the ionosphere and the direct signal. The time-difference between the direct signal and the ionospheric echo gives for each frequency radiated (f) the height at which the reflection takes place. The principle of this experiment is very simple : According to the theory of dispersion, the refractive index n in an ionized gas is given by

$$n^2=1-\frac{\varepsilon^2}{\pi m}\cdot\frac{N}{f^2}$$

where ε is the charge, m the mass of the charged particle and f the frequency of the incident wave expressed in cycles/sec. If the incidence is vertical, the reflection takes place at the point where $n=0$. In that case $N=\frac{\pi m}{\varepsilon^2}f^2$. Of particular interest is the critical frequency f_0 which is reflected by a given ionospheric layer; wavelengths shorter than this pass through the ionized layer concerned and are lost in interstellar space. This reflection is actually conditioned by the electrons and not by the positively or negatively charged ions, as is to be expected from the large mobility and smaller mass of the electrons compared to ions. This is also confirmed by the observational fact that the reflected wave is split up into an ordinary and an extraordinary component due to the influence of the earth's magnetic field and this splitting corresponds to the ratio ε/m for the electron. This critical frequency, therefore, gives the maximum electron concentration.

$$N_\varepsilon=\frac{\pi m}{\varepsilon^2}\cdot f_0^2=1.24\times10^{-8}.f_0^2\ldots(1)$$

From observations of the critical frequency (f_0) and the height (h') at which the reflection takes place, it is possible to draw several important conclusions with the help of some reasonable hypotheses. For example, we may assume, as in Chapman's classical theory (1931), that the ionospheric layer concerned is produced by the monochromatic photo-ionization (through solar ultra-violet radiation) of a single constituent distributed in the atmosphere according to the barometric formula with a constant scale height H (*i.e.*, an isothermal atmosphere). Now, all available spectroscopic evidence points to the conclusion that nitrogen and oxygen are the predominant constituents of the earth's atmosphere in the ionospheric levels. The proportion of molecular oxygen decreases in the stratosphere from about 20 km upwards and the dissociation of molecular oxygen into atomic oxygen increases with height so that the proportion of atomic oxygen increases upwards relatively to molecular nitrogen, which is not easily dissociated by ultraviolet light Photoionization involves the removal of an electron from the O_2 and N_2 molecules and from the O atoms. Some of the electrons thus set free may attach themselves to the molecules of O_2 and to O atoms and form negative ions; others may disappear through recombination with positive ions. An equilibrium state can be attained between the rate of ion production and the rate of ion destruction. In the state of equilibrium the following relations must hold :

$$\frac{dN_\varepsilon}{dt}=I-\alpha N^+N_\varepsilon-\beta N_0N_\varepsilon$$

$$\frac{dN^+}{dt}=I-\alpha N^+N_\varepsilon-\gamma N^+N^-$$

$$\frac{dN^-}{dt}=\beta N_0N_\varepsilon-\gamma N^+N^-$$

$$N^+=N_\varepsilon+N^-$$

In the above relations N_ε=number of free electrons per unit volume, N^+= number of positive ions, N^- =number of negative ions, N_0 = number of neutral molecules and atoms, I = number of charge-carriers produced per unit time and unit volume,

α = coefficient of direct recombination of electrons and ions, β = coefficient of attachment of electrons to neutral particles and γ = coefficient of recombination for positive and negative ions. In the equilibrium state electrons can disappear only through direct recombination with positive ions, the loss of electrons through attachments to neutral particles being always of short durations and therefore of little importance. Accordingly we can put $\beta = 0$, which implies that $N^- = 0$ and consequently $\gamma = 0$ and $N^+ = N_\varepsilon$. Thus we are left with only one eqation

$$\frac{dN_\varepsilon}{dt} = I - \alpha N_\varepsilon^2$$

When the steady state is attained $\left(\frac{dN_\varepsilon}{dt} = 0\right)$, this equation becomes simply

$$I = \alpha N_\varepsilon^2 \qquad \ldots(2)$$

Now, I being proportional to the ionizing radiation of the sun must depend upon the sun's zenith distance χ and upon the intensity S of ultraviolet radiation in the ionospheric layer concerned. Then denoting the intensity of such radiation outside the atmosphere by S_∞ and writing I_0 for I when the sun is overhead ($\chi = 0$), we have according to Chapman's theory

$$I_0 = S_\infty / e.H \text{ and } I = I_0 \cos\chi \quad ..(3)$$

where e = base of Naperian logarithms. Therefore, from (1), (2) and (3) the intensity of the ionizing solar radiation, expressed as the number of quanta arriving at the outer limit of the earth's atmosphere per second and per cm^2, for overhead sun is

$$S_\infty = e.\ H.\ \alpha\, N_\varepsilon^2$$
$$= e.H.\ \alpha.\ (1.24\times10^{-8})^2 \cdot f_0^4 \quad \ldots\ldots(4)$$

Thus the intensity of solar ultraviolet radiation at the outer limit of the earth's atmosphere could be accurately calculated with the help of (4), provided we had a precise knowledge of the recombination coefficient α and of the number of absorbing particles per unit volume. Unfortunately, the available theoretical estimates of α are very uncertain; and the number of absorbing molecules or atoms per unit volume at heights of the order of 150 km and above is uncertain by a factor of at least 10. The only practicable procedure, therefore, is to estimate the intensity of the ultraviolet radiation, as Kiepenheuer (1945) has done, by making use of only quantities that have been determined by direct observation. A total solar eclipse offers the possibility of determining observationally the "effective coefficient of recombination" α'. During the eclipse of 1 October 1940 Higgs found the following values for the three layers

E-layer : $\alpha' = 1{\cdot}7 \times 10^{-8}$ cc/sec
F_1- layer : $\alpha' = 2{\cdot}4 \times 10^{-8}$ cc/sec
F_2-layer : $\alpha' = 4 \times 10^{-11}$ cc/sec

It has been found that when the ionizing radiation from the sun is suddenly cut out during an eclipse, the electron densities in the E and F_1 layers show a marked fall only after a time of the order of 20 seconds and 100 seconds respectively. This implies that in order to maintain the observed steady state during these intervals ($\Delta\tau$) the same number of fresh electrons must be produced as are lost through recombination. In other words

$$I_0 = S_\infty / e.H = N_\varepsilon / \Delta\tau$$
$$\text{or } S_\infty = \frac{eH.N_\varepsilon}{\Delta\tau} \qquad \ldots(5)$$

In the F_2 layer there is no equilibrium between S_∞ and the number of electrons; however, one obtains the right order of intensity for the ionizing radiation if one assumes that the measured N_ε is produced in the interval $\Delta\tau = 10^4$ seconds. From such considerations Kiepenheuer has estimated the intensities of the solar ultraviolet radiations effective in producing the E, F_1 and F_2 layers. These are collected in Table 1, column 6.

In the above estimates the elementary processes responsible for the production of ions in the different ionospheric layers

Table 1

1	2	3	4	5	6	7	8
Layer	Average height (km)	Spectral Range (Å)	Composition	$N\varepsilon/cm^3$	Radiation required for ionization in quanta/cm² /sec	Black radiation at 5780° in quanta/cm² /sec	Ratio of column 6 to column 7= ultraviolet excess
E	120	744-661	N_2, O_2, O	10^6	10^{11}	2.7×10^5	3×10^5
F_1	220	661	N_2, O ?	10^6	2×10^9	9.0×10^3	2×10^5
F_2	300	910-744	N_2, N, O	10^7	4×10^{10}	5.5×10^7	7×10^2

have been supposed to be the same as considered by Bhar (1938) namely :

E-layer : $O_2+h\nu = \overset{+}{O_2}+\varepsilon$; $\lambda=744\text{-}661\text{Å}$

F_1-layer : $N_2+h\nu = \overset{+}{N_2}+\varepsilon$; $\lambda=661\text{Å}$

F_2-layer : $O+h\nu = \overset{+}{O}+\varepsilon$; $\lambda=910\text{-}744\text{Å}$

It is evident from column 8 of Table 1 that if solar ultraviolet wave radiation is the agency responsible for the formation of the ionospheric layers, then the sun must emit far more energy in the remote ultraviolet than a blackbody at 5780°. With the help of the data of a large number of ionospheric stations Allen (1948) has studied the variation of the critical frequency with the solar cycle. From this, by using a formula analogous to (4) above, he determines the number of ionizing quanta required for the formation of the different ionospheric layers in the absence of solar activities (relative sunspot number $R=0$). The intensities of the ionizing radiations in the range $\lambda < 1000$ Å thus obtained by Allen for the E, F_1 and F_2 layers are :

$S_E = 5 \times 10^8$ quanta/sec/cm² of atmosphere

$S_{F_1}=1.9 \times 10^9$ quanta/sec/cm² of atmosphere

$S_{F_2}=2.3 \times 10^9$ quanta/sec/cm² of atmosphere

These estimates are similar to the earlier ones due to Kiepenheuer. Even higher (10^6) ultraviolet excess was considered by Saha (1937) to be necessary in order to explain the ionization of molecular nitrogen by ultraviolet light. However, more recent estimates of the recombination coefficient (Bates and Massey, 1946) suggest that the ultraviolet excess given in Table 1 is probably too large; and Woolley (1946) has even concluded that the observed electron densities may be accounted for without requiring an ultraviolet excess if the effective recombination coefficient in the F_2 region is 10^{-11}. It may be mentioned that Woolley supposes that the E region is formed by the ionization of molecular oxygen and the F_2 region by the ionization of atomic oxygen, but that the electrons forming the F_1 region are provided by metastable N_2 are by NO. However, as has been mentioned earlier in this article, recent measurements of the far ultraviolet spectrum of the sun by means of rocket flights show that there is no ultraviolet excess down to about 1040 Å, but for $\lambda <$ 1040 Å an ultraviolet excess begins to develop. It is just the spectral region below 1040Å which is of the highest importance for the understanding of the E, F_1 and F_2 layers of the ionosphere. In the D region (altitude=75 to 100 km) the gas density and, therefore, the collision frequency are very much higher than in the three higher layers. This layer, therefore, does not reflect radio waves (except very long waves of wavelengths greater than 10000 *m*), but causes a diminution in the strength of the waves reflected by the higher layers through absorption during their passage across it in both directions. The radiation responsible for the formation of this layer is probably the wavelength range $\lambda\lambda$ 1000-1300 of photospheric origin and the chromospheric $L\alpha$ line (Nicolet 1949, Strantz 1950, Bates and Seaton 1950), the elementary process of ion production being the ionization of O_2.

So far as present theoretical indications go the sun does not seem to behave like a black body at about 6000° K. According to Bates (1949) the ultraviolet flux required for the formation of the F_2 layer through the photo-ionization of O is twice the flux radiated by a black body at 6000°. Also Giovanelli (1949) calculates that the chromosphere emits $2 \cdot 10^4$ times as much energy in the Lyman continuum ($\lambda \leqslant 912$ Å) as a black body at 6000°. Solar radiation of $\lambda < 910$Å is, therefore, not of photospheric origin, but can be emitted only by the outer layers, namely the chromosphere and the corona, which are now believed to be at very much higher temperatures than the photosphere. Kiepenheuer has made a detailed statistical study of the relationship between the ionizing radiation for the E, F_1 and F_2 layers and the sunspot relative numbers. He finds that the intensities of the ionizing radiation can be expressed by the following linear relationships.

$$J_E = 44\cdot4 + 0\cdot09\ R_{27} + 0\cdot22 R_3$$

$$J_{F_1} = 444 + 1\cdot58\ R_{27} + 2\cdot99 R_3$$

$$J_{F_2} = 622 + 4\cdot10\ R_{27} + 15\cdot4\ R_3$$

Here J_E, J_{F_1} and J_{F_2} are the intensities (expressed in arbitrary units) for the three ionospheric layers, R_{27} and R_3 are respectively the running 27-day mean and the 3-day mean of the Zürich relative sunspot numbers. Accordingly, the intensity has three components of which the first is independent of the sunspot cycle and is emitted uniformly by the whole solar disk. The source of this component is probably the hot innermost part of the corona as well as the chromospheric spicules which emit a continuum to the shortwave side of the head of the Lyman series of hydrogen at 912 Å. The second component has its origin in disturbed regions of the inner-corona which are long-lived and are activated to increased emission through sunspot activity. The third component is most closely correlated with spot regions and originates presumably in chromospheric faculae which always accompany sunspots. From measurements in the visible range of their spectrum the chromospheric faculae around spots appear to have a temperature of about 8000° giving an ultraviolet excess of the order of 10^6 at 800 Å. They emit the longer wavelenghts which are responsible for the ionization of the F_2 layer. The F_1 and E regions require shorter wavelengths which can originate only in the corona which, for wavelengths shorter than 750 Å, has a constant brightness of about 10^5 times that of the photosphere.

Up till now we have been considering the formation of the principle ionospheric layers through the ionizing action of the far ultraviolet wave radiation from the sun under normal conditions. There is, however, a type of ionospheric disturbance commonly called "Dellinger fade-out" which is caused by the action of sudden bursts of ultraviolet light from restricted and disturbed regions of the sun's surface. These ionospheric disturbances consist in the sudden disappearance of short waves transmitted by reflection from the E and F layers causing a complete or nearly complete breakdown of shortwave radio propagation lasting for a few minutes to nearly two hours. From systematic solar and radio observations made during the last 20 years or so it is evident that these fade-outs are synchronous (with an uncertainty of ±5 min) with chromospheric erruptions or flares and happen simultaneously over the whole of the sunlit hemisphere; the effect is however, most pronounced over that region of the earth where the sun is exactly at the zenith. The cause of the phenomenon is obviously an increase in the ultraviolet light emitted by the flare region which does not produce any marked change in the ionization of the F_2, F_1 and E regions, but causes a very pronounced increase in $N\varepsilon$ in the D layer further below. This radiation must, therefore, lie in a spectral region to which the earth's outer atmosphere is almost entirely transparent. Actually there is a gap in the absorption spectrum of the atmosphere in the region of 1200 Å ; this corresponds with the L_α line (1215·7 Å) of hydrogen which is the principle constituent of the sun's atmosphere. It is, therefore, natural to suppose that during an intense solar flare there is a marked enhancement of the L_α. emission which is effective in increasing the electron concentration and consequently the absorption of electromagnetic radiation in the D layer. The weak, but characteristic disturbance of the geomagnetic field, known as "Crochet", which appears on magnetic traces simultaneously with the optical observation of the solar flare, is probably to be attributed to the enhancement of the $L\alpha$ radiation and its effect upon the D layer and the lowest part of the E layer. From observations of solar flares it is well known that during flares the H_α line appears in emission and with very considerable brightness; this has generally led to the inference that the L_α line must also be enormously bright during flares. Now, it is found that a solar flare is accompanied by the phenomenon of sudden decrease in the phase difference between the ground wave and the sky wave in very long wave reception (Straker and Bracewell, 1949). From observations of a large number of flares Ellison (1950, 1953) finds that this phase anomaly caused by flares continues even after the emission of H_α has ceased. This has made him consider that the ionizing radiation responsible for the fade-out is perhaps not the L_α line, but may well be the helium series and its continuum at 584 Å. There is also the possibility that the emission of high energy corpuscles during flares may prolong the ionization of the D layer. It may be of interest to mention in this context that Woolley (1946) has contended, from theoretical considerations, that the fact that H_α is bright during flares does not imply that the L_α line must necessarily be intensely bright. On the other hand, Siedentopf (1948) and Schklovsky (1949) have suggested that the perturbations of the D layer are due to soft X-rays ($\lambda \sim 1$Å) of coronal origin, while Vassy and Mme Vassy (1947) claim that the enormous increase in $N\varepsilon$ (D) during solar flares is due to the enhancement of the metallic lines (particularly Fe^+) normally emitted by the chromosphere. It is worth noting here that M. and Mme Vassy attribute the formation of the D layer to the ionization of sodium ($Na + h\nu = Na^+ + \varepsilon$) by radiation of wavelength $\lambda = 2415$ Å; Bates and Seaton (1950) have, however, contended that the sodium content of the upper atmosphere is insufficient to explain the ionization of the D layer.

5. Indirect determination from the spectrum of the night sky

A detailed analysis of the light from the night sky provides an important means of studying the phenomena occurring in the highest regions of the earth's atmosphere. By "night sky light" we here understand of course the light received from the moonless and cloud-free sky; about half of this light originates from astronomical objects,—stars, galactic nebulae, zodiacal light and micrometeors—, while the other half is the proper "earth light" emitted by the constituents of our atmospehere in the form of line and band spectra. The radiations that can be said at present to have been definitely identified in the spectrum of the earth light are the three forbidden lines of OI at 5577·35 Å, 6300·23Å and 6363·88 Å the doublet of NaI at 5889·95 Å and 5895·92Å the atmospheric bands of O_2 at 8630 Å and 8660 Å the Meinel bands of OH extending from the infrared to the visible and the negative bands of N_2^+ in the blue-violet region. Very recently the forbidden line of NI at 5199 Å has also been detected in the spectrum of the twilight sky thereby establishing that atomic nitrogen is present in the upper atomosphere. It has also been claimed by certain workers that the night sky spectrum contains the bands of NO, CN, CH and H_2O, but these claims cannot yet be regarded as definitely proved. The Vegard-Kaplan bands of N_2 and the Herzberg bands of O_2 are present in the night sky spectrum, but their properties are yet not quite completely known.

The physical process responsible for the luminescence of the night sky, according to most current theories, is the emission of radiation as the result of recombination ; during the day solar radiation supplies the energy required for the dissociation and ionization of molecules and atoms and at night the process is reversed and this energy is given out by the concerned molecules and atoms in the form of line and band spectra. As the gas density and the collision frequency are high in the lower levels, this recombination process can occur only in the higher levels of the atomosphere. Also it is evident that the emission of the forbidden lines of OI can take place with sufficient intensity only in those tenuous regions of the ionosphere where the collision interval is either 0·5 sec. (*i.e.*, mean life in $1S_0$ level) or 100 sec. (*i.e.*, mean life in the $1D_2$ level). In other words, the altitude of emission of the forbidden OI lines (and also of the forbidden bands of N_2) ought to be the F_2 layer. However, the available observational values of the altitude of emission are far from being concordant and it does not at present seem possible to draw any definitive conclusions on this point. The position is equally indefinite in respect of the height of the layer from which the D-lines of sodium are emitted, although on the whole the level of emission for the D-line appears to be lower than that for the green line of oxygen.

The luminescence of the night sky shows not only a diurnal variation but also an annual variation (Rayleigh, Spencer Jones, Dufay 1935, 1942). It shows in addition a slow variation which appears to be correlated with the sunspot cycle. Furthermore, the intensity of the 5577 Å line of oxygen as well as the Vegard-Kaplan bands exhibits a remarkable tendency to follow the 27-day synodic period of the sun, but the red line of oxygen at 6300 Å and especially the D-lines of sodium are far more indifferent to solar activity (Dufay 1948). Taken by and large, the luminescence of the night sky appears to consist of an irregularly varying part and a comparatively steady part. The first depends upon the magnetic latitude of the place of observation and generally agrees in its fluctuations with other phenomena which are reliably known to be caused by the corpuscular emissions from the sun. The quasi-steady part on the other hand arises from the ultraviolet wave radiation of the sun which is spent in dissociating and ionizing the constituents of the earth's outer atmosphere during the day and is released during the night as a result of recombination. The spectroscopic examination of the spectrum of the night sky is therefore one method of studying the composition and electrical state of the highest regions of the atmosphere while electromagnetic sounding is another. The spectroscopic method is simpler and, in some ways, capable of giving a good deal more of detailed information regarding the nature of the constituents of the upper atmosphere than the electromagnetic method but it is a great deal more laborious. The frequencies of solar ultraviolet radiation, required for the excitation of the spectrum of the night sky are in perfect agreement with those required for the formation of the ionospheric layers. During the day, through photo-dissociation of molecular oxygen (due to absorption of light of wavelength ($\lambda < 1750$ Å) atomic oxygen is formed and the O atoms are ionized to O^+ ions by the action of light of wavelength $\lambda < 910$ Å., which leads to the formation of the F_2 layer. Similarly the F_1 and E layers are formed through the photo-ionization of N_2 and O_2 respectively due to the absorption of solar radiation of wavelength $\lambda < 661$ Å and $\lambda = 744$-661 Å. At night the dissociated and ionized constituents react upon each other and return to their original states ; this they can do by giving up the energy absorbed (from sunlight) in the form of line and band spectra which constitute the night sky spectrum. It would, therefore, be natural to expect a correlation between the brightness of the night sky and the electron concentration in the ionospheric layers. In fact, such a correlation between the electron concentration in the F_2 layer and night sky brightness has been found by Hechtel. The correlation is, however, weak ; but considering the existence of several disturbing factors this is not surprising. The energy emitted by the night sky is also consistent with the intensity of ultraviolet light necessary for the formation of the ionosphere; for instance, the average number of oxygen atoms per cm^2 in the F_2 layer produced by solar ultraviolet radiation is approximately 10^{16} and according to Rayleigh's measurement of the absolute intensity of the 5577 Å line of OI only 1.8×10^8 oxygen atoms perform the $1S_0$–$1D_2$ transition per second above every cm^2 of the earth's surface.

6. Indirect determination from geomagnetic field variations

It is well known that the three elements of the geomagnetic field are perpetually changing. It has, however, been found from the systematic records made with magnetographs at some 40 observatories scattered over the earth that the magnetic variations can be classified into two principal types, namely (a) the periodic variations connected with the solar and lunar days and (b) the irregular and sporadic variations including the so-called magnetic storms. There is little doubt that the irregular variations are almost entirely connected with the corpuscular streams emitted by the sun which under certain circumstances penetrate into the earth's atmosphere causing the phenomena of aurorae. The regular and periodic variations of the geomagnetic field have been studied in great detail from the mathematical and statistical standpoints by Chapman and Bartels, and from their work it is conclusively established that these periodic variations are ultimately due to the ultraviolet wave radiations from the sun. The connection between the semi-diurnal magnetic variation and the intensity of solar ultraviolet light is explained by the so-called Dynamo Theory originally proposed by Balfour Stewart (1882), but greatly developed in recent years by Chapman and his co-workers. As has been discussed earlier in this article, the conductivity of the ionosphere is a measure of the intensity of ultraviolet light of the sun. Under the action of tidal-forces and temperature variations the conducting layers of the ionosphere execute movements across the permanent magnetic field of the earth and therefore electric currents develop inside these layers. These currents are naturally accompanied by magnetic fields which become superposed on the permanent geomagnetic field and appear as diurnal variations. Now, the amplitude of diurnal variation of the geomagnetic field must depend upon the conductivity of the ionosphere which is caused by solar ultraviolet light. Consequently from the nature and magnitude of the diurnal magnetic variations it is possible, though by a complicated procedure, to draw conclusions concerning the ultraviolet light involved in the process. For an investigation of this kind it is naturally necessary to work with the data of magnetic observatories in the neighbourhood of the magnetic equator where the complications arising from the electrically charged corpuscles are least. Such an investigation has in fact been made by Bartels using the amplitudes of diurnal variations of *H* at the Huancayo Observatory (12°s, 75°w, 0°·6 south of the geomagnetic equator) for days with international character figures $C<1\cdot2$ during the period 1922—1939; he has derived the intensities of the ultraviolet light from the observed diurnal variations of the *H* field and compared them with the relative sunspot numbers. Bartels finds a very close correlation between the amplitude of diurnal variation in *H* and the relative sunspot numbers, the correlation coefficient being more than 0·9. He has also determined values for corpuscular radiations using the disturbances in the horizontal force. He finds a much weaker correlation between the corpuscular radiation and relative sunspot numbers, the coefficient of correlation in this case being only $+0\cdot724$.

In this cursory survey I have aimed at giving the non-specialist scientist merely a general impression rather than an extensive catalogue of what is currently known in this fascinating branch of research on the border-line between astrophysics and geophysics. A great deal of our present knowledge in this field is admittedly in the controversial stage. But it cannot be doubted that increasing definiteness will be achieved by applying to the outer atmosphere of the earth the theoretical procedures of research developed in pure astrophysics ; at the same time the information more directly gathered about the highest regions of our atmosphere will certainly help the understanding of many unsolved problems of stellar atmospheres.

In the preparation of this brief account I have drawn freely from a large number of original papers as well as from books like Chapman and Bartels' *Geomagnetism* and various reports such as those published under the auspices of the C. N. R. S. (France), the Fiat Review of German Science (Germany) and the Gassiot Committee of the Royal Society (England). The list of references appended to this article does not pretend to be exhaustive, nor even to include all the most important contributions.

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