THE SPECTRA OF THE NIGHT SKY AND OF THE AURORAE

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Information regarding the chemical composition and physical state of the earth's upper atmosphere may be obtained from spectra of the radiations emitted by the night sky, the aurorae, and the sky at twilight or dawn, by studies of meteors, by the measurement of the reflection of radio waves from the ionosphere, by measurements from V-2 rockets, by observation of noctilucent clouds, by studies of magnetic fluctuations, refraction of sound waves, and the ozone layer. A vast amount of new observational and theoretical data on phenomena of the night sky, of aurorae, and of twilight has been accumulated recently, especially in France, Norway, England, and Belgium. A discussion of all the published material leads to several important conclusions and to suggestions for further work which will be exposed here briefly.

The identification of the emission features observed in the night sky, the aurorae, and the twilight can proceed most efficiently if the three types of spectra are discussed together. Such a simultaneous investigation may also lead to a better understanding of the excitation phenomena taking place in each source. Great care has to be exercised in the identifications,[1] not only because of technical difficulties (low dispersion and low resolution; large number of bands; limited information on profiles), but also because the emissions correspond to a low temperature. This may give to certain bands an appearance which differs radically from the laboratory appearance at the normal temperatures of discharges. For a discussion of identifications, it is often desirable to compute "synthetic spectra" corresponding to a low temperature intensity distribution. This has been recently

[1] The absence of lines of an element does not necessarily mean that the element is absent in the atmosphere; an efficient excitation process must also exist.

proved conclusively by M. Nicolet[2] who succeeded in this way in finding several convincing (and other probable) new identifications of emission features in the aurorae-spectra in addition to (or in replacement of some of) the identifications already published by Vegard.[3]

There still remain a good many unidentified features in the spectra of the night sky and aurorae, although all the strongest emissions are satisfactorily identified as follows:

Night sky: (0, 0) band of first positive system of N_2 (λ 10440); [O I] (green and red lines); Na I (D-line); Vegard-Kaplan system of N_2; Herzberg system of O_2; a few bands of the first positive system of N_2 in the red region;

Aurorae: [O I] (green and red lines); [N I] (λ 3466 and λ 5200); negative system of $N^+{}_2$; first and second positive systems of N_2; Vegard-Kaplan system of N_2; occasionally lines of *Na, H,* and probably *He* I; probably $O^+{}_2$ ("second green line"); possibly *NO*.

In Vegard's tables of aurorae spectra, one finds many identifications of atomic lines, permitted or forbidden. Discussions by Nicolet,[4] Pearse,[5] and myself[6] show that these identifications cannot be considered as conclusive, since many of them violate the various intensity rules. It appears that most of the emission features attributed by Vegard to atomic lines will be found to be of molecular origin, once the low temperature intensity distributions of all the spectra involved have been discussed thoroughly. Some are probably unknown forbidden bands which may also be identified presently. There is a great need for further spectro-

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[2] Report to the 1947 meeting of the Gassiot Committee, London. The procedure followed by Nicolet is especially fruitful for the first positive system of N_2 and the first negative system of $O^+{}_2$. Nicolet studied $O^+{}_2$, *NO*, N_2, *and* $N^+{}_2$.

[3] *Geof. Pub., Oslo,* **16,** No. 7, 1945.

[4] *Annales d'Astrophysiques,* **1,** 381, 1938; *Bull. Ac. R. Belg., Cl. Sc.,* **25,** 81, 1939; *Mém. Inst. R. Météorologique de Belgique,* Vol. XI, 1939.

[5] Report to the 1947 meeting of the Gassiot Committee, London.

[6] Unpublished.

scopic observations of both the night sky and the aurorae, especially in long wave lengths.

In order to prepare the way for a discussion of the excitation mechanisms it is desirable to classify the various emissions according to their intensity, but this is not so simple as it would seem. For example the most characteristic emission of an aurora spectrum is the negative system of N^{+}_{2}. Yet the first positive system of N_2 will certainly appear as more intense when we observe the near-infrared region of the aurora: the observed N_2 bands are the weakest of the first positive system, the strongest being in the infrared. Similarly systems such as the Herzberg bands of O_2 in the night sky have their strongest transitions in the unobservable ultraviolet region. For the night sky where we observe peculiar selectivities among certain bands, the problem is even more complex than for the aurora. In fact what we really need is a classification of the emissions according to the populations on the excited levels, and this is complicated by the fact that we observe forbidden as well as permitted emissions; de-excitation phenomena play a major role for the forbidden lines, but are unimportant for the permitted lines.

There are theoretical methods for discussing the de-excitation phenomena, although several essential theoretical data on [O I] and [N I] are still lacking. But the problem may also and should be attacked observationally. Let us consider the red doublet, ^1D — ^3P, of [O I], observed in aurorae. The average lifetime of the O I atom in the ^1D level, if unperturbed, would be of the order of 100 seconds. The auroral structure is known to vary sometimes very quickly; the intensity fluctuations must occasionally take place in small fractions of a second. Hence it happens that the O I atom in the ^1D state does not actually live for 100 seconds, but for only, say, one-tenth of a second. This means that the de-excitation mechanism by collisions of the second kind is at least one thousand times more frequent than the radiative downward transition. Of course the intensity fluctuations vary with the height, the type of aurora, and the emission line considered, and they give only a minimum value of the de-excitation factor. It would be most valuable to make precise photoelectric measurements of monochromatic intensities (which are lacking) and, especially, of intensity fluctuations, with instruments somewhat similar to those recently used by Whitford for determining the angular diameters of stars from occultations by the moon (multiplier phototube and cathode ray oscilloscope, on moving film camera). Filters could separate the different radiations. Heights should be determined simultaneously, and the whole geometrical structure of the aurora considered. By accurate determinations of the speeds of intensity fluctuations for different heights, for various types of aurorae, valuable informations would be obtained as to the excitation mechanisms, the nature and density of the exciting solar particles, and the atmospheric densities.

There is no doubt that, at the most frequent heights of aurorae (90 to 120 km), de-excitation phenomena are of utmost importance for the red [O I] lines and for the ultraviolet [N I] line (average lifetime 100 seconds); probably they are also important for the green [O I] line (average life of ^1S level, about 0.45 second). At great heights, on the other hand, these de-excitation phenomena do not play any major role. This is illustrated by the following observation made by Götz:[7] in a high-altitude aurora, the λ 5200 line of [N I] (average life of upper level ^2D when unperturbed, eight hours) was still quite strong one hour after cessation of the aurora, while the green [O I] line had resumed its normal night-sky intensity.

Taking into account the extensions of band systems into unobserved spectral regions and reasonable estimations of the amount of de-excitation, a typical aurora of height around 100 kilometers would show a steadily decreasing population on the excited levels along the following sequence: red line of [O I] (level ^1D, exc. pot. 1.96v.), line λ 3466.4 of [N I] (level ^2P, exc. pot. 3.56v.) or green line of [O I] (level ^1S, exc. pot. 4.17v.),[8] Vegard-Kaplan system[9] of N_2 (level $A^3\Sigma_u$, exc. pot.

[7] *Experientia*, 3, 185, 1947.

[8] It is not at present possible to decide whether the ^2P level of N I has a higher or lower population than the ^1S level of O I.

[9] The place of the Vegard-Kaplan system in the sequence is a little indefinite; we do not know whether the de-excitation factor actually brings it above the first positive system.

6.2v.), first positive system of N_2 (level $B^3\Pi_g$, exc. pot. 7.4v.), second positive system of N_2 (level $c^3\Pi_u$, exc. pot. 10.5v.). The negative system of N^+_2 would come somewhere before or after the first positive of N_2. It is commonly assumed that the N^+_2 bands are excited directly from normal N_2 molecules. Similarly, it is often assumed that the twilight "flash" consisting in the N^+_2 bands is due to solar excitation from normal N_2 molecules. It is much more probable that in both the excitation arises in N^+_2 ions: in the aurora by impact, in the twilight by resonance fluorescence. If this latter point of view is correct, the negative bands of the aurora are also a low excitation emission (upper level $B'\,{}^2\Sigma^+_u$, exc. pot. 4v.). On the whole the excitation in the aurora favors the low energy levels.

The case of the night sky is not so clear since observational data on the emission heights are widely discrepant: they range all the way from 100 km (Dufay) to 1000 km (Vassy), with all kinds of intermediate values (Barbier: 900 km for the Vegard-Kaplan bands, and 350 km for the Herzberg bands; Vassy: two layers, one around 750–1000 km, one near 75–100 km; Elvey and Farnsworth: 500 km for red and green lines; Karimov: 260 km for green line; Elvey: 125 km for infrared radiation; etc.). This is one of the main pending problems regarding the night sky,[10] and I strongly suggest that a night-fired V-2 should carry equipment for photoelectric observations of the different strongest radiations of the night sky. At any rate we may say that the night-sky spectrum is due to a low excitation, in fact to an excitation lower than that of the aurora, since the second positive system of N_2 is not observed in the night sky.

All the temperatures obtained from the rotational intensity distributions of night-sky and aurora bands are very low, of the order of 200° K (Cabannes and Dufay: 230° K from the Vegard-Kaplan bands of the night sky; Barbier: 170 to 220° K from the Herzberg bands; Swings: 150° K from the Herzberg bands; Vegard: 230° K from the bands in aurorae, whatever their height may be). Vegard[11] found that the bands corresponding

[10] The problem is rendered complex by the "patchiness" of the night-sky emission and by its erratic variations.

[11] *Physica*, 12, 606, 1946.

to the upper limits of the auroral streamers gave no indication of any appreciable increase of temperature. This general result on the temperature is puzzling. Concerning the night sky, nothing definite may be said pending definite information on the heights of emission. But the result obtained from the spectra of the aurorae is entirely at variance with the scale heights obtained from ionospheric observations. One may indeed wonder whether the ionospheric scale heights—which refer to the atmospheric contituents that give rise to the ionization—should be considered as entirely trustworthy. Possibly, as Nicolet suggested,[12] the abundance of helium at great heights may be much greater than is usually accepted. One point is certain: the spectroscopic determinations of temperatures for auroral features of well-determined height should be pursued with the greatest care.

The interpretation of the night-sky and aurora spectra has not reached a satisfactory stage as yet. In the night sky, collisions of particles, whether solar or interstellar, do not seem able to produce the observed selectivities. Actually any attempt at interpretation should start with the strongest emission observed in the night sky, that of the (0,0) band of the first positive system of N_2 at λ 10440. As was shown by Stebbins, Whitford, and Swings,[13] the presence of this emission, while the (1,0) band is absent, requires the presence of nitrogen atoms and their recombination according to one of the following mechanisms:

either a three-body collision: $N + N + N_2 \rightarrow N_2 + N_2^{exc}$,

or a radiative recombination: $N + N \rightarrow N_2^{exc}$.

Such mechanisms are special cases of Chapman's general hypothesis according to which the energies of molecular dissociation or ionization would be converted into excitation energies. It appears possible to explain the main features of the night-sky spectrum by conversion of the dissociation energies of O_2, N_2, O^+_2, and N^+_2 into excitation energies of O, N_2, and O_2. Certain

12 *Mém. Inst. R. Météorologique de Belgique,* Vol. XIX, 1945.

13 *Physical Review,* **66**, 225, 1944; *Ap. J.,* **101**, 39, 1945.

mechanisms of excitation based on the ionized layers[14] may also play some role, although the recent papers by Bates and Massey[15] do not favor such mechanisms.

The case of the aurora is somewhat clearer since we know the heights of emission, and since there remains no doubt that the excitation is produced by the impact of particles coming from the sun. It is often assumed that these particles are electrons. But if these electrons were of low energy, as is required by the spectrum,[16] they would be absorbed in the highest layers of the atmosphere and would not reach the usual auroral height. It seems inescapable to assume that the exciting particles are atoms, the only kind compatible with the appearance of the aurora spectrum and with the solar abundances, being hydrogen. At any rate Vegard's explanations involving ozone or active nitrogen cannot be accepted, as was conclusively proved by Bates, Massey, and Pearse.[17] Mitra's explanation based on the excitation of N^+_2 from the ground state of N_2, followed by electron transfer collisions, cannot explain all the observations. It is, I believe, in the direction of collisions by hydrogen atoms that the best hope for a full interpretation of the aurorae exists.

A general result of the studies on the night sky and aurorae is the presence of nitrogen atoms in the upper atmosphere. From observations of the [N I] lines in aurorae, the N atoms turn out to have very high abundances, say comparable to or higher than the oxygen atoms. There is a possibility that they are formed by predissociation of N_2 molecules in the region of λ 1400A (Herzberg). Nicolet,[12] on the other hand, gives reasons for the

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[14] The radiative electronic recombinations (Ex.: $O^+ + e \rightarrow O^{\text{exc}} + h\nu$) are unimportant. The dissociative electronic recombinations (Ex.: $O^+_2 + e \rightarrow O^{\text{exc}} + O^{\text{exc}}$) would explain only atomic lines. Ionic recombinations (Ex. studied by Mitra: $N^+_2 + O^- \rightarrow N_2{}^{\text{exc}} + O^{\text{exc}}$) may possibly play some role.

[15] *Proc. Roy. Soc.,* **A,** 187, 261, 1946, and Report to the 1947 meeting of the Gassiot Committee, London.

[16] Solar particles traveling from the sun to the earth in about 24 hours have a speed of approximately 1000 miles per second; electrons moving with this velocity have an energy of only 6 volts.

[17] Report to the 1947 meeting of the Gassiot Committee, London.

formation of NO molecules and N atoms without photodissociation of N_2 molecules. Whatever process may actually be operating, it is certain that the usually adopted composition of the upper atmosphere, oxygen atoms and nitrogen molecules, is false. Nitrogen atoms should certainly be added.

Any of the excitation mechanisms considered should also be able to explain the variations in intensity (with time and location) of the night-sky radiations, and the behavior of the different radiations with height and type in aurorae.[18] There is also a close connection with the twilight phenomena. The appearance of an intense D-line of Na in the twilight spectrum is commonly attributed to resonance excitation, although some recent observations by Vegard seem to cast doubt on the hypothesis: such observations should be carefully repeated in different instrumental conditions. The N^+_2 flash, commonly observed for a short time at twilight and dawn, is probably not excited, as Saha suggested,[19] by photo-ionization and excitation of normal N_2 molecules into the $B'\,{}^2\Sigma^+_u$ level of N^+_2. It is much more likely, as suggested by O. R. Wulf[20] that the N^+_2 bands are excited by resonance fluorescence, the N^+_2 ions being permanent components of the upper atmosphere. If this is true, the rotational intensity distribution within the N^+_2 bands should reveal the influence of the solar absorption lines just as the bands of comets do.[21] Spectroscopic observations of the N^+_2 flash with sufficient resolving power would settle this matter.

The most important twilight phenomenon, as far as the structure of the upper atmosphere is concerned, is the enhancement of the red doublet of [O I] at twilight, and its steady decline in intensity for about three or four hours. The reverse appears during the two hours preceding dawn. Whether this enhance-

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[18] The energy variation of the exciting particles with height or type could be obtained from the changes in relative intensities of the first and second positive systems of N_2; such observational data are still lacking.

[19] *Proc. Roy. Soc.*, **A, 160,** 155, 1937.

[20] *Jour. Optical Soc. of Am.*, **25,** 231, 1935.

[21] Swings, *Lick Obs. Bulletin,* **19,** 131, 1941; *Monthly Notices R.A.S.*, **103,** 86, 1943.

ment is due to resonance excitation by solar radiation, by a photodissociation of O_2 ($O_2 + h\nu \rightarrow O[^3P] + O[^1D]$), or by photodetachment ($O^- + h\nu \rightarrow O[^1D] + e$) cannot yet be fully ascertained. At any rate the observations should eventually enable us to determine the densities in oxygen atoms at different heights. Such determinations, as made by Elvey and Farnsworth, are viciated since they neglected the de-excitation mechanisms, and should be repeated.

Astronomers cannot fail to notice how closely related the problems discussed here are to several purely astronomical questions: physics of the comets, shell stars, interstellar clouds. Indeed the detailed study of these connections is most instructive.