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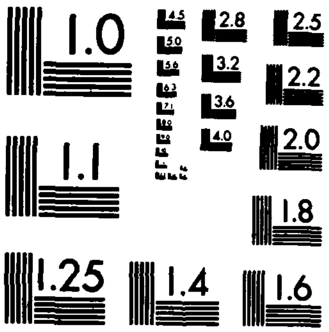

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Dual Maxwellian Space Plasma Modeling by the Logarithmic Method

A. L. BESSE
A. G. RUBIN
M. F. TAUTZ

5 July 1983

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HANSCOM AFB, MASSACHUSETTS 01731

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CHARLES P. PIKE,
Spacecraft Environment Branch
BRANCH CHIEF

Rita C Sagalyn
RITA C. SAGALYN
Space Physics Division
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A.L. Besse
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A common and useful practice in the study of spacecraft charging phenomena is the use of dual Maxwellian models of the particle distributions. These models frequently employ a least error fit to the logarithm of the measured distribution function over an energy range that may exceed three decades. By example, we demonstrate that the resulting models are not satisfactory for the calculation of spacecraft charging. The models do not have a sufficient number of adjustable parameters to fit the measured spectra over such a wide energy range. More satisfactory models are obtained by weighting →(Contd)

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20. Abstract (Contd)

the spectral data according to their relevance to the spacecraft charging phenomena under investigation. In addition, reasonable limits must be placed on the temperatures of the models to prevent the artifacts that have been experienced in a minority of cases.

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Dual Maxwellian Space Plasma Modeling by the Logarithmic Method

1. INTRODUCTION

A very common practice in the study of spacecraft charging is replacing measured spectra with dual Maxwellian models. Dual Maxwellian models are easily visualized, reduce the number of parameters per species to a manageable four (N_1, T_1, N_2, T_2), and minimize or eliminate the need for numerical integrations. Originally, the models were fitted exactly to the four moments of the distribution function corresponding to number density, number flux, energy density, and energy flux as described by Garrett[1]. Many investigators felt that this method was unsatisfactory and changed to a least-root-mean-square error fit to the logarithm of the distribution function using all data points above the noise level, as described by E.G. Mullen, M.S. Gussenhoven, and H.B. Garrett[2]. This least error fit to the logarithm of the distribution function is the subject of this report.

(Received for publication 27 June 1983)

1. Garrett, H.B. Modeling of the Geosynchronous Orbit Plasma Environment--Part 1 (1977) AFGL-TR-77-0288, AD A053164.

2. Mullen, E.G., Gussenhoven, M.S., and Garrett, H.B. (1981) A "Worst Case" Spacecraft Charging Environment as Observed by SCATHA on 24 April 1979, Figure 8, AFGL-TR-81-0231, AD A108680.

1.1 General Comments

The least error fit to the logarithm of the distribution function gives equal weight to a 10 percent change anywhere in the spectrum. In that sense, this method is impartial. It is mathematically identical to a least error fit to the logarithm of the differential flux.

If the logarithm of the distribution function had the same random error at all energies and if the distribution was known in advance to be a dual Maxwellian distribution, then the method would be statistically correct. However, the random error in the logarithm of the distribution function is not constant; it is highest at the two ends of the spectrum where the count rate is low. More important, the measured spectrum is generally not a dual Maxwellian spectrum and cannot be approximated by a dual Maxwellian model within a factor of 2; in some cases, the best approximation is off by a factor of 10 at some energies. Therefore, a modeling method for spacecraft charging calculation must be judged by how well it models that region of spectrum most intimately involved in spacecraft charging.

Plotting the logarithm of the distribution function (both as measured and according to the model) against the logarithm of the energy is deceptive. It gives no indication of the relative importance of various energy regions. On the scale usually employed, a factor of 2 is represented by a mere 3 mm, which causes a poor fit to look good. Therefore, this type of plot will not be used.

1.2 Test Spectrum

In the present context, a prime requirement of a modeling system is that it reliably predict severe spacecraft charging. Accordingly, the spectrum selected is the "worst case" electron spectrum (component perpendicular to magnetic field) reported by E.G. Mullen, M.S. Gussenhoven, and H.B. Garrett[2]. This spectrum was obtained by the SC5 instrument aboard the SCATHA spacecraft at approximately 0650 on 24 April (day 114) 1979. Six spectra obtained on the SC9 instrument over a 3-minute interval centered at 0650 are also used for comparison.

1.3 Criteria

The electron impact rate determines the primary electron current, and the energy distribution of these impacts determines the opposing secondary electron current. Therefore, two criteria for a model are that (1) it correctly gives the number flux (particles $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{ster}^{-1}$); and (2) it correctly gives the mean impact energy. The mean energy is twice the rms temperature. This temperature is, by definition, one-half of the energy flux divided by the number flux.

A third criterion is that the impact energy distribution of the model must be similar to that of the input spectrum. The energy distribution can be shown visually either by a plot of

$$\frac{dJ}{du} \text{ vs } u \tag{1}$$

or by a plot of

$$u\,\frac{dJ}{du} \text{ vs } \ell n\,u \tag{2}$$

where J = number flux ($\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{ster}^{-1}$)*

u = energy (ev)

dJ/du = differential number flux ($\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{ster}^{-1}\ \mathrm{ev}^{-1}$)

$(u\ dJ)/du$ = differential energy flux ($\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{ster}^{-1}$)

The second plot will be used because it results in an approximately equal spacing of the data points. It is very similar to a plot of count rate vs channel numbers.

2. FOUR MODELS OF SC5 ELECTRON SPECTRUM

The four dual Maxwellian models of the SC5 electron spectrum are all least-root-mean-square-error fits to the logarithm of the measured distribution function. The first level of the calculation consists of two steps:

(1) The high-temperature component is fitted to the data above some break point v_B.

(2) The low-temperature component is fitted to the data below the break point plus any residue above the break point.

If the second level of calculation is used, the results of level one are used as

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*The flux in any energy interval is given by

$$J(u_1, u_2) = \int_{u_1}^{u_2} \frac{dJ}{du}\, du = \int_{\ell n\, u_1}^{\ell n\, u_2} \left(u\ \frac{dJ}{du}\right) d\ \ell n\, u$$

input to a code intended to further reduce the rms error. No break point is used in level two calculations.

The first model, shown in Figure 1, is a level one calculation by Mullen et al[2] using a 4 keV break point. The parameters are listed and the differential energy flux is plotted. Densities (N) are in cm^{-3}, temperature (T) in keV, and fluxes (J) in cm^{-2} sec^{-1} $ster^{-1}$. The high-temperature component's flux (J_2) is given as a percent of the model's total flux. For this model, it is 99 percent. In other words, for all practical purposes, it is a single Maxwellian distribution. Figure 1 shows a poor fit between the differential flux of the model and of the observed spectrum. The root-mean-square-error in the logarithm (base e) of the distribution function is 1.43. This is equivalent to a factor of 4.

The remaining models, shown in Figures 2, 3, and 4 are by Tautz using the ALLES code. Model 2 (Figure 2) uses a 15 keV break point, thereby reducing by two the number of data points used in the high-temperature fit and increasing by two those in the low-temperature fit. It is also a level one calculation. Like the first model, this model shows a poor fit to the observed differential energy flux. The rms error in fitting the logarithm of the distribution function is 1.33, a fit not significantly better than that of model 1.

Model 3 (Figure 3) was obtained by using the model 2 results as inputs to a level two calculation. This model shows a markedly improved fit to the observed differential energy flux. The fit to the logarithm of the distribution function is a little worse, with an rms error of 1.55.

The fourth model (Figure 4) uses a level one calculation and a break point of 5 keV. The critical difference between this model and the other three is that the two lowest and the two highest energy data points have been discarded. These four data points contribute very little, only 3.5 percent, to the integrated flux. The plot of this model shows the best fit to the observed differential energy flux. The fit to the logarithm of the distribution function with the two highest and the two lowest energy data points deleted has an rms error of 0.42, which is relatively small. If all the data points are included, the rms error in the logarithm of the distribution function jumps to 4.18. This represents a mean error of over a factor of 10 in the distribution function itself.

Figures 1, 2, 3, and 4 specify the flux and rms temperature according to the models. The flux and rms temperature calculated directly from the SC5 data are 1.09×10^9 cm^{-2} sec^{-1} $ster^{-1}$ and 14.8 keV respectively.

3. SC9 ELECTRON SPECTRA

The dual Maxwellian parameters were fitted to the six spectra obtained by the SC9 instrument. This was done with both the complete measured spectra and with the lowest 2 keV discarded.

The results for both instruments are summarized in Table 1.

Table 1. Range of Dual Maxwellian Parameters for "Worst Case" Electron Spectrum Obtained by the SC9 Instruments

Parameter	Range of values		
	Data Source		
	SC5	SC9	SC9 2 keV
N_1	0.2-2.5	0.1-0.4	0.1-0.9
T_1	0.4-10.7	0.5-2.6	2.6-7.9
N_2	0.03-2.3	1.2-1.8	1.0-1.4
T_2	13.0-40.7	9.1-13.3	10.4-14.9
J 10^9x	1.1-2.0	0.7-1.0	0.7-1.0
T_{rms}	11.8-24.5	8.8-13.0	8.7-13.5

4. COMMENTS

Figures 1, 2, and 3 illustrate that the models obtained by the method are extremely sensitive to some rather arbitrary decisions. The portion of the spectrum controlling spacecraft charging is not satisfactorily described in any of these models.

The model illustrated in Figure 4 used a crude weighting system. All points in the spectrum contributing substantially to the flux were given a weight of one, and all others, a weight of zero. As a result, this model fits the measured spectrum far better than the others do in the energy range that is important in spacecraft charging phenomena. The price for this improvement is a much worse fit over other portions of the spectrum. From a different point of view, the model shown in Figure 4 is fitted to the measured spectrum over an energy range of 2.2 orders of magnitude rather than the 3.4 orders of magnitude used for the other models.

The conclusion is that the method is satisfactory only if the various spectral regions are weighted according to their relevance to the task at hand, and then only if the relevant section of the spectrum is relatively narrow, for example, if it covers not more than two decades. To model a wider spectral range accurately,

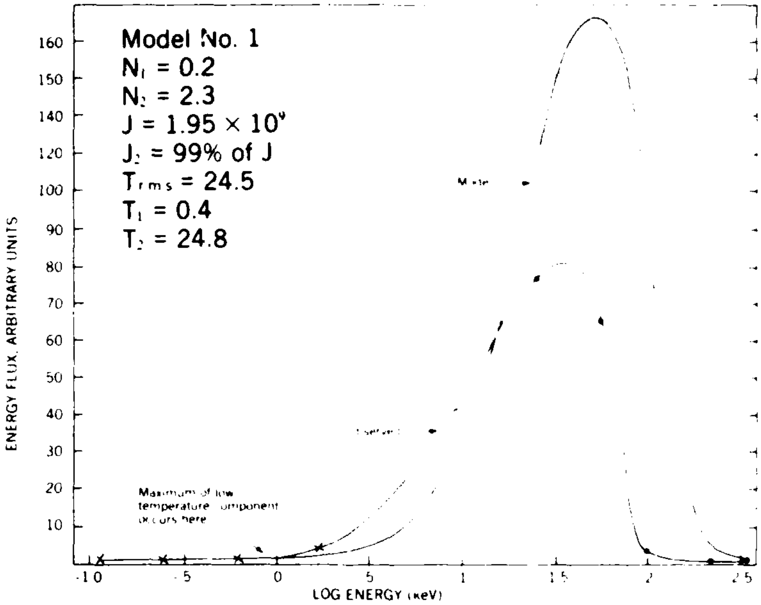

Figure 1. Observed SC5 electron spectrum and model 1 thereof. High and low temperature components of model were fitted to data points indicated by circles and crosses respectively

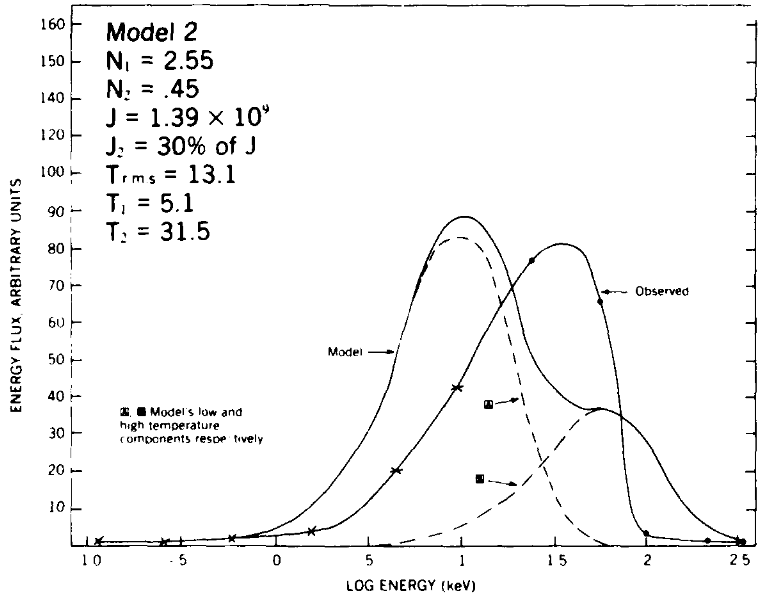

Figure 2. Observed SC5 electron spectrum and model 2 thereof. This is similar to model 1 except for shift of two data points from determination of high temperature component to determination of low temperature component

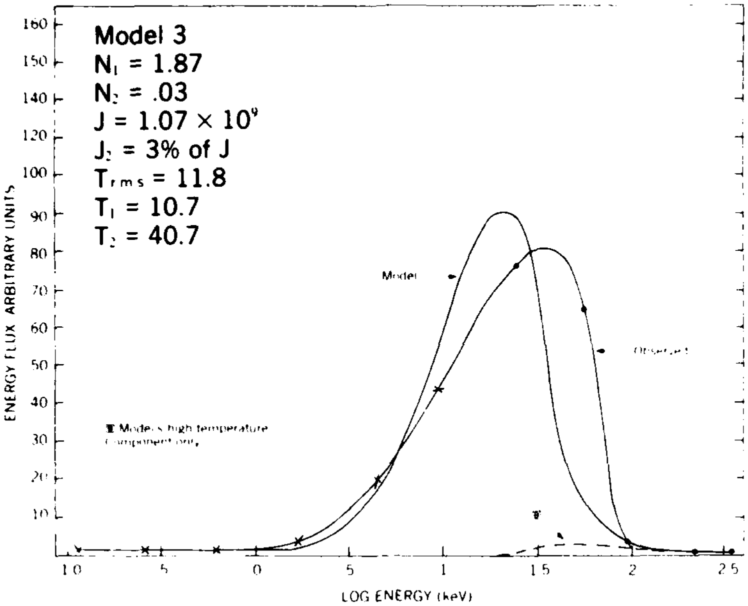

Figure 3. Observed SC5 electron spectrum and model 3 thereof with a level two rather than a level one calculation

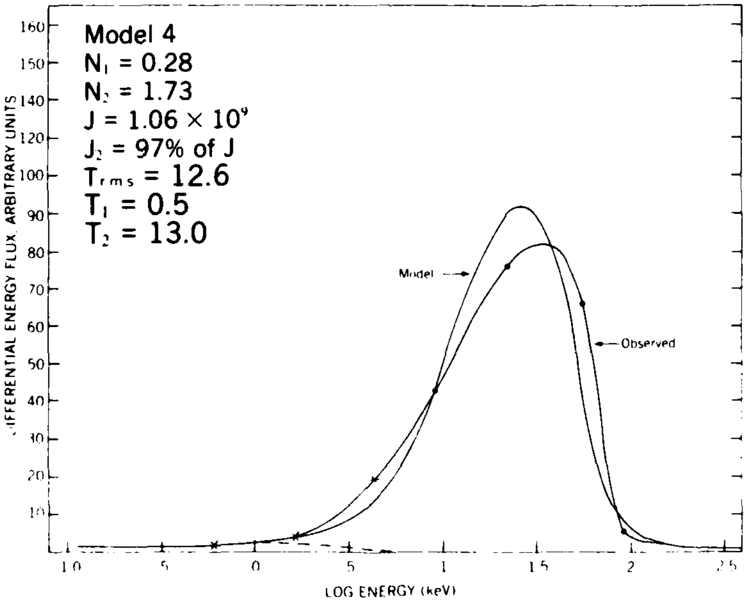

Figure 4. Observed SC5 electron spectrum and model 4 thereof. The two highest and the two lowest data points were not used

the model must be modified to contain more than the present four adjustable parameters.

Forcing a dual Maxwellian model fit on a spectrum occasionally produces artifacts, the most common being a low-temperature component whose temperature approaches zero and whose density approaches infinity. These artifacts can be prevented by placing a quite reasonable requirement on the model, the requirement that each of the two temperatures fall within the energy band which contributes substantially to spacecraft charging.

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1. Garrett, H.B. Modeling of the Geosynchronous Orbit Plasma Environment--Part 1 (1977)
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2. Mullen, E.G., Gussenhoven, M.S., and Garrett, H.B. (1981) A "Worst Case" Spacecraft Charging Environment as Observed by SCATHA on 24 April 1979, Figure 8,
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