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AN EMPIRICAL DETERMINATION OF THE
PRODUCTION EFFICIENCY FOR AURORAL
6300 Å EMISSION BY ENERGETIC
ELECTRONS

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AN EMPIRICAL DETERMINATION OF THE PRODUCTION EFFICIENCY FOR
AURORAL 6300 Å EMISSION BY ENERGETIC ELECTRONS

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ABSTRACT

Auroral data from the Soft Particle Spectrometer and the Red Line Photometer on the ISIS-2 spacecraft have been selected to form an electron energy flux and optical auroral emission data base. The energy fluxes are stored as integrated fluxes over four energy bands, and the corresponding stored optical emission rates are corrected for airglow and for albedo. Because of the variety of electron energy spectra represented in the data base it was possible to perform a regression analysis that yielded the production efficiency for the production of emission for each of the four bands. While the results of this analysis are interesting to compare with theoretical predictions of 6300 Å excitation processes, these statistical results are not as precise as the comparisons of individual experiments where all parameters, such as the atmospheric composition and temperature profiles are measured. The significance of this approach is that it permits a multiparameter description of an electron energy spectrum, and its relationship to a specific optical emission, by purely empirical means. This is particularly useful in the interpretation of ISIS-2 data from the instruments which provided the results, but should find further application in optical-particle auroral studies.

1. Introduction:

Considerable attention has been given to the calculation of optical auroral emissions from a knowledge of the primary electron spectrum, and by the early 1970's reasonable success seemed to have been obtained for the major emissions (Rees and Luckey, 1974). However, at that time adequate experiments to test the validity of the calculations had not been done. A coordinated experiment with this objective was conducted by Rees et al. (1977). From the satellite measured primary spectrum they obtained reasonable agreement for the 3914 Å N_2^+ emission, excellent agreement for the 6300 Å atomic oxygen emission, and poorer agreement for the 5577 Å atomic oxygen emission. In a subsequent analysis of the same experiment, but using the secondary electron spectrum measured on the rocket, Sharp et al. (1979) found the calculated 6300 Å emission an order of magnitude too low, and concluded that the excitation mechanism for the 6300 Å emission was unknown. Still more recently, Rusch et al. (1978) proposed that energy transfer from $N(^2D)$ to O_2 would produce enough $O(^1D)$ to explain the results. If so, the puzzle is now solved, but at the present time one cannot be sure that the 6300 Å processes are fully understood.

The difficulties with the 5577 Å emission have extended over a longer period of time, beginning with the rocket measurements of Donahue et al. (1968). Ten years later, Deans and Shepherd (1978) made rocket measurements that were nearly self-consistent, using energy transfer from $N_2(A^3\Sigma_u^+)$ to $O(^3P)$ as the major source (in contrast Rees et al. (1977) found it unnecessary to use this reaction). Solheim and Llewellyn (1978) and Yau and Shepherd (1978) have proposed energy transfer from $O_2(A^3\Sigma_u^+, C^3\Delta_u, \text{ or } c^1\Sigma_u^-)$ as an important mechanism, with the former authors considering it to be the dominant mechanism, with $O_2(c^1\Sigma_u^-)$ the only important agent. So the 5577 Å puzzle may also be solved, though it is probably too early to be sure of that as well.

An interesting aspect of the puzzle is that the older Rees and Luckey (1974) formulation seems to give the correct $I(6300)/I(5577)$ intensity ratio. This point has been discussed by Arnoldy and Lewis (1977), and examples of situations where it

seems to give reasonable results are given by M.M. Shepherd and Eather (1976) and McEwen and Bryant (1978). The use of ISIS-2 satellite maps of these emissions (Winningham et al. 1978) for morphological interpretation requires some procedure for interpreting optical emissions in terms of particle fluxes. Auroral spectroscopists have long known that this was possible in principle, but the difficulties with the mechanisms described seemed to preclude a satisfactory quantitative formulation. In view of these theoretical difficulties it was decided to attempt an empirical determination, using the optical and particle detectors on the same spacecraft. This has the practical advantage that any calibration or like factors are self-consistent from the parameter determination to the morphological interpretative analyses. When the Rees et al. (1977) and Sharp et al. (1979) studies are considered together they raise the very important question as to whether the primary electrons observed by a higher altitude satellite do in fact produce secondary electrons measured at lower altitudes by a rocket through simple ionization and energy degradation processes or whether some other acceleration or plasma instability processes are at work. If the latter is true, then the ISIS results derived here may be at variance with those of other experiments, including those from rockets, and so may not apply in all situations, nor may they agree with theoretical calculations. Nevertheless, such comparisons are critically important for this very reason, and may serve as a guide to future work. However, the prime motivation for this work is the establishment of an empirical procedure that will provide a basis for further ISIS data analysis.

2. The Data:

Figure 1 shows an example of what may be considered raw optical data. The intensity of the 6300 Å emission is shown on a linear scale, plotted versus Universal Time (UT). The spacecraft was in a cartwheel mode for the acquisition of these data, so that the photometer, viewing perpendicular to the spin axis (Shepherd et al. 1973a) scanned the same emitting region along the spacecraft track for many successive spacecraft rotations. For each latitude range viewed the data are selected from the spacecraft which yields the minimum time delay between the opt-

ical viewing of that latitude, and the crossing of the spacecraft past the magnetic field line that intersects this latitude point at the emission altitude. In this "minimum-time-delay" analysis the delay can never be more than about one-half spin period which means in general a maximum of ten seconds. This continuous curve shown in Fig. 1 is therefore composed of segments of data spliced from many rotations; the time scale at the bottom thus does not correspond to the viewing time, but is the smoothly varying time of the spacecraft motion, for which the invariant latitude is shown at the top.

Figure 2 shows the same 6300 Å optical data, in the bottom frame; the presentation differs only in that the scale is logarithmic and that the 5577 Å emission and the N_2^+ 3914 Å emission from Dr. C.D. Anger's Auroral Scanning Photometer (Anger et al. 1973) have been added as well. The upper part of the diagram contains data from the Soft Particle Spectrometer (Heikkila et al. 1970) which we now discuss.

For reasons that will become clear later, the particle data have been integrated over energy into four energy bands, which from bottom to top correspond to 5-60 eV, 60-300 eV, 300 eV - 1 keV, and 1-15 keV. The SPS looks perpendicular to the spin axis and so in this cartwheel mode a full range of pitch angles is scanned; the pitch angle sawtooth is shown at the top such that a downward tooth corresponds to downgoing electrons. In these instantaneous fluxes one can see the nature of the pitch angle distributions. For the 1-15 keV channel (the top trace) the fluxes form a smooth symmetrical narrow region centred at 65° invariant; this is the diffuse (or continuous) auroral belt. The pitch angle distributions appear isotropic in the poleward half of this region but going equatorward from the centre of the region the loss cone deepens and the 90° fluxes are enhanced, finally corresponding to trapped particles. For the 0.3 - 1 keV channel there is a similar distribution, except that anisotropy sets in further equatorward than it did at higher energies. More importantly, there are now large structured irregular fluxes in the $68-73^\circ$ invariant region, where the 1-15 keV fluxes were low. This is the discrete aurora, which appears as a region of low-energy precipitation in this kind of ISIS data presentation. The same trends continue in the

60-300 eV band, with the discrete auroral fluxes substantially higher than for the diffuse region, and with the flux extended both further equatorward and poleward. The discrete and diffuse auroral patterns are readily seen in the linear 6300 Å data of Fig. 1. A detailed analysis of the electron morphology has been given by Winningham et al. (1975).

The lowest energy channel, 5 - 60 eV, continues the same trend, except that there seems to be no equatorward limit to the flux. This effect is explained by noting the additional scales at the top of Fig. 2. "INVT" stands for invariant time, "SDEP" for solar depression at the viewed point, "CDEP" for the solar depression in the conjugate hemisphere to the viewed point and "SANG" denotes sun angle, the angle between the photometer optical axis at the time of viewing and the satellite-sun line. The indication "DARK" means that the spacecraft was in darkness so that SANG is not relevant. The solar depression angles show that the local ionosphere is very dark, but that it is twilight in the conjugate hemisphere. The conjugate sun sets at 63.5° invariant but the 5-60 eV fluxes continue undiminished to a conjugate solar depression of 10° at 52.7° invariant - beyond this the fluxes decrease as expected. These are clearly fluxes of conjugate photoelectrons.

The three optical emission channels can be seen to contain much of the information provided by the electron energy bands. The 5577 Å emission is the strongest one in the diffuse aurora followed by the 3914 Å emission and then the 6300 Å emission. The first two emissions are smooth and symmetric in the diffuse aurora but their ratio is not symmetric, indicating a larger $I(5577)/I(3914)$ ratio on the poleward side, suggesting a lower average electron energy there. In the discrete aurora the 6300 Å emission lies near the other two, with almost the same intensity as the 5577 Å emission, and the 3914 Å emission is the lowest. This indicates a still lower average electron energy. The analysis described in this paper may provide a basis for future multiple wavelength studies, but that will not be explored here.

These plots of "instantaneous" fluxes and intensities are interesting and useful in their own right, but for quantitative flux and optical emission comparisons further analysis is required. For the energy bands the precipitated flux is integrated over the loss cone - this is done for the two halves of the cone - ascending and descending from the magnetic zenith. These two values are the same in a region of stable precipitation; their difference gives a measure of this stability. For the optical emissions corrections must be made for airglow background and for earth albedo. The airglow is subtracted by manually selecting baseline regions outside the auroral region, on one or preferably both sides of the aurora. A linear interpolation is used inside the auroral region. An albedo correction is made using the method of Hays and Anger (1978). As applied to the 6300 Å emission the method assumes that the aurora is of uniform intensity in the east-west direction. An albedo of 0.5 was used, as larger values gave evidence of overcorrection. The data resulting from these corrections are plotted against invariant latitude, one data point per spin as shown in Fig. 3. For the electron energy fluxes, each half-cone flux is shown by a short bar, with the bars connected with a vertical line. These values are also stored in an on-line data base for the analysis to be described. Values of optical emission rate averaged over the corresponding time regions are also stored in the data base along with other temporal and spatial parameters.

3. The Empirical Analysis:

Earlier analyses by Bunn (1974) had shown non-linear relationships between total energy flux and 6300 Å emission rate, which might be expected from the known energy dependence in the excitation of the emission. More energetic precipitation penetrates to lower levels of the atmosphere where the $O(^1D)$ level is more heavily quenched by N_2 (Hays et al. 1978), and yields correspondingly less emission. The non-linear plots obtained by Bunn (1974) have additional interest in that they seem to imply a systematic relationship between energy spectrum and energy flux but that will not be pursued here. However, for a given energy band, to the extent that it may be assumed monoenergetic, there must be a linear relationship between the

precipitated energy and the amount of emission it produces. For the i th energy band we can therefore define a production coefficient as follows:

$$I_i = e_i F_i \quad (1)$$

where I_i is the emission intensity and F_i the energy flux for the i th band. For the units used here the production coefficient e_i will be in rayleighs $\text{erg}^{-1} \text{cm}^2 \text{sec}$. A given aurora may then be represented by a linear superposition of energy fluxes giving some total intensity I :

$$I = \sum_{i=1}^N e_i F_i \quad (2)$$

The data base was established with the intent of determining the coefficients e_i by regression analysis of the stored I and F_i values. It was judged at the outset that four bands were about as many as the method and data would accomodate, at least for an initial study. The bands were divided originally in a way that allocated roughly the same energy flux to each band, and that associated certain geophysical significance to each (e.g. photoelectrons, E and F region energy deposition values). The result was the four bands shown in Figs. 2 and 3.

From a larger number of candidate orbits, 12 orbits were selected for the regression analysis, yielding 172 data points. These orbits were between Oct. 2 and Nov. 24, 1971, so that a rather narrow range of season and local time is represented. A regression analysis was performed, to minimize the sum of the squares of the differences between the observed intensities, and the intensities as calculated from (2).

4. The Results:

The production coefficients obtained are shown in Table 1, in rayleighs $\text{erg}^{-1} \text{cm}^2 \text{sec}$, along with their probable errors and limits on the regression estimate. A more fundamental way to express the production efficiency is in terms of the number of photons that are emitted from a 1 cm^2 column for each incident electron that enters the column at the top (unit incident flux). The production coefficients are also given in these units in this table, but since the conversion factor is energy dependent it is necessary to assign an "average" energy to each band to make the conversion. We have assigned subjective weighted average values that reflect the shape of the spectrum within each band, and these values are given as well.

To assess the validity of the coefficients determined we show in Fig. 4 the optical intensities calculated for orbit 2840, using the measured fluxes and the coefficients. This was done for two sets of coefficients, the set from Table 1 which was derived using data from all 12 orbits, and another set derived from all of the orbits except 2840. The differences between the calculated intensities for the two sets were so small that they cannot be seen on the plot. This indicates that the coefficients are adequate to reproduce the initial intensities, and that they are not sensitive to the data of one particular orbit.

Although as explained in the introduction we do not wish to become embroiled in a discussion of excitation mechanisms, it is still appropriate to make some comparisons with theoretical calculations. In Fig. 5 are shown the values of production coefficient as a function of energy for the 6300 Å data of Fig. 4, for the calculations of Banks et al. (1974), for the calculations of Mantas and Walker (1976), and for an in situ rocket measurement into conjugate photoelectrons by Shepherd et al. (1978). The values of Rees and Luckey (1974) cannot be compared directly because their results are for power-exponential spectra. But taking their production coefficient for the 4278 Å N_2^+ band at 1 kR emission rate of $160 \text{ R erg}^{-1} \text{ cm}^2 \text{ sec}$ and their $I(6300)/I(4278)$ ratios as a function of characteristic energy, α , and using the average energy which is 2α , we obtain the points shown in the figure (A constant $I(3914)/I(4278) = 3$ was applied). The agreement between all of these is surprisingly good, considering that no attention has been paid to standardization of model atmospheres, ionospheric electron densities, reaction rates and the like, and further considering the order of magnitude discrepancies cited in the introduction.

5. Discussion and Conclusions:

Although our confidence in the method is limited to use with ISIS data, there is in principle no reason why it cannot be applied in general, and specifically with ground-based data. However, one would like to calibrate this application and the only comparisons we have are those using rocket data, which as explained, seem at variance with satellite data. Applying our formulation to the estimation of 6300 Å emission rate, using the measured fluxes of Arnoldy and Lewis (1977), Rees et al. (1977), and Sivjee and McEwen (1976), values obtained are lower by at least an order of magnitude than observed experimentally. This is surprising, but is at least consistent with the result that the ISIS data and theoretical calculations agree, and the theory is an order of magnitude too low compared with rocket results. All of this has a certain compatability with the observation of Hones et al. (1971) that plasma sheet fluxes are an order of magnitude larger than fluxes observed by rockets in auroral events, which returns us again to the question of whether all the processes involving the precipitation of auroral electrons have been identified.

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Table 1

6300 Å production coefficients¹ determined by regression analysis

	Electron energy			
	5-60 eV	60-300 eV	.3-1 keV	1-15 keV
6300Å production coefficients $R \text{ erg}^{-1} \text{ cm}^2 \text{ s}$	1120	1520	277	14.3
Probable error	263	84	22	1.2
Lower limit	603	1354	231	11.8
Upper Limit	1462	1688	322	16.7
Weighted mean energy	30 eV	200 eV	.5 keV	5 keV
Production efficiency Photons/electron	0.05	0.49	0.22	0.11

¹The quantity of fundamental interest is the production efficiency, in photons/electron, as shown in the last row of the table.² The quantity in the first row, expressed in $R \text{ erg}^{-1} \text{ cm}^2 \text{ sec}$, is not properly an efficiency, and is referred to as a production coefficient.

Figure Captions

- Fig. 1. The 6300 Å emission rate along the foot of the field line passing through the Isis-2 spacecraft, as a function of spacecraft time, and invariant latitude. A "minimum-delay-time" analysis is used as described in the text. The discrete aurora is evident from 07:29 to 07:31, and the diffuse aurora from 07:31 to 07:33/30. The spike at 07:36/20 is the city of Chicago.
- Fig. 2. Comparison of the optical data of Fig. 1 with the instantaneous electron fluxes. The 5577 Å and 3914 Å emissions are shown, by courtesy of Dr. C.D. Anger, as well as the 6300 Å emission, all shown on a logarithmic scale. The instantaneous energy-integrated fluxes in the four energy bands indicated are shown above, and above that the pitch angle of the measured electrons. The legends above are explained in the text.
- Fig. 3. The corrected data for the orbit of Fig. 1, used as input to the regression analysis data base. The fluxes are integrated over the loss cone, once for each spacecraft rotation, and the 6300 Å emission has been corrected for airglow and for albedo.
- Fig. 4. Comparison of the measured 6300 Å emission for the orbit of Fig. 1, along with the emission rate calculated from the measured electron fluxes shown in Fig. 3, and the production coefficients presented in Table 1.
- Fig. 5. A comparison of theoretical and experimental efficiencies for the production of 6300 Å emission by precipitating electrons as a function of electron energy, and expressed in units of photons/electron.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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Key words: aurora, electron precipitation, 6300 Å emission, production efficiency, satellite observations.