EXCITATION PROCESSES OF THE AURORAL SPECTRUM

By S. N. Ghosh.

(Communicated by Prof. S. K. Mitra, F.N.I.)

(*Received May 29 ; read August 30, 1946.*)

Abstract.

The paper discusses in detail the hypothesis recently offered by Mitra (1946) regarding the mode of excitation of the auroral spectrum. From the many common features of the night sky and of the auroral spectra, Mitra concluded that there must be common factors in the modes of their excitation and extended his theory of the emission of the former (1943*a*) for the explanation of the latter.

The origins of the similarities and of the differences in the two spectra are discussed in the paper and are as follows:—

The first negative bands of N_2^+ are excited by direct bombardment of N_2 molecules by fast charged particles.

The excitation process of the first positive bands and of the atomic oxygen lines is the same as that for the night spectrum, namely, electron exchange between O^- and N_2^+ (Mitra, 1943*a*).

The difference in the intensity of the Vegard-Kaplan bands in the auroral spectrum and in the night sky (weak in the former and strong in the latter) is traced to the difference in the heights at which the two lights originate.

Attention is drawn to the close similarities of the spectrum of sunlit aurora and of spectrum of night sky during twilight when the rays of the rising or the setting sun touch the high atmosphere. It is shown that the causes of enhancement of red auroral lines and of the negative bands of N_2^+ are the same.

The so-called *Height Effect* in which the intensity of the red lines relative to that of the green line is found to increase and the intensity of the green line decreases with height more rapidly than that of negative bands of N_2^+ is explained as due to decrease of collisional frequency with height and of the longer life of ^1D state than that of ^1S state.

1. Introduction.

The auroral spectrum consists mainly of band systems due to ionised and neutral N_2 molecule and certain forbidden lines of atomic oxygen. Besides these, there are probably present lines of ionised and neutral nitrogen atom and also of ionised atomic oxygen. The identification of these is still somewhat doubtful. Many attempts have been made, but not convincingly, to explain the special features of the auroral spectrum, the intensity distribution for example, why the observed lines and bands in particular and not others are excited.

Vegard (1933), for instance, assumes that the excitation of ^1S or ^1D states of the O atom, from which the green and red auroral lines are emitted, is caused by the intermediary of N_2 molecules which are loaded with energy by bombardment of charged particles from the sun. Such energised particles, according to Vegard, may be active nitrogen (E_a) which he assumes to have energy of 9·55 eV. Thus

$$E_a + O_2 \rightarrow O(^1S) + O + \epsilon.$$

It is argued that since the surplus of energy ϵ is only 0·25 eV, the reaction has a high probability. [It is to be noted, however, that according to Mitra (1943*b*, 1945) active nitrogen is simply N_2^+ ions in the X'-state.] For the excitation of red auroral lines, the presence of ozone is further assumed. The probable reaction according to Vegard is

$$N_2(A)+O_3 \rightarrow O_2+O(^1D)+\epsilon.$$

Again, Ta-You-Wu (1943) supposes that the oxygen and the nitrogen molecules in the upper atmosphere are dissociated partly by solar ultraviolet rays and partly by charged particles in the case of aurora. These recombine at night producing metastable molecules. The metastable molecules also by colliding amongst themselves produce metastable atoms. These atoms and molecules collide amongst themselves and give rise to excited atoms and molecules from which the night sky spectrum and also the auroral spectrum are emitted.

According to Chapman (1937) the charged particles from the sun, both ions and electrons, by their impacts, highly excite, ionise, and also ionise and excite at the same time the atmospheric particles—the O atoms and the N_2 molecules. Some of the highly excited oxygen atoms are brought by impact to ^1P state and then descend to ^1S or ^1D states. From these latter states, the green and the red auroral lines are emitted. Similarly the excited N_2^+ ions emit the negative bands and come down to the normal level. The recombination of the ions with electrons, however, does not in general emit the observed bands of N_2. The recombinations are accompanied by radiation in the ultraviolet region only. The emission of the observed bands are due to the production of excited N_2 molecules in the C and the B states by direct impact.

Without making any detailed comment on these hypotheses it may be said generally, that based on many assumptions as they are, the hypotheses are more or less speculative.

In what follows we shall seek explanations of the auroral lines and bands after the theory of emission, as postulated by Mitra (1943*a*, 1945), of similar lines and bands from the night sky luminescent layer.

2. AURORAL AND NIGHT SKY SPECTRA.

The auroral spectrum has many features in common with the spectrum of night sky particularly when they are observed during twilight. As a matter of fact, the night sky luminescence has, for this reason, been sometimes described as the *permanent aurora*. In the accompanying Table the two lights are compared for convenience. It is to be noted that in both the spectra the forbidden lines of atomic oxygen appear with great intensity and the first positive bands of nitrogen are present with fair intensity. The second positive bands are present in aurora with small intensity; they are also reported to be present in the night sky luminescence but with extreme faintness. It is to be particularly noticed that the spectrum of sky light in the early morning and evening—when the solar rays are touching the high atmosphere—has remarkable resemblance to the spectrum of the sunlit aurora. From these resemblances one is justified in concluding that there must be factors common to the modes of excitation of the spectra of the two lights.

The only significant difference between the two spectra is the presence of Vegard-Kaplan bands in the night sky with great intensity—comparable with that of the green auroral line—but its extreme weakness in the aurora. It will presently be shown that this and other differences between the two spectra are to be traced to the difference in the heights of the atmospheric levels at which these sources act (see Table). The atmospheric densities at the two heights and the frequencies of collisions of the particles—on which excitation of the spectra depends—differ by more than two orders.

	Aurora.	Night sky luminescence.
Geographical distribution	Observed in polar regions.	Observed all over the world.
Height of occurrence ..	Occurs most frequently in the region 90–120 km.; sunlit aurorae occur at much greater heights—350–550 km. and occasionally extend up to 1100 km.	Luminescent layer located approximately between 200–400 km. (Region-F of the ionosphere).
Primary source ..	Charged particles from the sun.	Ultraviolet radiation from the sun.
State under which observations are made.	Observations are made when the source is in action. In the case of sunlit aurora the ultraviolet solar rays are also acting.	Observations generally made at night when the primary source is not acting. In the special case of early morning and evening observations, the source is acting on the high atmosphere.
Spectra:		
(1) First negative bands due to $N_2^+(A'\to X')$	Strongest of all nitrogen radiations. Greatly enhanced in sunlit aurora.	Generally absent; but when the high atmosphere is illuminated by the rays of the rising or the setting sun, they are very strong.
(2) First positive bands of $N_2(B\to A)$	Strong in ordinary aurora. Enhanced in sunlit aurora.	Strong.
(3) Second positive bands of $N_2(C\to B)$.	Comparatively faint.	Very faint.
(4) Vegard-Kaplan bands of $N_2(A\to X)$	Very weak.	Very strong.
(5) Forbidden lines of O λ5577 (green) ($^1S\to{}^1D$) $\left.\begin{array}{l}\lambda6300\\\lambda6363\end{array}\right\}$ red ($^1D\to{}^3P_{2,1}$)	Green radiation is very strong, usually much stronger than the red. But in going up an auroral streamer the intensity of the red lines increases.	Both green and red lines are very strong and are of nearly equal intensity.
	In sunlit aurora the red is greatly enhanced. The intensity of the red is about 4-5 times that of the green.	In high sunlit atmosphere the intensity of red lines is greatly increased while that of green is hardly affected.

Note.—The prevalence of atomic oxygen is due to photo-dissociation of O_2 during daytime by absorption of ultraviolet radiation $\lambda < 1750$ (Majumdar, 1938; Wulf and Deming, 1938; Rakshit, unpublished paper). The dissociation commences from a region somewhat below 100 km. and, at 115 km., it is practically complete. Dissociation of O_2 may also be produced by charged particles from the sun.

3. EXCITATION OF THE AURORAL SPECTRUM.

We first note that the primary source—bombardment by charged particles—cannot be the immediate cause of excitation of all the observed lines and bands of the auroral spectrum. Several considerations lead to this conclusion.

Firstly, if the excitations were due to direct bombardment, the different spectral lines and band systems would have developed at different heights. It is well known that for simple excitation (without ionisation) the energy of the bombarding electrons must lie close to the exciting voltage. The bombarding particles, as they penetrate into the atmosphere, attain the required velocities at different heights within narrowly defined limits. The corresponding spectra should therefore be emitted only from these strata unless, of course, one assumes that the bombarding particles possess a wide range of velocities.

Secondly, it is well known that the upper atmosphere spectra are not ordinarily excited in discharge tubes or by bombardment of air by charged particles. The reason for this difference is that in the case of discharge tube spectra, the walls of the tube play an important part in promoting quick disappearance of the products of discharge, e.g. electrons, ions and metastable particles. The electrons and ions recombine mostly on the walls rather than in the volume of the discharge tube. The walls act as the third body absorbing the excess of energy and momentum. The metastable particles also, as they find their way to the walls, deliver up their energy rather by collision with the glass surface than by radiation. In the case of the upper atmosphere on the other hand, since there is no wall, the products of bombardment persist and by reacting amongst themselves or with the neutral particles excite spectra not ordinarily obtained in discharge tubes.

[In connection with the action of the glass walls discussed above Mitra's hypothesis of active nitrogen (1943*b*, 1945) may be recalled. The active particles—the N_2^+ ions—persist in the afterglow vessel due to special conditioning of the walls which prevents the neutralisation of the electrons and ions on the surface. The conditioning is probably caused by adsorption of nitrogen which has very little electron affinity.]

In consideration of the above the lines and bands of the auroral spectrum may be classified under two categories: (i) *spectra excited as a result of direct bombardment*—first negative bands, (ii) *spectra excited as a result of reactions between neutral and the charged particles produced by the bombardment*—second positive bands, first positive bands, Vegard-Kaplan bands and the auroral lines.

First Negative Bands (N_2^+).—It may be recalled that the first negative bands are easily produced in the laboratory by electronic bombardment of nitrogen. Hence the explanation of the occurrence of these bands is simple. The primary act of the fast charged particles is to ionise the atmospheric gases and at the same time to raise the N_2^+ ions produced to the A'-state. These latter dropping to the normal X'-state emit the first negative bands.

The evidence of the upper atmospheric regions being ionised during auroral displays is furnished by ionospheric observations in high latitudes (Appleton, Naismith and Ingram, 1937). It is found that the ionisation extends to Region-D below Region-E and causes obliteration of echoes in ionospheric soundings.

The distribution of ionisation with height caused by electronic bombardment of the upper atmosphere has been calculated by Vegard (1912). This distribution agrees closely with light distribution in certain types of aurorae.

First Positive Bands of N_2 *and the Forbidden lines of Atomic Oxygen.*—It will be seen from the Table that these bands and lines are common to both aurora and night sky luminescence. As such, their modes of excitation may be assumed to be the same. The mode of excitation for the night sky spectrum according to Mitra's hypothesis is fully discussed in reference (Ghosh, 1943). It is briefly mentioned here for the sake of completeness.

Since oxygen atoms have very high electron affinity, O^- ions are readily formed. These O^- ions react with N_2^+ ions as follows:

$$N_2^+(X')+O^- \rightarrow N_2(B)+O(^1S). \quad .. \quad .. \quad .. \quad (I)$$

The process is one of so-called electron transfer and has a high probability when the resonance condition is satisfied. Since the ionisation potential of N_2 is 15·58 eV and the electron affinity of atomic oxygen is 2·2 eV, the energy released on neutralisation is 13·38 eV. This energy is taken up almost entirely by both N_2 and O, if on neutralisation, the former drops to the vibrational level of $v' = 9$ of the B-state (9·1 eV) and the latter is excited to the ^1S (4·2 eV) state. The $N_2(B)$ molecules thus produced come down to the A-state and emit the first positive bands. Similarly the excited O (^1S) atoms drop to the ^1D and then to the ^3P state and in the course emit the green and the red auroral lines respectively. If account is taken of the thermal energy of the colliding particles (average value of 0·2 eV corresponding to temperature 1000°K) then to accommodate it the neutralised N_2 molecule will drop to the vibrational level $v' = 10, 11$ or 12. The emissions corresponding to transitions from these levels are just those that are found enhanced in the first positive band system in the auroral and in the night sky spectra.

Recent experiments of Vier and Mayer (1944) give the value 3 eV as the electron affinity of O. Taking this value, energy available for the excitation of N_2 molecule after the excitation of O to ^1S is 8·38 eV. The N_2 molecules may therefore be excited to $v' = 5$ of B-state if the thermal energy of the colliding particles is taken into consideration.

Second Positive Bands.—Reaction (I) cannot produce the second positive bands. This is because the energy left for the excitation of N_2 molecules after excitation of oxygen atom to ^1S state is about 9·1 eV, whereas the energy of ground level of C-state is 11 eV. Further, from the fact that the N_2 molecules after emission of the second positive bands are left in the levels 1–4 of the B-state, while the most intense first positive bands originate from levels 11–8 of the same state, it is clear that the mode of excitation of the two systems cannot be the same. We can explain the emission of second positive bands if we assume that there is radiative recombination of N_2^+ ions and electrons. This is because the nuclear separations of N_2^+ ions in the normal state and of N_2 molecules in C-state are nearly the same (1·113 and 1·146 atomic units respectively). According to the Franck-Condon principle there is a fair probability of ions capturing electrons in this state. We thus have

$$N_2^+(X') + e \rightarrow N_2(C) + h\nu. \quad .. \quad .. \quad .. \quad .. \quad \text{(II)}$$

The cross-section for such reaction is however only of the order 10^{-19} cm.^{2} (Bates, Buckingham, Massey and Unwin, 1939) and is very small compared to that of reaction (I) which is 10^{-14} cm.^{2} (Ghosh, 1944) The intensity of the band is therefore also very small compared to that of first positive bands.

Vegard-Kaplan Bands.—As shown in the Table, there is a marked difference in the intensity of the Vegard-Kaplan bands in the aurora and in the night sky light. Since the N_2 molecules after emission of the first positive bands are left in the A-state, it might seem strange why the V-K bands, which are due to transitions of the N_2 molecules from this state to the X (ground) state, would be weak in the former but strong in the latter. The explanation is however simple. The A-state of N_2 is known to be a highly metastable state, i.e. it has a long life. Now a metastable molecule may come down to a lower state by either radiation of energy or by a radiationless process by giving up its energy to another particle with which it collides. In order that the process may be a radiative one it is necessary that the average interval of collision must be greater than $T\epsilon$ where T is the average lifetime of the metastable state and ϵ is the efficiency of collision. ($^1/_\epsilon$ is the average number of collisions necessary to bring the metastable particle down by a radiationless process.) Now, the auroral spectrum is emitted from the comparatively low height of 90 to 120 km. The atmospheric density in this region is much higher than that in the region of the night sky luminescence 200–400 km. (Density and collisional frequency in Region-F are estimated to be 10^{10} per c.c. and 10^3 per sec. respectively; the corresponding figures for the lower auroral level are 10^{13} per c.c. and 10^5 per sec.) In the lower levels the collisional frequency is high and the metastable $N_2(A)$ molecules are brought down to the normal state by collision with the other atmospheric particles before they have a chance of emitting the V-K bands. That the relative weakness of the *V*-*K* bands in the auroral light may be due to the higher collisional frequency at auroral levels has also been suggested by Chapman (1937).

The Spectrum of Sunlit Aurorae.—The spectral characteristic of sunlit aurorae consists in the enhancements of the red lines of atomic oxygen (leaving the green line unaffected) and of the first negative bands due to N_2^+. These effects are strikingly analogous to those of the night sky spectrum during early morning or evening hours when the rays of the rising or the setting sun touch the high atmosphere (see Fig. 1). These enhancements are simply explained.

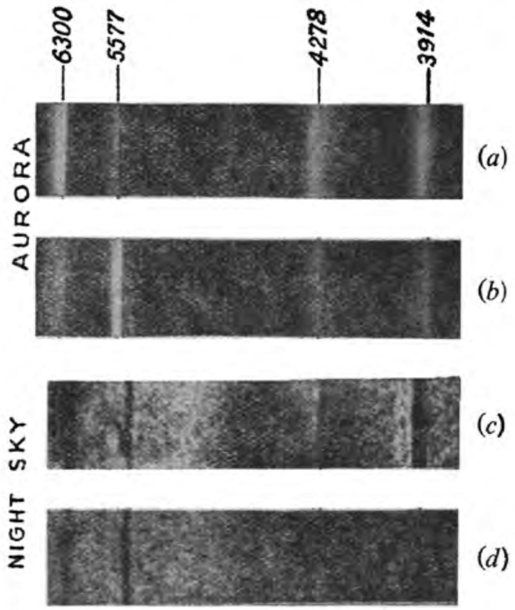

FIG. 1.

Illustrating the enhancements of red oxygen lines and of the first negative bands of N_2^+ in sunlit aurora and in dawn spectra of the upper atmosphere. (*b*) and (*d*) are spectra of aurora and of night sky when not acted upon by sunlight; (*a*) and (*c*) are spectra of same when solar rays illuminate the high atmosphere. The two auroral spectra were taken by Störmer (1938) on September 15, 1938, Southern Norway. [(*a*)—height 400–600 km.; exposure from $2^h\ 35^m$ to $3^h\ 55^m$; (*b*)—height 90–120 km.; exposure from $21^h\ 45^m$ to $21^h\ 55^m$.] The night sky spectra were taken by Elvey (1942) at the McDonald Observatory, Texas, U.S.A. [Exposures of (*c*) and (*d*) are 15 minutes and one hour respectively.]

Taking the case of oxygen atoms we note that they are raised to ^1D state (from which the red lines are emitted) by absorption of $\lambda < 6300$ and to ^1S state (from which the green line is emitted) by absorption of $\lambda < 2900$. But the number of O atoms raised to the ^1D state is much larger than that raised to the ^1S state. This is due to two factors. Firstly, the absorption coefficient of O atoms for excitation to the ^1D state is much higher than that for excitation to ^1S state and secondly, the density of solar radiation in the spectral region corresponding to the transition ^1S state is about 100 times smaller than that in the region corresponding to transition to ^1D state. As a result of this, the red oxygen lines are emitted in much greater intensity than the green line. [These points are discussed fully by Ghosh (1943).]

It is to be noted that the enhancement of red oxygen lines is due to a large increase in the population of atoms in the ^1D state by absorption of $\lambda < 6300$ and not merely to increase in the rate of stimulated transition to ^3P state of the existing ^1D atoms. In regard to the latter Vegard (1912) comments that since the rate of spontaneous transition to the ground state is much larger than stimulated transition to some higher or to some lower state, the increase in the intensity of red lines is not due to the action of solar radiation. Evidently he did not take note of the large increase of the population of ^1D atoms which would occur as a result of absorption of solar radiation.

Regarding the N_2 molecules the strong absorption in the region $\lambda < 661$ ionises and raises the N_2^+ ions produced to the A'-state (Hopfield, 1930). This leads to the emission of the negative bands. That the blue sunlit aurorae in which there must be N_2^+ ions in abundance are observed only rarely is as expected. The sunlit aurorae occur generally in the very high regions 400 km. and above. At such heights the density of the heavy N_2 molecules may be expected to be much less than that of the light O atoms. On occasions when the sunlit aurorae occur at comparatively lower levels or when the atmospheric gases are blown upward as a result of bombardment (due to heating?) the increased density of N_2 molecules causes an intensification of the negative bands and the blue aurorae are observed.

4. HEIGHT EFFECTS.

It has been mentioned that the relative intensities of the red and the green auroral lines of O and of the negative bands of N_2^+ vary with height. The effects are as follows: Firstly, the intensity of the red lines relative to that of the green line is found to increase with height. Secondly, the intensity of the green line decreases with height more rapidly than that of negative bands.

Regarding the former effect difficulty may be felt for the following reason. According to reaction (I) the O-atoms are raised to ^1S state and then come down to the ground state by successive radiations of the green and the red lines $^1S \rightarrow {}^1D \rightarrow {}^3P$. Since for every emission of the green line there is to be a corresponding emission of the red line, one would expect the intensities of the two to be of the same order at all heights. (The probability of emission by $^1S \rightarrow {}^3P$ jump is considered to be very small compared to $^1S \rightarrow {}^1D$ or $^1D \rightarrow {}^3P$.) The difficulty is removed if the great difference in the lives of the oxygen atoms in the metastable ^1S and ^1D states are recalled. The value of the former is 0·5 second while that of the latter is 100 seconds. At lower levels, on account of higher collisional frequency, a larger proportion of ^1D atoms comes down to the ground state by radiationless process. With increasing height the collision frequency decreases and an increasing number of the atoms in the ^1D has chance of emitting the red lines. Hence the intensity of the red lines increases with height.

The change in the relative intensities of the negative bands and the green oxygen line is also understood if it is recalled that excitations of the two are by processes which are not immediately related to one another. The former is excited by direct bombardment of the N_2 molecules by the charged particles entering the atmosphere. The latter is excited as a result of a number of successive reactions occurring between the charged particles which are produced as a result of the bombardment. In particular, according to the reaction (I) the production of O^- ions is first necessary for the excitation of the O lines. There may be many reasons why the production and the density of the O^- ions will be restricted at greater heights in an auroral streamer. For instance, the bombarding particles might knock the electrons off the O^- ion formed. Again, the density of neutral O atoms might be greatly decreased owing to their ionisation. These factors will tend to reduce the number of O atoms excited to ^1S state.

There has been some confusion regarding the height effect as discussed above with the sunlight effect discussed earlier, it being recalled that in so far as the enhancements of the red oxygen lines and of the negative bands of N_2^+ are concerned, the two effects are similar. While Störmer (1938) believed that the characteristics of sunlit aurora as observed by him were true effect of sunlight, Vegard (1929) was of opinion that the effect was merely an extension of the height effect as observed by him. There, however, need be no confusion; because, the portions of the aurora studied by Störmer were actually within the sunlit portion of the atmosphere and the enhancements are exactly similar to the effect of sunlight on high atmosphere as first observed by Slipher (1933) and later confirmed by Elvey (1942). Further, the region observed is generally 300 to 600 km. and is much above the region in which Vegard observed his height effect.

ACKNOWLEDGMENTS.

The work described in the paper was carried out when the author was enjoying an Adair, Dutt Research Scholarship. It is his pleasant duty to record his thanks to the Adair, Dutt Research Fund of the Indian Science News Association for having granted him the Scholarship. He also expresses his sincere and grateful thanks to Prof. S. K. Mitra for suggesting the work to him and for many helpful discussions in course of the preparation of the paper.

REFERENCES.

Appleton, E. V., Naismith, R. and Ingram, L. J. (1937). British Radio Observations during the Second International Polar Year 1932-33. *Phil. Trans. Roy. Soc.*, A, **236**, 191.

Bates, D. R., Buckingham, R. A., Massey, H. S. W. and Unwin, J. J. (1939). Dissociation, Recombination and Attachment processes in the Upper Atmosphere—II. *Proc. Roy. Soc.*, A, **170**, 322.

Chapman, S. (1937). On the Production of Auroral and Night-Sky Light. *Phil. Mag.*, **23**, 657.

Elvey, C. T. (1942). The Light of the Night Sky. *Rev. Mod. Phys.*, **14**, 140.

Ghosh, S. N. (1943). Excitation Processes of the Night Sky Spectrum. **9**, 301.

——— (1944). A Note on 'Effective Recombination Coefficient' in the Ionospheric Regions. **10**, 333.

Hopfield, J. J. (1930). New Spectra in Nitrogen. *Phys. Rev.*, **36**, 789.

Lozier, W. W. (1934). The Heat of Dissociation of CO and the Electron Affinity of O. *Phys. Rev.*, **46**, 268.

Majumdar, R. C. (1938). The Theory of Molecular Dissociation and the Fundamental Mechanisms in Upper Atmosphere. *Ind. Journ. Phys.*, **12**, 75.

Mitra, S. K. (1943*a*). Light of the Night Sky. *Science and Culture*, **9**, 46.

——— (1943*b*). The Nature of Active Nitrogen. *Science and Culture*, **9**, 49.

——— (1945). Active Nitrogen—A New Theory. Published by the Indian Association for the Cultivation of Science, Calcutta.

——— (1946). The Auroral Spectrum. *Nature*, **157**, 692.

Rakshit, H. Unpublished Paper.

Slipher, V. M. (1933). Spectrographic Studies of the Planets. *Mon. Not. Astr. Soc.*, **93**, 657.

Störmer, C. (1938). Blue Sunlit Aurora Rays and their Spectrum. *Nature*, **142**, 1034.

Ta-You-Wu (1943). Excitation Processes in the Night Sky and the Aurora. *Proc. Ind. Acad. Sci.*, **18**, 40.

Vegard, L., (1912). Über die Lichterzeugung usw. *Ann. Physik*, **39**, 111.

——— (1929). Variation of the intensity distribution, etc. *Nature*, **124**, 947.

——— (1933). Investigations of the Auroral Spectrum, etc. *Geofys. Pub.* No. **4**, vol. 10.

——— (1937). Intersitätsänderungen der grünen usw. *Zs. Physik*, **106**, 108.

Vier, D. T. and Mayer, J. E. (1944). A direct experimental determination of the electron affinity of Oxygen. *J. Chem. Phys.*, **12**, 28.

Wulf, O. R. and Deming, L. S. (1938). On the Production of the Ionospheric Region E and F and the Lower-altitude Ionisation causing Radio Fade-outs. *Terr. Mag.*, **43**, 283.