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E. Barouch

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NOTE TECHNIQUE
CRPE / 87

Energy spectra of incident electrons from auroral ionisation profiles

Par
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NOTE TECHNIQUE CRPE/87

ENERGY SPECTRA OF INCIDENT ELECTRONS FROM AURORAL IONISATION PROFILES

par

E. BAROUCH

RPE/HMA
Echelon Issy
3 avenue de la Rébublique
92131 ISSY-les-MOULINEAUX

Le Directeur Adjoint

I. REVAH

Le Responsable de l'Echelon
RPE/Issy

P. BAUER

Septembre 1980

Résumé :

On discute les méthodes de calcul de la production de paires électrons-ions dans la région E de nuit par les précipitations d'électrons auroraux, et la variation en altitude du profil d'ionisation qui en résulte. On montre qu'il faut une bonne connaissance du profil du coefficient effectif de recombinaison α_e pour un calcul précis du profil d'ionisation produit par un spectre de précipitation électronique donné. On propose des formules empiriques donnant α_e selon que la température électronique est connue ou non. Enfin, partant de profils de concentration électronique mesurés de nuit en zone aurorale dans des conditions d'aurore diffuse, on calcule le spectre d'énergie des électrons auroraux incidents, son flux total, et sa température équivalente.

ENERGY SPECTRA OF INCIDENT ELECTRONS FROM AURORAL IONISATION PROFILES

E. BAROUCH

CRPE/CNET, 92131 ISSY-LES-MOULINEAUX (FRANCE)

ABSTRACT

The production of ionospheric ionisation at night by auroral electrons and its height dependence are discussed. It is found that the altitude dependence of the effective recombination coefficent α_e of the ions involved is of great importance in determining the ionisation profile produced by a given incident electron spectrum. Empirical formulas are proposed for evaluating α_e as a function of height when the temperature profile is known and when it is unknown. Electron intensity profiles obtained in the auroral zone at night are examined for several nights during conditions of diffuse aurora. The incident electron spectra are computed from these measurements.

INTRODUCTION

The coupling between the magnetosphere and the ionosphere is the subject of intensive research at the present time. Recent papers by Wolf (1975), Atkinson (1978) and Potemra (1979) provide a description and review of current work in this area. Inductive coupling between the corresponding current systems occurs at all latitudes, but in the auroral and polar regions other important mechanisms are at work. The most spectacular and well-studied of these are the visible aurorae. These are initiated (see Rees, 1969 or Meng, 1978 for review articles) by electron precipitations from the plasmasheet or possibly other regions of the magnetosphere into the ionosphere. Indeed, this process is the main ionizing mechanism for the upper atmosphere at night. The consequences of these precipitations on ionospheric characteristics are far-reaching : at night, the conductivity of the ionosphere is increased manyfold which modifies the current systems, coupling and energetic relations in both the magnetosphere and ionosphere. Investigation of the phenomenon of electron precipitation may yield important information

energy electron which can reach the depth z_i, i.e. which has not lost all its energy above this level. Thus the matrix K has zeros in many places. If M is chosen equal to N, K is a triangular matrix with non-zero diagonal elements ; this ensures that it has an inverse, and in this case the solution of (6) is :

$$G = F = K^{-1}Y \tag{7}$$

In essence this is the procedure chosen by Vondrak and Baron (1977).

If M is not equal to N, the solution of (6) is

$$G = F = (K^{*}K)^{-1}K\,Y \tag{8}$$

if $(K^{*}K)$ is not singular.

Solving equation (6) by equation (7) or (8) may lead to violently oscillatory behaviour of the values of a curve drawn through the points $(E_i, F(E_i))$ in the E-F plane, if there are substantial errors in the measured samples $y(z_i)$. This is because of the very large dynamic range in the eigenvalues of $K^{*}K$, which leads to error amplification (see Twomey for detailed explanations of this phenomenon). Several methods have been proposed to get around this problem, one of the easiest to implement on a computer being the "constrained minimisation" method proposed by Twomey, wherein solutions are found to the equations

$$G = (K^{*}K - \mu I)^{-1}\,K\,Y \tag{2}$$

where I is the unit matrix, and μ is an arbitrary parameter. If $Y^{*} = KG$, choosing μ such that $|Y-Y^{*}|$ is of the order of the error ε is a reasonable compromise between smoothing the solution G but not satisfying (1) exactly - and satisfying (1) but having unphysical, oscillatory solutions. Some of the results presented hereinafter were obtained by this method. Previously, the eigenvalues of C_{ij} have been calculated for an energy range in E of 1 to 30 KeV, and a measurement accuracy of 5 %, corresponding, hopefully, to an energy deposition accuracy of 10 %. It was found that as the number of measurements increased from 8 to 30, equally spaced in the corresponding range of depths $\underline{z}$, the number of independent parameters one could extract for the f_i only increased from 8 to 14 (Below 8 measurements the overlap in kernels is sufficiently

reduced for the number of parameters to equal the number of measurements). With perhaps overconfident optimism it was decided to perform the calculations seeking for 12 independent parameters.

A lot of trouble can be avoided by being more modest in the number of parameters sought and assuming a specific functional form for the spectrum, such as a Maxwellian

$$f(E)dE = AEe^{-E/E_o}\,dE \qquad (8)$$

which is not a bad guess, as far as diffuse auroras are concerned. From this one can compute as in the previous paragraph an ionisation density profile for a few values of E_o and after suitable normalisation, compare this computed ionisation profile with the measured profiles, then selecting the parameter E_o which best fits the data, normalised in the same way. This procedure yields a value of E_o and an estimate on the error in $\underline{E}_o$, and a value of $\underline{A}$ which is probably quite reliable although the error on $\underline{A}$ is hard to estimate. An advantage of this method is that the raw data are not squared as in the first method, thus avoiding doubling the error. Some calculations performed in this way will also be presented.

THE EFFECTIVE RECOMBINATION COEFFICIENT

All the above calculations are fairly sensitive to the value and height dependence of the effective recombination coefficient. Torr & Torr (1979) have reviewed the best present values and temperature dependence of rates of the chemical reactions of interest in the atmosphere ; those which concern our problem are the recombination of NO^+ and O_2^+, which are the most important sinks for the (thermalised) electrons resulting from ionisation by the incident particles. The effective recombination coefficient is the average of these recombination coefficients weighted according to the relative concentrations of these ions, and with due account being taken of the temperature.

Two problems arise in this connection. The ionospheric temperature in the night-time auroral zone is affected by Joule heating, by ionospheric currents and by this direct particle heating. In turn the Joule heating depends on the integrated ionospheric conductivity, which is partly at least due to the ionisation caused by the precipitating electrons. Since the recombination

coefficients for the relevant chemical processes are strongly temperature dependent, and are needed to calculate the incident electron energy spectrum, one cannot rely on "average" temperature-height profiles but must use measured temperatures at the appropriate heights in the calculation. If this is not done then appreciable error may be introduced into the calculation.

The second problem is the weighting of the recombination coefficients of NO^+ and O_2^+ according to the relative concentrations of these ions. Again, the electron precipitations affect these concentrations through the ionisation process and the subsequent chemical reactions. Although radar scattering techniques can yield simultaneous measurements of ionospheric electron density and temperature, they are insufficiently sensitive to provide information about the relative concentration of the ions NO^+ and O_2^+. Measurements by other means will not always provide data at the same time and place, so that this necessarily remains an open question in most instances. Thus a model for the NO^+/O_2^+ ratio in the auroral ionosphere is indispensable.

In figure (2) which is adapted from Swider and Narcisi (1977) some measured NO^+/O_2^+ ratios measured by rocket flights in the auroral zone at night are plotted. These results have been augmented by measurements by Arnold and Krankowsky (1977) and by Sharp et al. (1979). The heavy dashed curve shows a height dependence of the NO^+/O_2^+ ratio which has been assumed to be "representative" in some sense of this ratio, and which has been used in the remainder of this work. The great variability in the data is probably not due to experimental errors but to actual fluctuations normally present in the auroral ionosphere, so that the "representative" relation chosen is necessarily only an approximation. Figure (3) shows the (normalised) ionisation profiles resulting from a Maxwellian incident electron distribution in an atmosphere with a specified temperature-height profile for three extreme cases : 1) recombination due only to NO^+, 2) recombination due only to O_2^+, 3) recombination by the mixture represented by the dashed line in figure (2). As one can see there are notable differences in the shape of the ionisation profiles. The NO^+/O_2^+ ratio apparently varies widely ; it follows that there is an uncertainty in the effective recombination coefficient which in turn leads to an uncertainty in the calculated incident electron spectrum. However, the position of the maximum of the ionisation profile does not seem to be greatly affected : thus, hopefully, for Maxwellian incident electron distributions the position in height of the maximum of the ionisation profile is a "good" estimator of the charac-

teristic energy E_o of the distribution $f(E)dE \approx E \exp^{-E/E_o}$. This parameter E_o is quite important for theoretical studies of the auroral precipitation phenomenon, where as the absolute number of electrons precipitated can hardly hope for a theoretical explanation ; so that this method provides information in a form well μ suited for theoretical analysis, relatively independent of the complications with the recombinaison coefficient.

Figure 4 shows the height dependance of the effective recombinaison coefficient obtained from the considerations described, for a model atmosphere with a given temperature profile. Other assumptions about the temperature profile would lead to a slightly different shape of this curve.

TRANSPORT EFFECTS AT LOW ELECTRON DENSITIES

Equation (2) is a consequence of the continuity equation for the electronic density

$$\frac{dn(z)}{dt} = \frac{y(z)}{\bar{I}} - \alpha_z (n(z))^2 + \nabla(nV_e) \qquad (9)$$

where V_e is the electronic drift velocity at the depth z. The R.H.S. are respectively the production, loss and transport terms.

Since the recombinaison loss term is quadratic in the electron density, its influence will be preponderant at sufficiently high electronic densities. To estimate the transport term, we can take typical values of α_z of 3.10^{-7} cm^3 sec^{-1}, and 10^4 cm/sec for V_e. The characteristic length for the region of interest, is 7.10^5 cm. Setting $\nabla(nV_e)$ equal to nV_e/L as a reasonable order of magnitude estimate, one sees that $\alpha n^2 >> nV_e/L$ if $n >> 10^4/(3.10^{-7} \times 7.10^4)$ cm^3, i.e. $n >> 5.10^4$ cm^{-3}. Thus great caution should be taken with calculations based on equation (2), which neglects the third term on the R.H.S. of equ. (9), at electron densities less than about 10^5 cm^{-3}, as the validity of the approximation breaks down for sufficiently high electron drift velocities, of the order of 100 m/sec. Such values are frequently encountered in the auroral zone.

EXPERIMENTAL RESULTS

Auroral observations using the Chatanika radar on April 12-14 1978* were analysed by both methods with satisfactory results in both cases. The energy spectra obtained by the fit to a maxwellian were satisfactory, which may be due to the fact that diffuse aurorae mainly were detected - either because no auroral arcs were within the line-of-sight or because they were not sufficiently stable to give recognizable signatures in the induced electron density profile. Possibly the more monochromatic electron distributions associated with stable auroral arcs might have caused numerical difficulties which were not encountered during this observation campaign. Figure (5) shows the electron spectra obtained by both methods for a case in which the fit was quite good. Figure (6) shows the fit to the ionisation profile obtained by the maxwellian fit method when the fit is good. A histogram of the quality of the fit using the maxwellian assumption for the total of 87 observations is shown in figure (7).

We can achieve some confidence in the quality of these calculations by looking at the temporal variations of the average incident particle energy total electron number and energy flux (the product of these). Figure (8) shows these quantities plotted at approximately 15 minute intervals throughout the night of April 14th 1978. The prominent features in the figure are the general increase in electron intensity starting around 09 30 UT and the three increases in electron temperature at 10 30, 11 10 and 11 45 UT. From the electric field measured by the Chatanika radar during the same night, one can deduce that the Harang discontinuity swept over the radar site at 09 30 UT, which is the time of the sharp rise in electron temperature and intensity. The magnetogram data shows that a substorm was in progress. Large excursions which occur in several magnetograms coincide roughly in time with the three increases in electron temperature displayed on figure 8. It is satisfying to observe that some measure of compatibility between the electron spectra calculated from the observed density profiles and the concomitant geophysical observations is found, but of course a single night's measurements can only serve to demonstrate that the method is not wholly wrong.

* We are grateful to the Stanford Research Institute team for their kind hospitality at Chatanika and for permission to use this data.

It is hoped to pursue systematic observations of incident electron spectra during aurorae seen from high-latitude incoherent radars and provide data helpful to the clarification of the auroral precipitation program.

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The kind hospitality and permission to use the data provided by the incoherent scatter radar group of SRI International at Chatanika is acknowledged with gratitude. I thank C. TAIEB and M. BLANC for helpful discussions and advice, and G. NEHOU for technical assistance.

FIGURE CAPTIONS

Figure 1. Number of eigenvalues of C_{ij} whose square root is greater than ε (abscissa in the graph). This is equal to the number of independant variables one can hope for when inverting equation (1).

Figure 2. Measurements of the NO^+/O_2^+ ratio by rocket flights : Swider and Narcisi (1977), Arnold and Krankowsky (1977), Sharp et al. (1979).

Figure 3. Ionisation profiles for recombination due only to NO^+ (dashed line), only to O_2^+ (dotted line), and for the mixture chosen in this work (continuous line), and for a maxwellian incident electron distribution.

Figure 4. Recombination coefficient as a function of altitude calculated for the NO^+/O_2^+ ratio given in fig. 2.

Figure 5. Incident electron spectra obtained by inversion (individual points) and by fitting to a maxwellian (continuous line) from a measured ionisation profile.

Figure 6. Computed and measured normalized ionisation profiles.

Figure 7. Distribution of RMS errors for 87 analysed profiles.

Figure 8. Characteristics of incident electron energy spectra during the night of April 12th 1978 from radar measurements at Chatanika. 1000 U.T. is local midnight.

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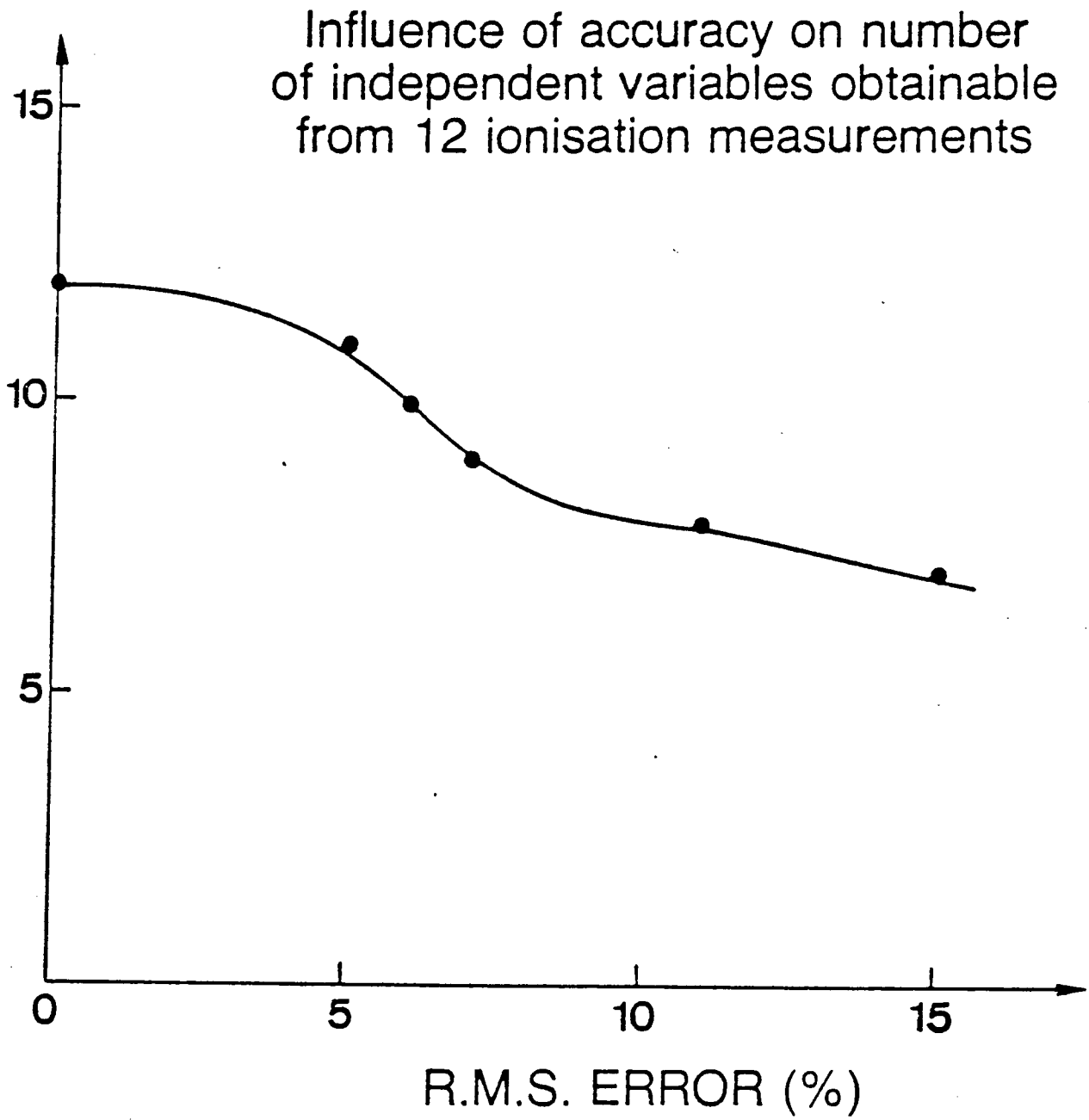
Influence of accuracy on number
of independent variables obtainable
from 12 ionisation measurements
15
10
5
0
5
10
15
R.M.S. ERROR (%)

Figure 1

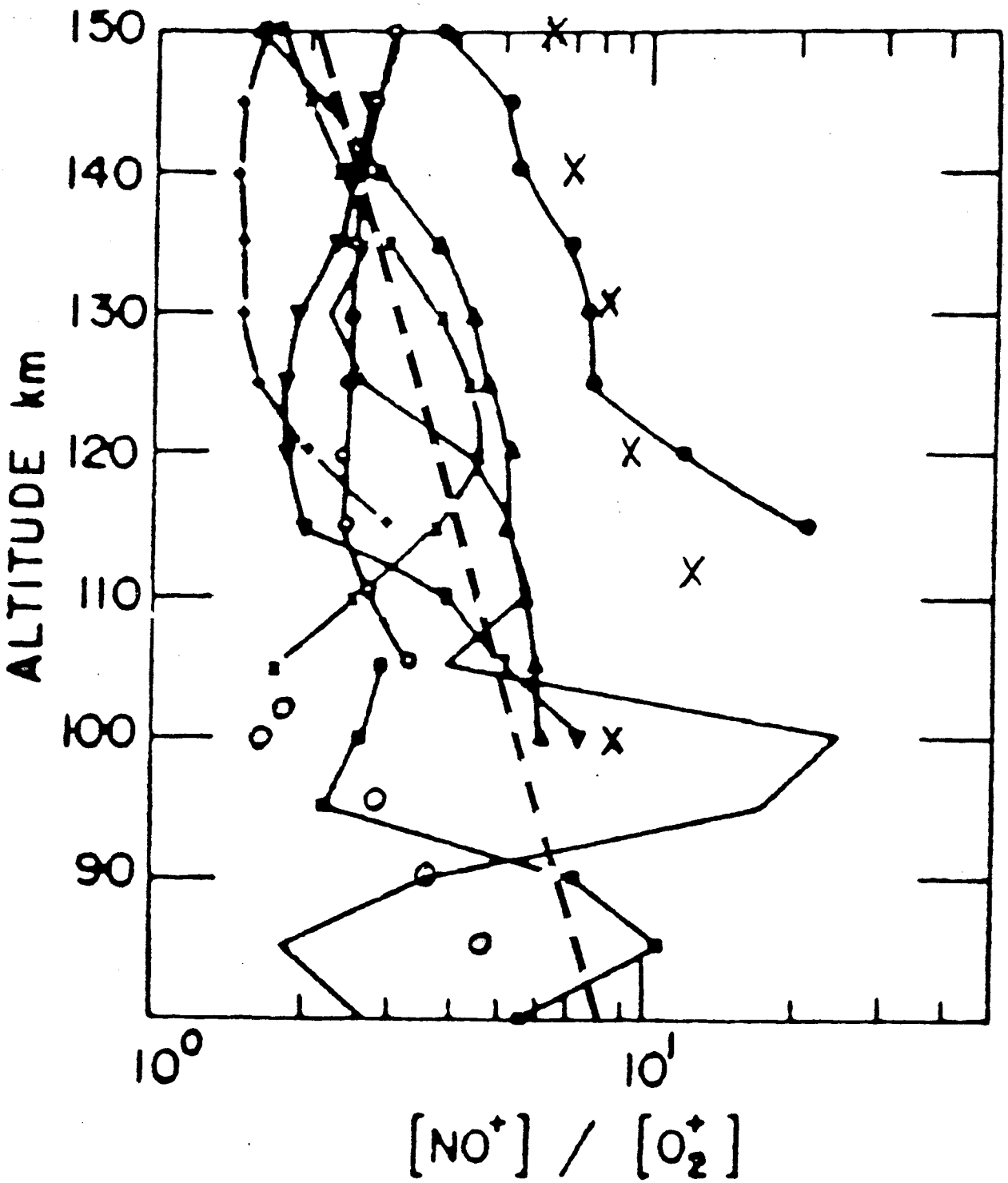

Figure 2

Ionisation profiles for various recombination coefficient profiles

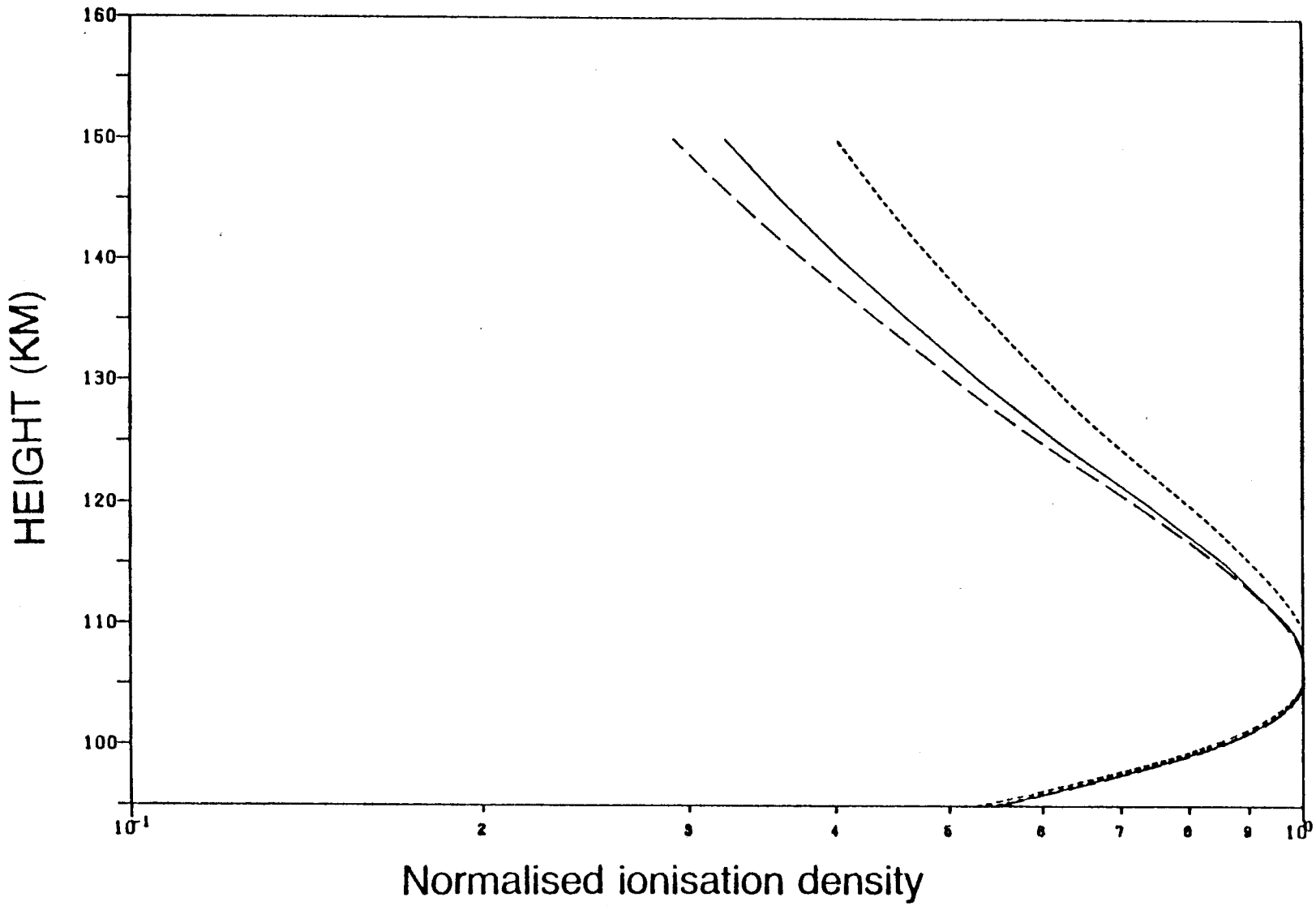

Figure 3

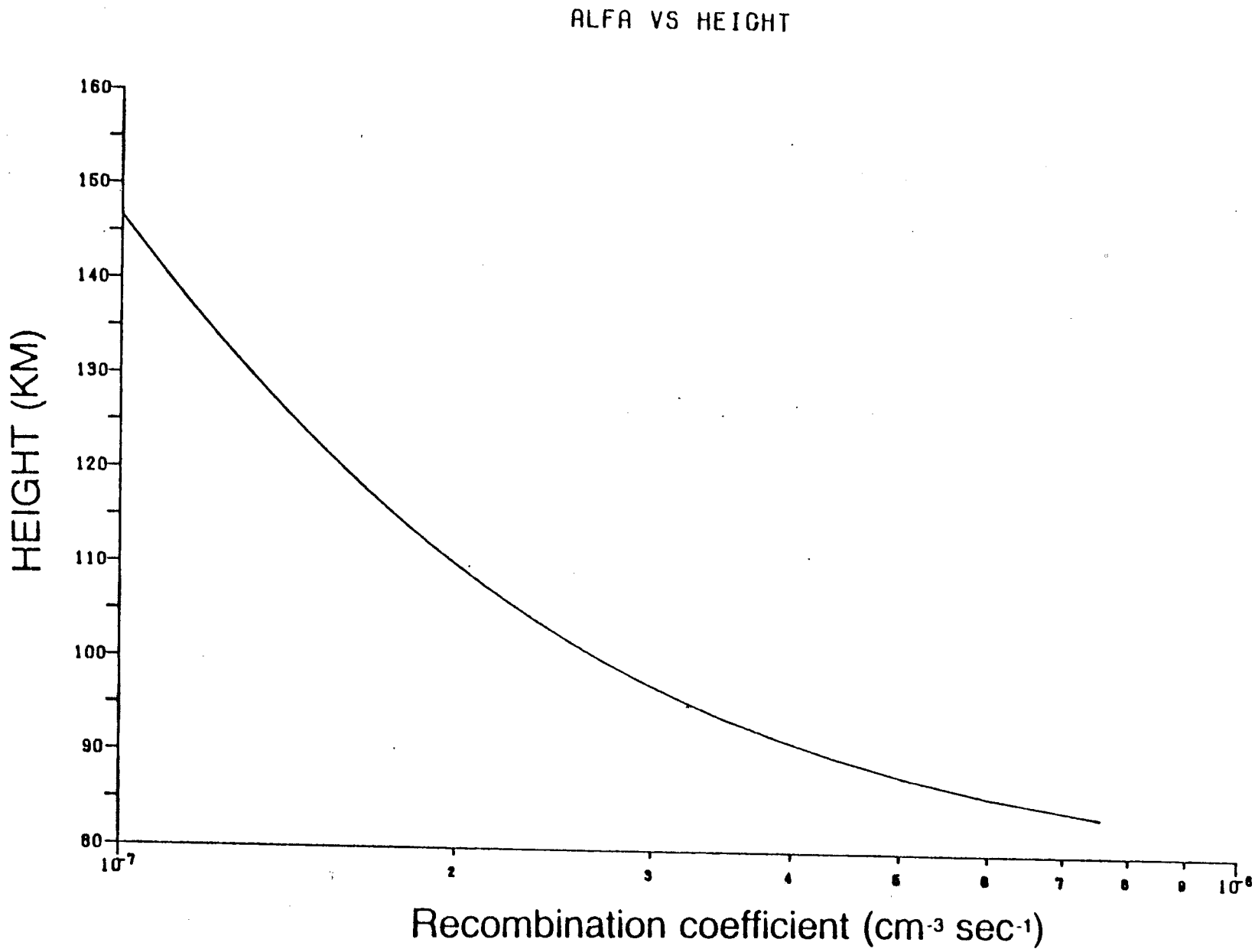
ALFA VS HEIGHT
HEIGHT (KM)
160
150
140
130
120
110
100
90
80
10^{-7}
2
3
4
5
6
7
8
9
10^{-6}
Recombination coefficient (cm^{-3} sec^{-1})

Figure 4

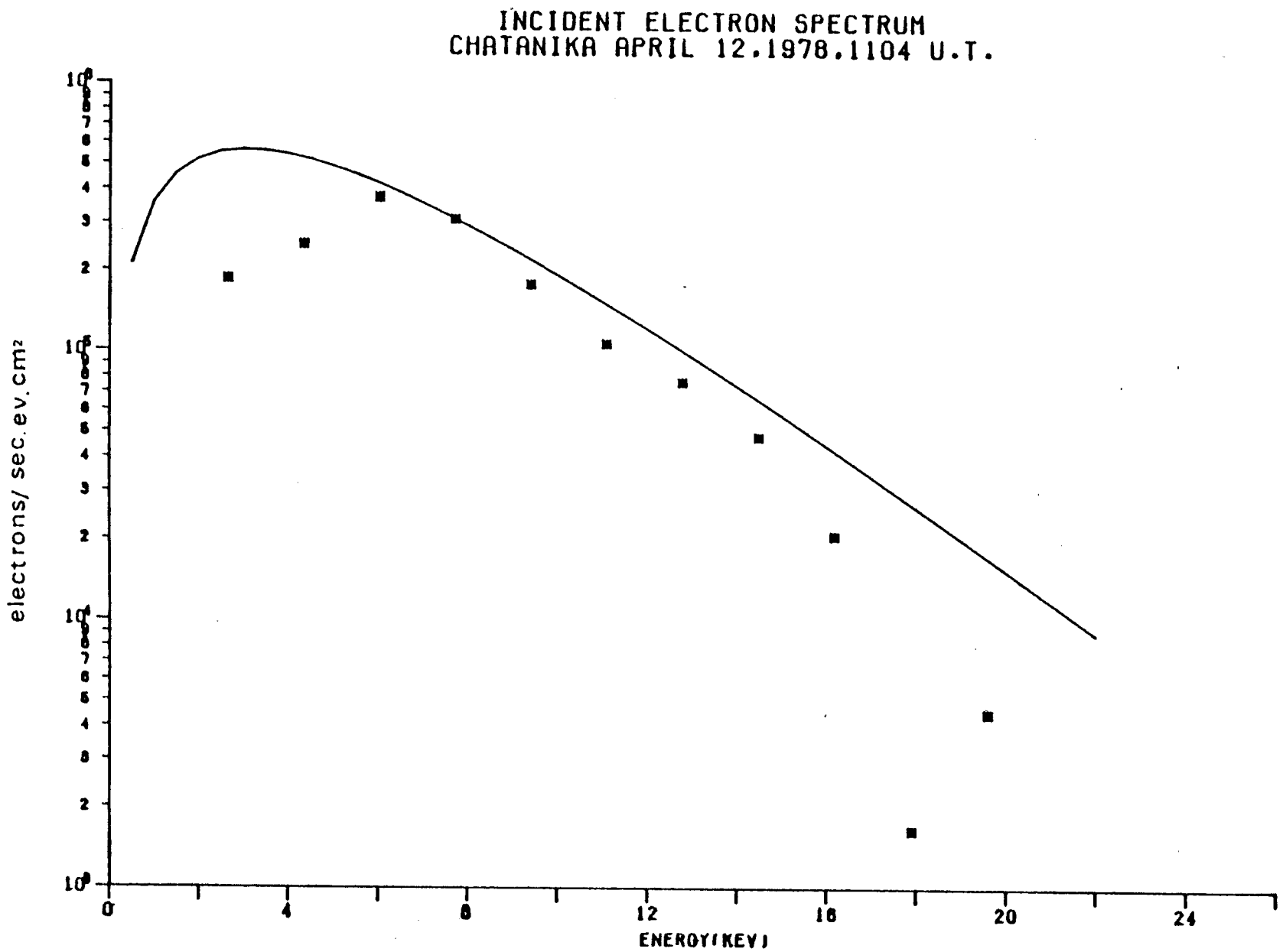
INCIDENT ELECTRON SPECTRUM
CHATANIKA APRIL 12.1978.1104 U.T.
electrons/ sec.ev.cm²
ENERGY(KEV)
0
4
8
12
16
20
24

Figure 5

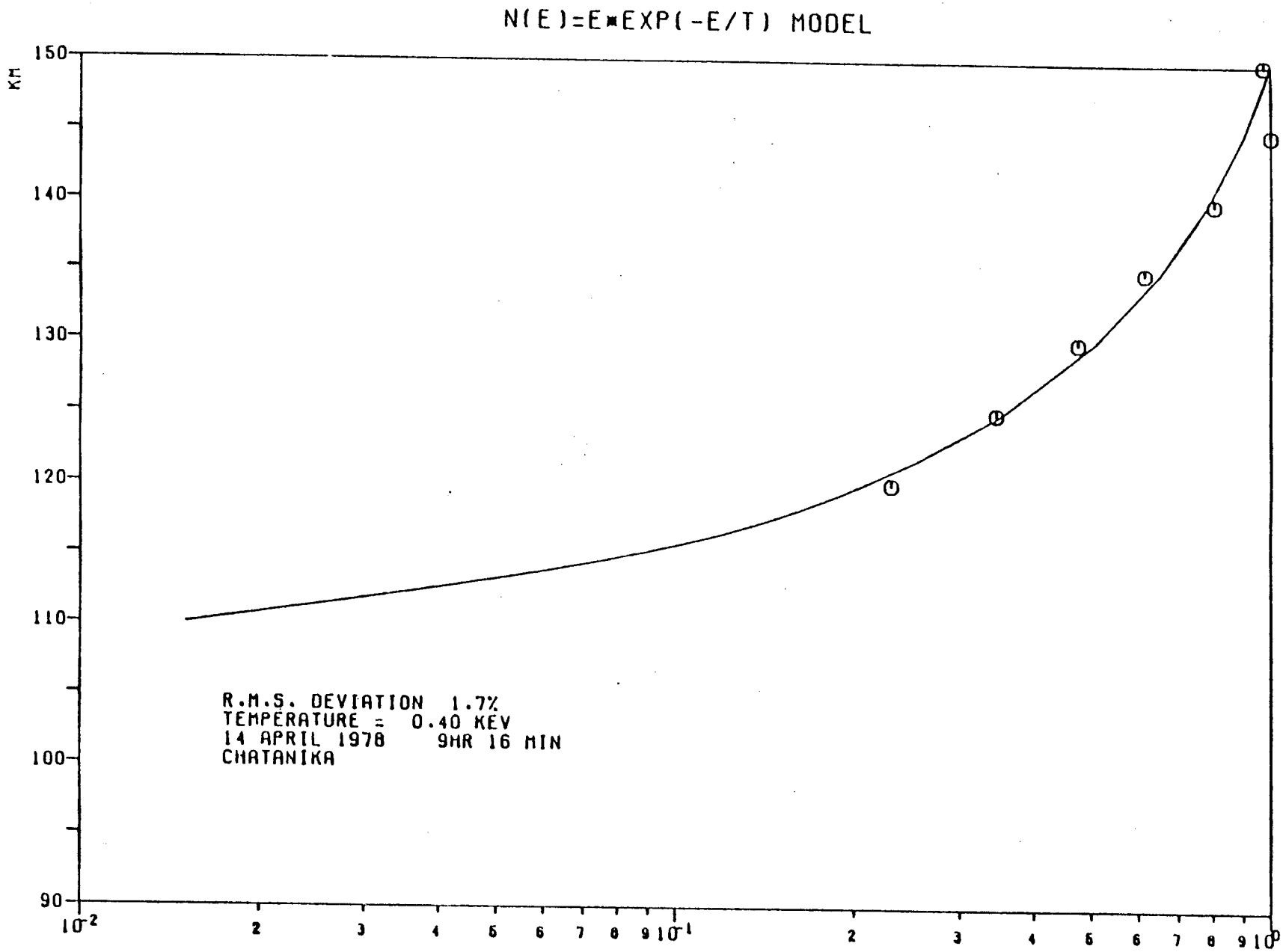
N(E)=E*EXP(-E/T) MODEL
KM
150
140
130
120
110
100
90
R.M.S. DEVIATION 1.7%
TEMPERATURE = 0.40 KEV
14 APRIL 1978 9HR 16 MIN
CHATANIKA
10^-2
2
3
4
5
6
7
8
9
10^-1
2
3
4
5
6
7
8
9
10^0

Figure 6

Distribution of RMS errors
of fitted ionisation profiles

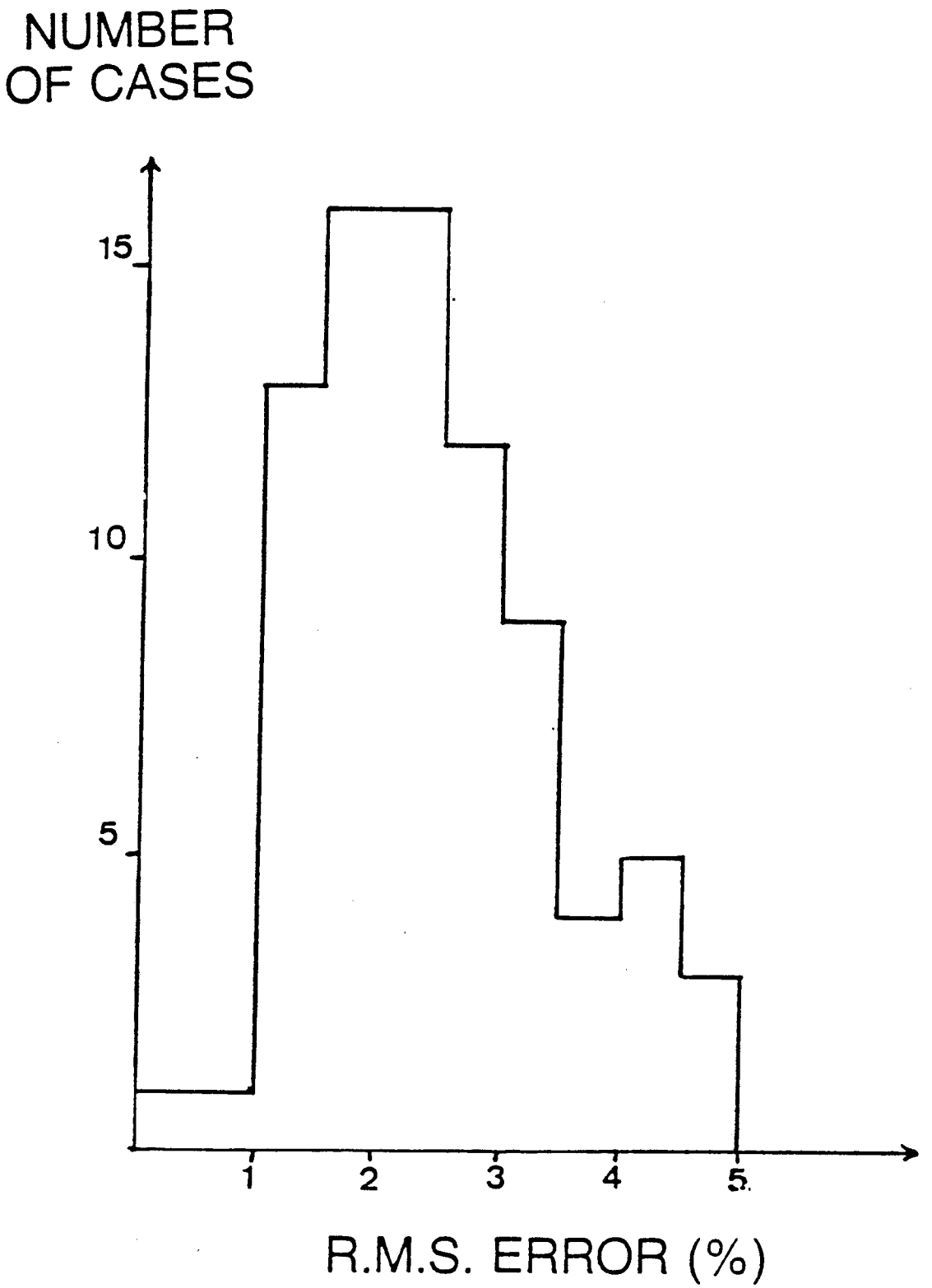

Figure 7

APRIL 14 1978, CHATANIKA

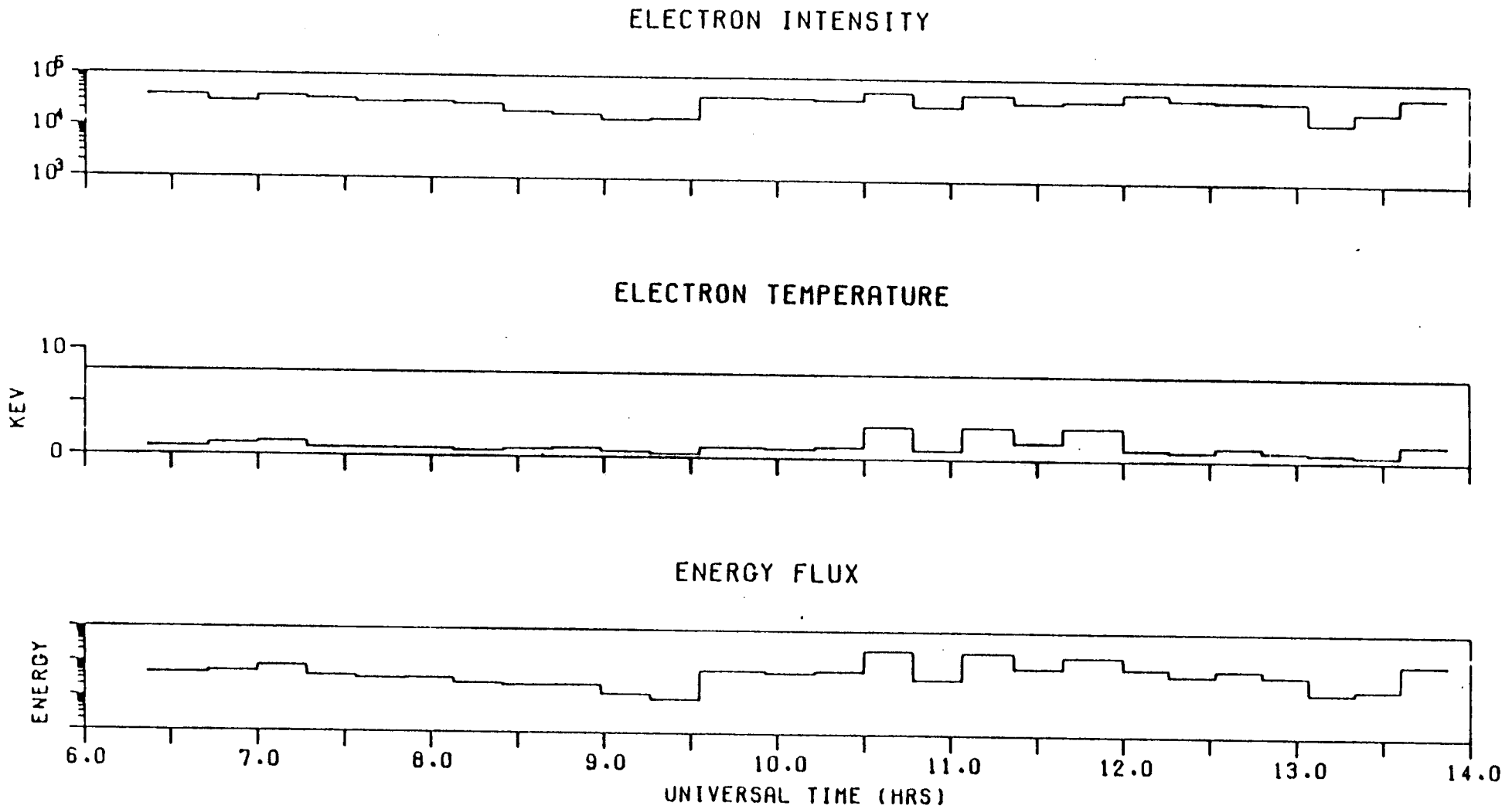

Figure 8

LISTE DE DIFFUSION NOTE BAROUCH

BELGIQUE

LEMAIRE, Joseph	Institut d'Aéronomie Spatiale, 3 Avenue Circulaire, 1180-BRUXELLES

FINLANDE

KANGAS, Jorma	Department of Physics, University of Oulu, Linnanmaa, 90570 OULU-57

FRANCE

BAUER, Pierre	CRPE/CNET 92131 ISSY-LES-MOULINEAUX
BEGHIN, Christian	CRPE/CNRS, La Source, 45045 ORLEANS CEDEX
BLANC, Michel	CRPE/CNET 92131 ISSY-LES-MOULINEAUX
CAIRO, Laurent	CRPE/CNRS, La Source, 45045 ORLEANS CEDEX
DECREAU, Pierrette	CRPE/CNRS, La Source, 45045 ORLEANS CEDEX
ETCHETO, Jacqueline	CRPE/CNET 92131 ISSY-LES-MOULINEAUX
FEHRENBACH, Michel	Observatoire de Haute-Provence, 04300 FORCALQUIER
GARNIER, Michel	Physique et Dynamique de l'Atmosphère, Tour 14, 4, Place Jussieu, 75230 PARIS CEDEX 05
HARVEY, Christopher	Observatoire de Meudon, 92190 MEUDON
HIEBLOT, James	CRPE/CNRS, La Source, 45045 ORLEANS CEDEX
HIGEL, Bernard	CRPE/CNET 92131 ISSY-LES-MOULINEAUX
KOFMAN, Wladek	C.E.P.H.A.G., B.P. 46, 38402 ST-MARTIN D'HERES
LATHUILLERE, Chantal	" " " "
LEJEUNE, Gérard	" " " "
PELLAT, René	Centre de Physique Théorique, Ecole Polytechnique Plateau de Palaiseau, 91128 PALAISEAU CEDEX
PETITDIDIER, Monique	Service d'Aéronomie, B.P. 3, 91370 VERRIERES-LE-BUISSON
PIRRE, Michel	CRPE/CNRS, La Source, 45045 ORLEANS CEDEX
POTTELETTE, Raymond	Laboratoire de Géophysique Externe, 4 Avenue de Neptune, 94100 SAINT-MAUR DES FOSSES

PRANGE, Renée	Laboratoire de Physique Stellaire et Planétaire, B.P. N° 10, 91370 VERRIERES-LE-BUISSON
REME, Henri	C.E.S.R., B.P. 4346, 31029 TOULOUSE CEDEX
REVAH, Isaac	CRPE/CNET 92131 ISSY-LES-MOULINEAUX
ROUX, Alain	" "
SAUVAUD, Jean-André	C.E.S.R., B.P. 4346, 31029 TOULOUSE CEDEX
STOREY, Owen	CRPE/CNRS, La Source, 45045 ORLEANS CEDEX
TREILHOU, Jean-Paul	C.E.S.R., B.P. 4346, 31029 TOULOUSE CEDEX

REPUBLIQUE FEDERALE D'ALLEMAGNE

BAUMJOHANN, Wolfgang	Institut für Geophysik, Gievenbecker Weg 61, D-44 MÜNSTER/WESTF
DIEDRICH, Wolfgang	Institut für Geophysik, Herzberger Landstr. 180, D-3400 GÖTTINGEN
HÄRENDEL, Gerhardt	Inst. für Extraterrestriche Physik, Max-Planck Institut für Physik u. Astrophysik, D-8046 GARCHING b. MÜNCHEN
KREMSER, Gerhard	MPAE, 3411 KATLENGURG-LINDAU
LANGE-HESSE, Günther	" "
VASYLIUNAS, Vytenis	" "
VILLAIN, Jean-Paul	" "

HOLLANDE

PEDERSEN, Arne	Space Science Department, ESA, Postbus 299, 2200 AG-NOORDWIJK

NORVEGE

HARANG, Ove	I.M.R., University of Tromsø, Boks 953, 9001-TROMSØ

SUEDE

BOSTRÖM, Rolf	Uppsala Ionospheric Observatory, S-75590 UPPSALA
ELIASSON, Lars	Kiruna Geophysical Institute, P.O.B. 704, S-98127 KIRUNA
HAGFORS, Tor	Kiruna Geophysical Institute, P.O.B. 704, S-98127 KIRUNA

GRANDE-BRETAGNE

CHRISTIANSEN, Peter	Physics Building, Sussex University, FALMER, BRIGHTON BN1 9QH
GOUGH, Paul	" " " "
MADAHAR, Bob	Lancaster University, Bailrigg, LANCASTER LA1 4QQ
WRENN, Gordon	Mullard Space Laboratory, Holmbury St. Mary, DORKING, Surrey RH5 6NS

U.S.A.

GREENWALD, Raymond	APL, Johns Hopkins University, LAUREL, MD. 20810
POTEMRA, Thomas	" " " " "
KRIMIGIS, Stamatos	" " " " "
DOUPNIK, J.R.	CASS, VMC-41 Utah State Univeristy Logan, UT 84322
BARON, M.	Radio Physics Lab, SRI, Menlo Park CA 94025
DE LA BEAUJARDIERE, O.	" " " " "
VICKREY, J.	" " " " "
REES, F.	Geophysical Institute, University of Alaska, FAIRBANKS, ALASKA
AKASOFU, S.I.	" " " "

U.R.S.S.

LAZUTIN, Leonid	Polar Geophysical Institute, APATITY 184200, MURMANSK REGION
USPENSKY, Mikhail	" " " "

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Centre de Recherches
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Avenue de la Recherche scientifique
45045 ORLEANS CEDEX

Département ETE
Etudes par Télédétection
de l'Environnement

CNET - 38-40 rue du général Leclerc
92131 ISSY-LES-MOULINEAUX

CNET imp 75.1163