I-4. Aurora and Airglow Including Auroral X-Rays

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part I

I-4-1. Behavior of 6300A OI in the Night Airglow at Sacramento Peak, New Mexico during Magnetically Quiet and Magnetically Disturbed Periods

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§1. Introduction.

The red line of atomic oxygen is one of the more intense emissions of the night sky. During and since the IGY a considerable amount of study has been devoted to this emission line throughout the world. In this paper we shall consider some aspects of the work done at Sacramento Peak, New Mexico (geographic coordinates 32°43′N, 105°45′W; geomagnetic latitude 41.6°N) and its relationship to current theories. The emphasis will be on the work of the past few years, and no attempt will be made to provide a complete bibliography. Zenith intensities only have been used in this paper.

The height of red line emission has recently been determined as 250–300 km (Barbier, 1959; Delsemme and Delsemme, 1960) for the normal airglow, and as about 400 km for the maximum luminosity of red auroral arcs (Roach, et. al., 1960; Moore and Odencrantz, 1961). This height is, of course, in the *F*-region of the ionosphere. Correlations of the red line intensity with ionospheric parameters have been made by St. Amand (1955), Barbier (1959) and Delsemme and Delsemme (1960). Correlations of the red line intensity with magnetic activity for Scott Base, Antarctica (Sandford, 1961) and Camden, Australia (Duncan, 1960) have indicated an

* During the Conference a paper by T. Nakamura (to be published in Rep. Ionos. Space Res. Japan **15** (1961)) was brought to my attention. Nakamura applies a very similar analysis to that given in this paper to calculate the charge exchange rate constant and the density of molecular oxygen. His value of $n(O_2)$ is of the same order as we have calculated.

increase of intensity for K greater than 4. At Camden, whose geographic and geomagnetic latitudes are almost the same in the southern hemisphere as Sacramento Peak in the northern hemisphere, no correlation is found between the green line intensity and magnetic activity. The lack of correlation (or possibly even a negative correlation) for the green line is also true for Sacramento Peak (Ward, Silverman and Shapiro, 1961), indicating that at these latitudes the red line responds much more strongly to magnetic activity than the green line which is so prominent in aurorae. Theoretical treatments of the mechanism for production of the red line are all based on the discussion by Bates and Massey (1947) of recombination of electrons in the ionized layers. Chamberlain (1958) has given the fullest treatment of the normal airglow for a mechanism involving the charge exchange of O^+ with O_2 and the subsequent dissociative recombination of O_2^+. King and Roach (1961) have discussed the ion-atom interchange of O^+ and N_2 with dissociative recombination of the resulting NO^+, for the aurora of 27/28 November 1959. The behavior of electron densities in the F-region during magnetic storms has been discussed by a number of authors, of whom we mention here only Maeda and Sato (1959) and Seaton (1956).

§ 2. The red line during magnetically quiet and moderately disturbed periods.

Figure 1 shows the red line intensity during the night of December 19, 1960. This behavior is typical of that for magnetically quiet nights. Following ionospheric sunset the intensity declines monotonically over a period of several hours and reaches a relatively steady value some time after midnight. Towards dawn the intensity begins to rise, with a slope less than for the evening twilight. This behavior is what would be expected on theoretical grounds, briefly discribed in the following. We assume first one of the following sequence of reactions:

$$O^+ + O_2 \longrightarrow O_2^+ + O \qquad (1)$$

$$O_2^+ + e \longrightarrow O' + O'' \qquad (2)$$

or,

$$O^+ + N_2 \longrightarrow NO^+ + N \qquad (3)$$

$$NO^+ + e \longrightarrow N + O' \qquad (4)$$

or,

$$NO^+ + e \longrightarrow N' + O \qquad (4a)$$

where the primes indicate excited atoms. For either mechanism the dissociative recombination step is considerably faster than

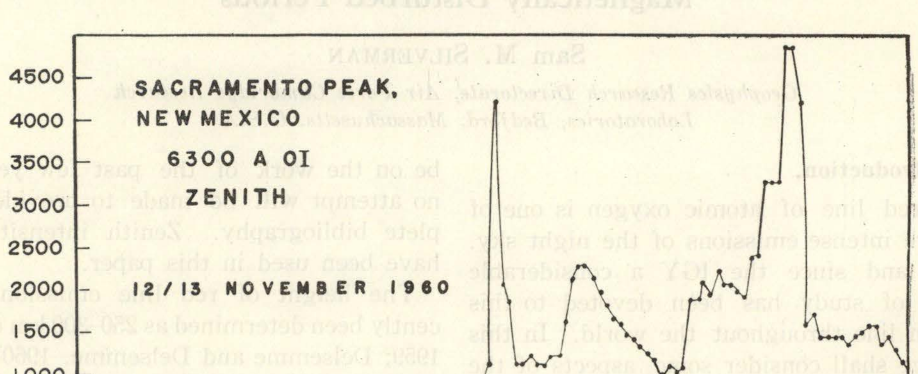

FIG. 1. 6300 A OI intensities at Sacramento Peak, New Mexico for a magnetically disturbed night (12/13 November 1960) and a magnetically quiet night (19/20 December 1960).

the exchange reaction, and the latter reaction therefore becomes the rate determining step. Hence, if each recombination leads to the emission of one red line quantum, the emission per cubic centimeter per second is

$$\varepsilon=k_1 n(\mathrm{O}_2)n(\mathrm{O}^+) \qquad (5)$$

or,

$$\varepsilon=k_3 n(\mathrm{N}_2)n(\mathrm{O}^+) \qquad (6)$$

depending on which mechanism is correct. If we now make the assumption that $n(\mathrm{O}^+)\approx n_e$, then the intensity, integrated over the height, becomes

$$Q=k_1\int n(\mathrm{O}_2)n_e dh=k_1 n_h(\mathrm{O}_2)\int n_e dh$$

$$=C_1 n_h(\mathrm{O}_2)(n_e)_{\max}=C_3 n_h(\mathrm{O}_2)(f_0\mathrm{F}_2)^2 \qquad (7)$$

or,

$$Q=k_3\int n(\mathrm{N}_2)n_e dh=k_3 n_h(\mathrm{N}_2)\int n_e dh$$

$$=C_3 n_h(\mathrm{N}_2)(f_0\mathrm{F}_2)^2 \qquad (8)$$

where f_0F_2 is the critical frequency for the F_2 layer. The parameters $n_h(\mathrm{O}_2)$ and $n_h(\mathrm{N}_2)$ have values intermediate between the minimum and maximum molecular densities in the region of integration, but, because of the exponential decrease of density with height, this value will presumably be close to that at the minimum height of the F_2 region. For convenience we shall call $n_h(\mathrm{O}_2)$ and $n_h(\mathrm{N}_2)$ the mean molecular densities for this region. In the right hand side of (7) and (8) we have made the additional assumption that the critical frequency is proportional to the integrated electron content of the F_2 layer.

Equations (7) and (8) predict that the red line intensity will be proportional to the electron density and the mean molecular density in the F_2 region. Chamberlain (1958) now assumes that diffusive equilibrium is operative and that the molecular oxygen density remains constant with time, and by assuming a distribution with height for this density derives the equation

$$I=fn_e^{(0)}H_2/t \qquad (9)$$

for the variation of the intensity with time in the course of a night. In eq. (9) f is the number of quanta emitted for each recombination, $n_e^{(0)}$ is the electron density at ionospheric sunset, H_2 is the scale height of molecular oxygen, and t is the time. The hyperbolic dependence of intensity on time has been checked for several twilights and appears to be valid. Furthermore eq. (9) predicts that if different nights are compared then the ratio of intensities for two different times of the night should be inversely proportional to the ratio of the times after ionospheric sunset. Consequently all plots of the ratio of intensity at time t to that at some standard time for different nights should all fall on the same curve. Figure 2 shows such a plot using the monthly means for

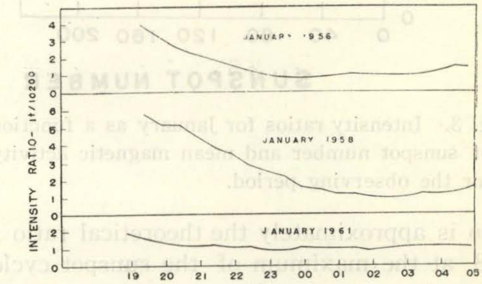

Fig. 2. Ratios of monthly average intensities at time t to that at 0200 (105° WMT) for January of 1956, 1958 and 1961 for Sacramento Peak, New Mexico.

January of 1956, 1958 and 1961, from which it is clear that the plots do not all fall on the same curve. In this figure the standard time is taken as 0200 local time since the intensity is fairly steady for about an hour on either side of this time. The comparison is made for the same month of each year to avoid the disturbing effects of seasonal variations on the intensity and differences in the time of ionospheric sunset. Barbier (1959) has published a graph of the enhancements at the winter solstice which shows substantially the same effect, with a greater enhancement at sunspot maximum. Figure 2 suggests that an effect of sunspot number or magnetic activity is also operative. In order to test this a plot was made of the ratio at 2000 hours for the years 1956–61 (with the exception of 1957) against sunspot number and against the mean K_p-sum for 00–12 hours U. T. (the hours during which observations are made at Sacramento Peak) for those days for which observations were available. This plot is shown in Figure 3, from which it appears that a definite effect of sunspot number and magnetic activity is present. Furthermore the only year for which the

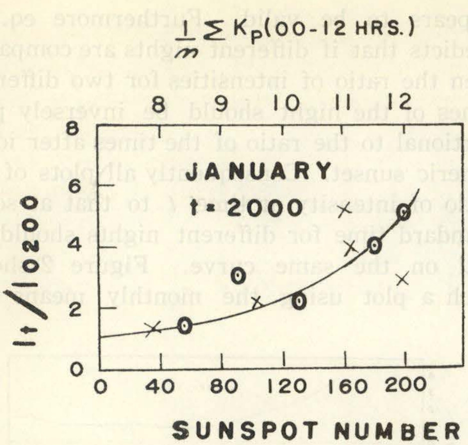

Fig. 3. Intensity ratios for January as a function of sunspot number and mean magnetic activity for the observing period.

ratio is approximately the theoretical ratio is 1958, at the maximum of the sunspot cycle. These discordant results can be reconciled with the theory if we drop the assumption that the molecular oxygen density remains constant during the night but assume instead that this density decreases. In this case the intensity would fall more rapidly than expected during the initial part, and the enhancement would be less the further the oxygen density was from constancy.

§ 3. The red line during severely disturbed periods.

The red line behavior during the severe magnetic storm of 12/13 November 1960, as shown in Figure 1, is considerably different from that of the magnetically quiet night. Typically, rather than a monotonic decrease during most of the night, the intensity will have one or more maxima. Normally there will also be an enhancement of red line intensity toward the NNE. In this section we will consider only the variations of zenith intensity and their relationship to theory. Furthermore this comparison will be carried out primarily for the November 1960 events, for which a good deal of auxiliary data throughout the world exists. A more complete description of the Sacramento Peak observations for these events can be found in a paper by Silverman, Bellew and Layman (1961). Here only the more important conclusions will be summarized.

Eqs. (7) and (8) predict that for constant molecular density the intensity should vary linearly with the electron density at ionospheric sunset. During the November events, however, it is found that, during the quiet parts of night, the red line intensity varies inversely with the electron density. This suggests that the mean molecular density is varying. Therefore, if eqs. (7) or (8) are solved for this mean density, this quantity should vary over a period of several days in a manner similar to the air densities as determined from satellite orbit perturbations. Silverman, Bellew and Layman (1961) have shown that this appears to be, at least approximately, the case during the November events. Additional studies are in progress for other disturbed periods. On the basis of these results we may say that the same mechanism is valid for the production of the red line during magnetically quiet days and during the quiet parts of disturbed periods. It should be emphasized here that much additional work needs to be carried out before the interrelationships pointed out here between air density, electron density and the airglow intensity can be conclusively established.

A final comment must be made about the large maxima observed during severely disturbed nights, as, for example, the maximum at about 0300 local time during the night of 12/13 November 1960 shown in Figure 1. The red line intensity during these relatively short periods can not be easily explained on the basis of the recombination theory. It is therefore probable that an additional mechanism becomes dominant during these periods, but the nature of this mechanism is not clear at this time. It is possible to conceive of mechanisms which would produce the observed intensity. Dissociation of molecular oxygen in the Schuman-Runge region, for example, would require a density of the order of $10^5/cm^3$ of electrons with energies of the order of 20 ev in order to produce the maximum intensity observed. Whether such densities of energetic electrons are present for short times, however, during these severely disturbed nights can not be determined from the airglow measurements alone. The question of the mechanism responsible for the large photometric maxima observed can therefore not be answered at this time.

§ 4. Discussion and conclusions.

The evidence and arguments presented above show that the observed intensities of 6300A OI during quiet periods and during the quiet parts of disturbed periods are consistent with the two-step mechanisms given in eqs. (1) to (4). The airglow and ionospheric data alone are insufficient to distinguish between the two possibilities of O^+ exchange with O_2 or N_2. It is possible, however, to use these data to establish bounds on certain upper atmosphere parameters. If charge exchange with O_2 is assumed to be the dominant mechanism with a rate constant of 2.5×10^{-11} cm³/sec, then the product $fn(O_2)$, where f is the number of ^1D atoms produced per dissociative recombination of O_2^+ and $n(O_2)$ is the night time particle density of O_2 at about 250 km, must be, typically, of the order of 2×10^6/cm³. If f is taken to be unity, then $n(O_2)$ is 2×10^6/cm³, which is not inconsistent with rocket measurements. If ion-atom interchange with N_2 is assumed to be the dominant mechanism, then the product $fk_3n(N_2)$, where f is the number of ^1D oxygen atoms produced per dissociative recombination of NO^+, k_3 is the rate constant for reaction (3), and $n(N_2)$ is the particle density of N_2 at 250 km, must be, typically, of the order of 5×10^{-5}. If $n(N_2)$ is taken to be of the order of 5×10^8, then fk_3 is of the order of 10^{-13}. Neither f nor k_3 have yet been measured in the laboratory. Current estimates of k_3 range from 10^{-9} to 10^{-11} cm³/sec, and if these are correct then the efficiency of production of excited oxygen atoms from the dissociative recombination of NO^+ would be low. The combination of airglow and ionospheric data thus enables us to obtain limit on parameters of photochemical interest.

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