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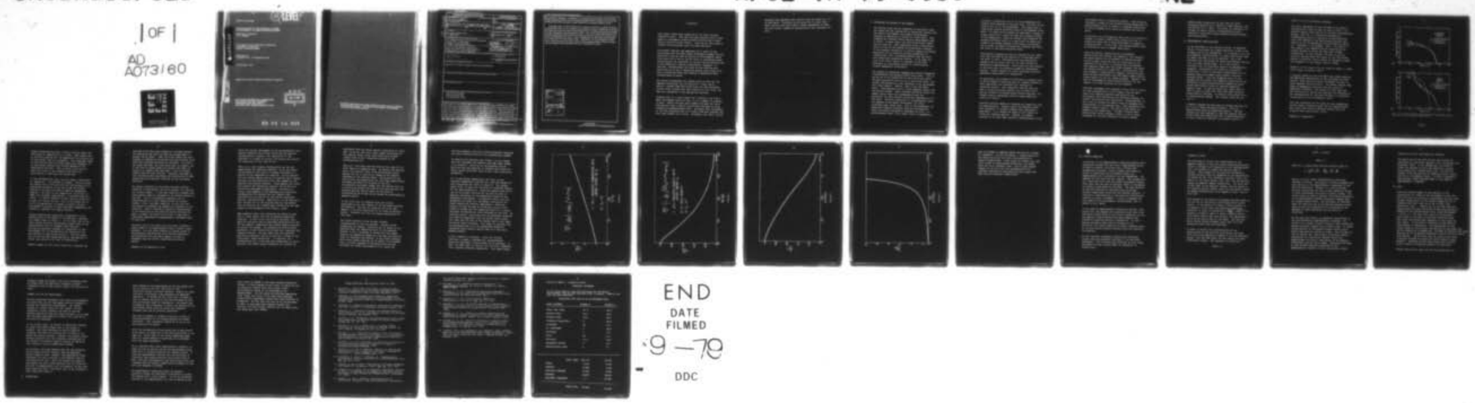

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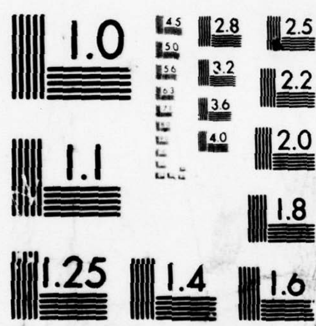

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SPECIFICATION OF THE NATURAL PLASMA ENVIRONMENT AT GEOSYNCHRONOUS ORBIT

Sherman E. DeForest
E.C. Whipple

The Regents of the University of California
University of California
LaJolla, California 92093

Final Report
1 October 1977 - 30 September 1978

10 December 1978

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-79-0060	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SPECIFICATION OF THE NATURAL PLASMA ENVIRONMENT AT GEOSYNCHRONOUS ORBIT		5. TYPE OF REPORT & PERIOD COVERED Final Report 1 Oct 1977 - 30 Sep 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Sherman E. DeForest, E.C. Whipple		8. CONTRACT OR GRANT NUMBER(s) F19628-77-C-0014
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Regents of the University of California, University of California, LaJolla, California 92093		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 766108AA
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts 01731, Monitor/H.B.Garrett, Capt/PHG		12. REPORT DATE 10 December 1978
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

spacecraft charging
environmental atlas
geosynchronous orbit

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers work supported by Air Force contract F19628-77-C-0014. This work has made extensive use of data taken by instruments funded by NASA contracts NAS 5-10364 (ATS-5) and NAS 5-21055 (ATS-6). Much use has been made of software also developed under the same contracts. The present contract was negotiated as a result of the realization that the UCSD plasma instruments onboard the ATS spacecraft could be used to specify an environmental model which would be of use to the Air Force in developing design specifications for spacecraft to prevent faulty operation due to environmentally induced

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Formally this is a final report for a contract, but from a model development point of view, it is a summary of progress to date. Within the next year, SCATHA will make the first observations from a vehicle specifically designed to study charging at geosynchronous orbit. We expect that refinements to the data presented here will result from that program, and that new models will result. Ultimately the users, vehicle designers, and operators must benefit from this work if it is to have merit. Therefore, we are gratified to learn that a model derived from this study is being implemented at NOAA and that several commercial manufacturers have requested our data.

FOREWORD

This report covers work supported by Air Force contract F19628-77-C-0014. This work has made extensive use of data taken by instruments funded by NASA contracts NAS 5-10364 (ATS-5) and NAS 5-21055 (ATS-6). Much use has been made of software also developed under the same contracts.

The present contract was negotiated as a result of the realization that the UCSD plasma instruments onboard the ATS spacecraft could be used to specify an environmental model which would be of use to the Air Force in developing design specifications for spacecraft to prevent faulty operation due to environmentally induced electrostatic charging. In addition, reorganization and study of the existing data would also be of use in developing models which could be of use in predicting times when hazards to spacecraft from charging might be great.

The authors acknowledge the support given by AFGL and the numerous discussions and aid given by C. Pike, and H. Garrett, without whom this study could not have proceeded. Several other persons have been involved in this study and they are referenced in the appropriate sections.

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I. BACKGROUND AND NATURE OF THE PROBLEM

For several years now the community of spacecraft users has known that the interaction of spacecraft surface with the natural environment can produce electrostatic charging to potentials in excess of 10,000 volts. This charging can severely affect particle measurements made in space. In many cases, the desired particles cannot even be observed. More importantly from an operational point of view is the problem of differential charging. If two adjacent surfaces on a vehicle charge to different potentials due to different surface properties or illumination, then a discharge between them can occur with potentially disastrous results. In at least one case an Air Force vehicle is thought to have been destroyed by a discharge induced in a particularly intense geomagnetic disturbance.

The hazards of spacecraft charging are usually thought of in association with geosynchronous earth orbit. This is partly due to the popularity of this particular orbit. The more spacecraft there are in a particular place, the greater the possibility that something in the environment will prove harmful. However, that is not the whole story. Geosynchronous orbit is also somewhat special for the natural plasma. Lower altitude equitorial orbits are almost always within the plasmasphere where the spacecraft are only exposed to particle temperatures of a few volts. Similarly spacecraft in interplanetary space are exposed to the highly directional, but still relatively cool, solar wind. Only in the plasmasheet do spacecraft normally encounter particle distributions which can produce charging to thousands of volts. At geosynchronous orbit, with normal levels of geomagnetic activity, a spacecraft will be in the plasmasphere for several hours centered on the dusk side. The rest of the time it will be in the plasmasheet. This means that it experiences several different types of environments every orbit. It would not be unusual to experience a change in plasma density of a factor of 1000 and a similar change in the temperature. When the various time constants for charging different parts of a spacecraft are taken into account, the sudden changes in the natural environment can be shown to produce differential charging that would not exist in the time stationary state.

Differential charging can also be produced by the simple fact that one side of any vehicle is in sunlight while the other is dark. This means that the equilibrium potential of the front side will be lower because of emission of photoelectrons. Since these are not produced on the back side, the potential might be considerably greater. Either process can create hazardous potential gradients across parts of a spacecraft.

In particular, the problem of differential charging could be solved simply by ensuring that all exposed surfaces of every spacecraft are conductors all fastened to spacecraft ground. This simplistic solution does not work in practice because objects such as solar cells, optical surfaces (including second surface mirrors), and thermal control subsystems cannot be made conductive easily and cheaply.

Therefore detailed models of charging are needed for each new configuration. Whipple (1977) and DeForest (1978) have discussed the various elements that constitute a good model. It is beyond the scope of this report to review the complete process. However, all models required as an input some realistic representation of the environment which is causing the effect. This study was initiated in order to use already existing plasma data at geosynchronous orbit to prepare a condensed description of the environment which would be suitable for such an input.

In addition, the environmental data were to be studied to attempt to produce a model which could be of use in predicting times when a spacecraft might be exposed to charging events. In this way, safe configurations could be selected so that no damage would occur.

These two efforts, modelling and environmental specification are related, but separate. For instance, one could specify the environment by quoting the most intense plasma injection seen and requiring all new spacecraft to be built to withstand that environment. This approach might work for design purposes, but would not advance predictive capability. Alternatively, one could imagine a comprehensive computer code which could make accurate predictions and also supply sample natural plasma spectra to use for design purposes. However, this form of environmental specification would be far too complex to be used routinely by the designer.

Therefore throughout this program we have tried to evolve our data presentation in such a manner that we could supply the simplest possible description of the environment while maintaining the accuracy necessary to predict interactions with spacecraft. Simultaneously, we have tried to develop new models based on semiempirical understanding of the measured data. Both approaches have produced useful results. The bulk of this report is a summary of the plasma data. The more advanced model using kinetic theory (Whipple, 1978c) is still being developed but has been presented to several groups.

Another model to grow out of this work has been developed primarily by H. Garrett at AFGL (Garrett, 1977 and Garrett et al. 1978). This model is essentially an attempt to predict fluxes at geosynchronous orbit (hereafter called GEO) using previously defined ground based observations.

II. ENVIRONMENTAL SPECIFICATIONS

As was mentioned in the previous section, an important factor in specifying the plasma conditions at GEO is the ultimate use of the information. If a designer is to use environmental specifications, he would like to have them as simple and easy to use as possible. He is not concerned with specifying the exact distribution function over the whole nearby range. He is not directly concerned with the underlying physics of magnetospheric dynamics. Unfortunately the nature of spacecraft interaction is that an equivalent monoenergetic fit to measured data will almost surely predict incorrect charging levels. This was recognized early in the program and the initial environmental specification was performed by distributing selected examples of actual plasma observations stored on computer-compatible magnetic tape. It was envisioned that these could be used as input to codes that could then make accurate predictions of charging. In practice this proved to be an unsatisfactory method. The ultimate users did not like it.

A counter proposal has been made to average the data and fit it to a simple Maxwellian spectra. Then the specification could be simplified greatly. The main problem with this approach is that the original data is usually much more complicated that a simple Maxwellian. In fact, using this approach can produce errors of a factor of two in predicting charging.

The final compromise we have developed is to select a representative subset of days as seen by ATS-6. The measured spectra were then fit to the best two-Maxwellian plasma. This fit is a convenient mathematical transformation which is equivalent to specifying the first four moments of the distribution function (for details of the transformation see the Quarterly Report for 1 September to 30 November, 1977). The output is four numbers; the temperatures and densities of two plasmas assumed to occupy the same place without intermixing. In this fashion, the user can get an intuitive feeling about the nature of the real plasma. However no physical reality should be assigned to these two components of the complex natural plasma.

Examples of this type of fit are shown in Figure 1, taken from a paper by Garrett (1977).

A selected subset of data from ATS-6 was chosen based on the operating configuration of the instrument and data quality. These days were spread throughout the year to avoid seasonal biasing effects. The subset contains many types of geomagnetic activity from very quiet to completely disturbed. The spectra on these days were then corrected for spacecraft potential and converted to the two-Maxwellian fit and made available to interested investigators as an environmental atlas.

Also upon completion of this phase of data preparation, certain types of analyses could then be completed much more easily than would be possible working with the unreduced data (see Garrett, 1977).

Comments on Temperature

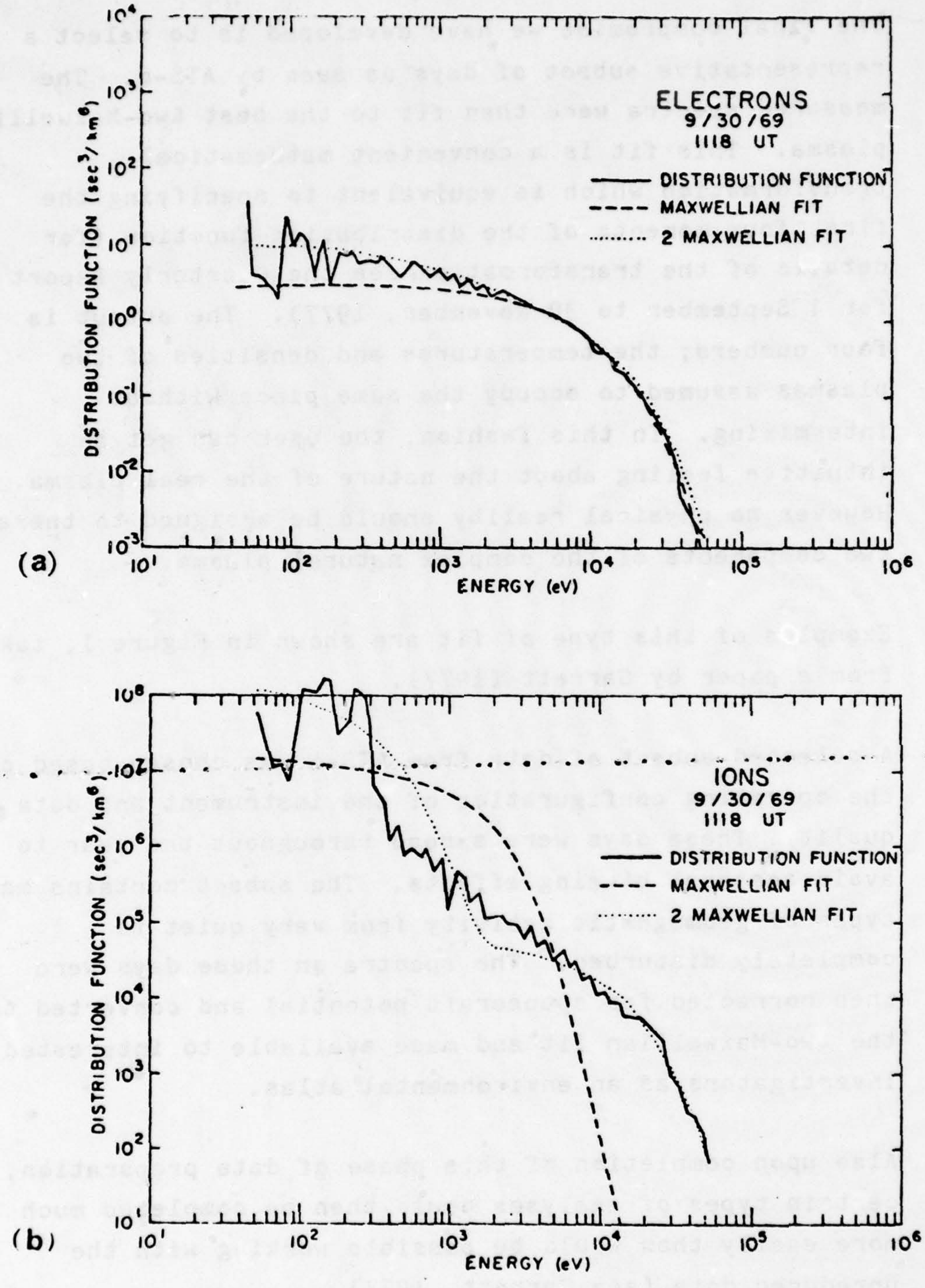


Figure 1. Actual Maxwellian Fit and 2 Maxwellian Fit Distribution Functions for 30 Sept 1969; (a) Electrons, and (b) Ions

FIGURE 1

Before presenting the data, a word of caution about the definition of temperature is in order. Most people have an intuitive feeling for the temperature of an object and so they prefer that as a parameter. This sometimes leads to difficulties since for many theoretical purposes, it is much better working with various moments of the distribution function. This is particularly true in cases that exist in the plasma at GEO where the distribution is definitely not Maxwellian.

In the non-Maxwellian case, one must adopt a definition of temperature. Two methods are common. One can divide the energy flux by the particle flux and multiply by an appropriate constant, or one can divide the energy density by the particle density times an appropriate constant. We refer to the temperatures so derived as "RMS" and "average" respectively. In general they will differ. In spectra observed at GEO, they can differ by as much as a factor of two. This is one reason why we find it inappropriate to attempt to specify the GEO environment by giving a single equivalent temperature and density to represent the complex spectra.

Another problem with specifying a temperature is the meaning given to the number in calculations. Consider the example shown in Figure 1. If the total flux of the lower energy particles approximately equals that of the photoelectrons (not an uncommon case) then the equilibrium potential assumed by a spacecraft in that environment will be determined by the details of the distribution of high energy particle. From the figure one can see the high energy portion of the spectrum is fitted very poorly by the best fit Maxwellian.

Another example of this effect would be to consider the feelings of private pilot landing at a strange airport. The controller had told him that the average speed in pattern was 70 knots. Later the pilot learns that this average is composed of 90 percent civilian aircraft at 60 knots and 10 percent military at 160 knots. If traffic was light that day, the pilot would have no trouble, but if the flux of planes about the airport were high, he would be in trouble from both ends -- but in the most trouble from the fast aircraft. Similarly one might be very concerned about specifying the distribution of high energy particles separate from that of the low energy particles.

The effort described to this point has been oriented primarily at describing a series of spectra in a concise, but accurate manner. It has been implicitly assumed that these spectra would be presented in an ordered fashion to the user. This is an expedient approach, but is unsatisfactory as a final specification for several reasons. First, and most important, is the fact that this method is probably too complex and expensive to use routinely. Also it contains no physical understanding, so the possibility of an unskilled person misusing the model is higher than would be the case if some easily understood progression of magnetospheric phenomena could be specified.

Therefore part of the effort has also been to prepare a global model of the magnetosphere using a kinetic theory approach. This has great promise of leading toward an environmental specification which would be physically self-consistant and much more compact and easy to implement than the current time-ordered series of spectra.

Comments on Two-Maxwellian Fits

Since the initial development of the two-Maxwellian fits, several questions have arisen concerning the physical interpretation, accuracy, and convenience of use. Therefore it is good to review a few points and consider the properties of this type of fit.

There is no valid simple interpretation for the two temperatures and densities reported. We do not assert the existence at any time of a plasma consisting of a mixture of two components as reported. We only measure the real energy spectra and try to simplify their complex structure by calculating the first four momemts of the measured distribution function. These moments are useful and relevant for theoretical studies, but do not have intuitively meaningful significance. Therefore we convert these moments to the mathematically equivalent two-Maxwellian fit because the four numbers that characterize this type of fit have easily understood physical interpretations. Empirically, we can also get a more accurate fit to the original data by this method than we could get by a simple power series with the same number of free parameters (see Garrett, 1978).

Some potential users have expressed the desire to work with a single energy and flux to simulate spacecraft charging. If this is not sufficiently accurate, they would be willing to use an equivalent Maxwellian fit with the two numbers, temperature and density being sufficient to specify the plasma. The problem with both of these approaches is that neither one of them will reproduce the charging behavior. We have shown that the predicted equilibrium potential can be in error by a factor of two from using a single Maxwellian. In contrast, the two-Maxwellian fit is not much more complicated to use in practice, and almost always reproduces the correct (as determined from the actual spectra) potentials to within 20%. We do not feel that a more simple expression for the spectral shape exists which would give as good results with as low a computing overhead as the two-Maxwellian fit.

There are a few other peculiarities of this type of fit which should be commented upon. We measure the spectrum from a few electron volts to 80 kilo-electron volts. However the fit is derived as though we had complete knowledge of the spectral shape. Particularly in the case of very low temperatures (or very high temperatures) one might ask about the accuracy of the fit. Alternatively one might assume that the derived fits are reflecting accurately the shape of the spectrum over the measured portion and ask about the accuracy of extrapolating the fitted curves beyond the experimentally measured points.

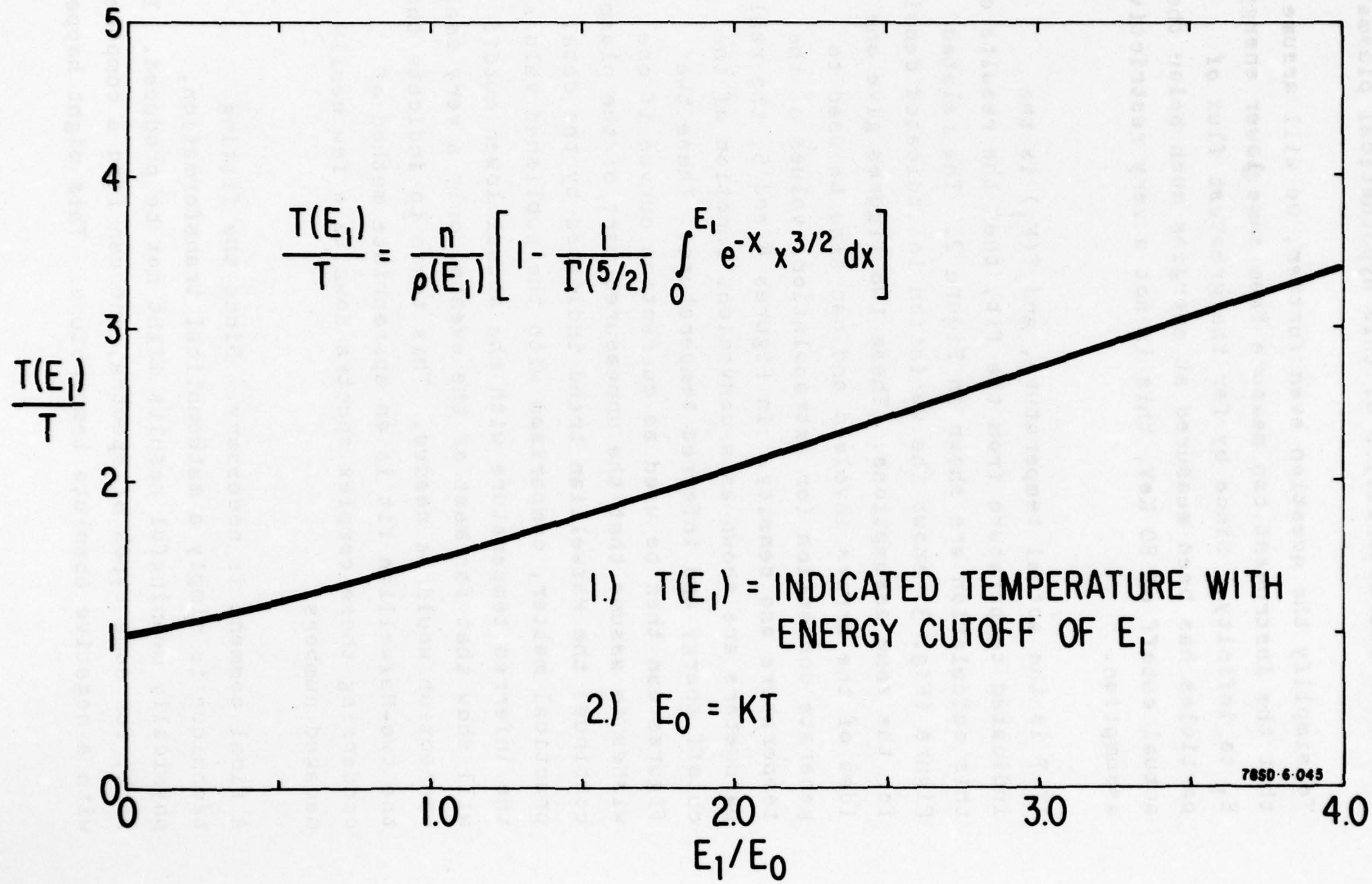
In the first case we recognize that the fitting algorithms do not care whether or not the whole spectrum was measured. The best fit based on the first four moments is returned regardless of the range of measured points. Therefore the fits are always appropriate for this data.

The second question of how to make rational extrapolations is not well-defined. Several ad hoc assumptions are needed. Obviously one is unable to say anything about the unmeasured parts of the spectrum. However if one is disposed to assume that the plasma contains no unmeasured components, and that the spectral shape is reasonably well-bahaved at the lowest energies, then a more simple question can be asked: if the plasma were in reality composed of two Maxwellians and one performed the normal measurements on it, would the derived parameters from this fitting procedure reproduce the known characteristics of this hypothetical plasma?

To simplify the question even further, we will assume that the instrument can measure from some lower energy, E_1 to infinity. Since by far the greatest flux of particles has been measured at energies much below the actual cutoff of 80 KeV, this is not a very restrictive assumption.

If T is the actual temperature, and $T(E_1)$ is the indicated temperature from the fit, then the results of this calculation are shown in Figure 2. The related Figure (Fig. 3) shows the variation in indicated density for the same assumptions. These two figures give one an idea of the errors involved and can also be used to generate correction (or extrapolation) values of the temperature and density. In Figures 4 and 5, the real parameters are shown as a convenient function of the cutoff energy and inferred temperature. These two figures can then be used as correction curves if one wishes to assume that the unmeasured part of the plasma continues the Maxwellian trend indicated by the data. As practical matter, comparison with the published values of the inferred temperature with the actual lower cutoff will show that for most of the events, only a very small correction would be needed. This tends to indicate that the two-Maxwellian fit is an appropriate method of condensing these complex spectra down to a few easily managed numbers.

A final comment is necessary. Since the fitting technique is simply a mathematical transformation, physically meaningful results might not be produced. In fact, for some types of spectra, one can find a component with a negative absolute temperature. This might happen



T(E1)/T = n/ρ(E1) [1 - 1/Γ(5/2) ∫0^E1 e^-X x^3/2 dx]
T(E1)/T
5
4
3
2
1
0
0
1.0
2.0
3.0
4.0
E1/E0
1.) T(E1) = INDICATED TEMPERATURE WITH ENERGY CUTOFF OF E1
2.) E0 = KT
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FIGURE 2

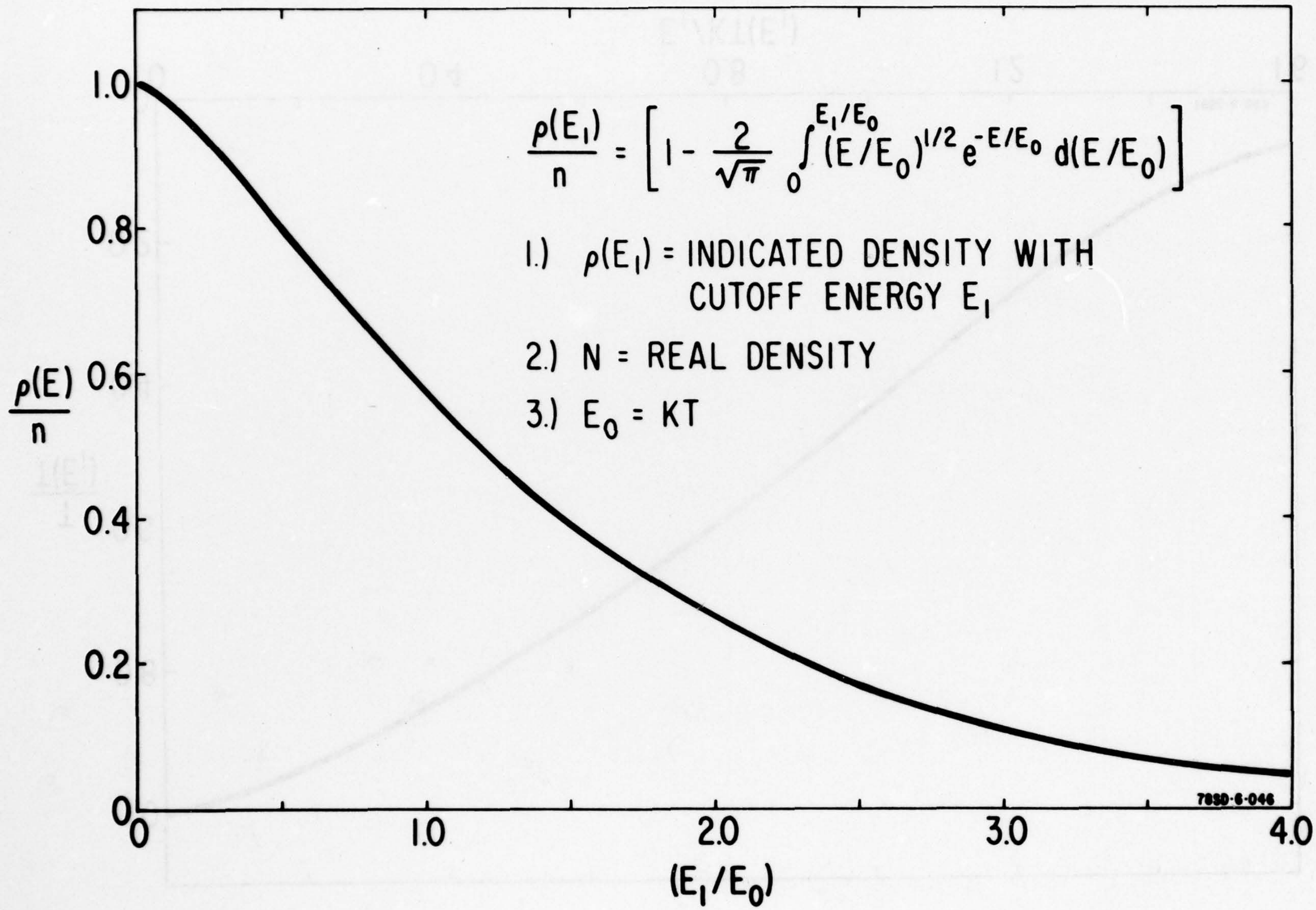
$\frac{\rho(E_1)}{n} = \left[1 - \frac{2}{\sqrt{\pi}} \int_0^{E_1/E_0} (E/E_0)^{1/2} e^{-E/E_0} d(E/E_0)\right]$
1.) $\rho(E_1)$ = INDICATED DENSITY WITH CUTOFF ENERGY E_1
2.) N = REAL DENSITY
3.) E_0 = KT
$\frac{\rho(E)}{n}$
1.0
0.8
0.6
0.4
0.2
0
0
1.0
2.0
3.0
4.0
(E_1/E_0)
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FIGURE 3

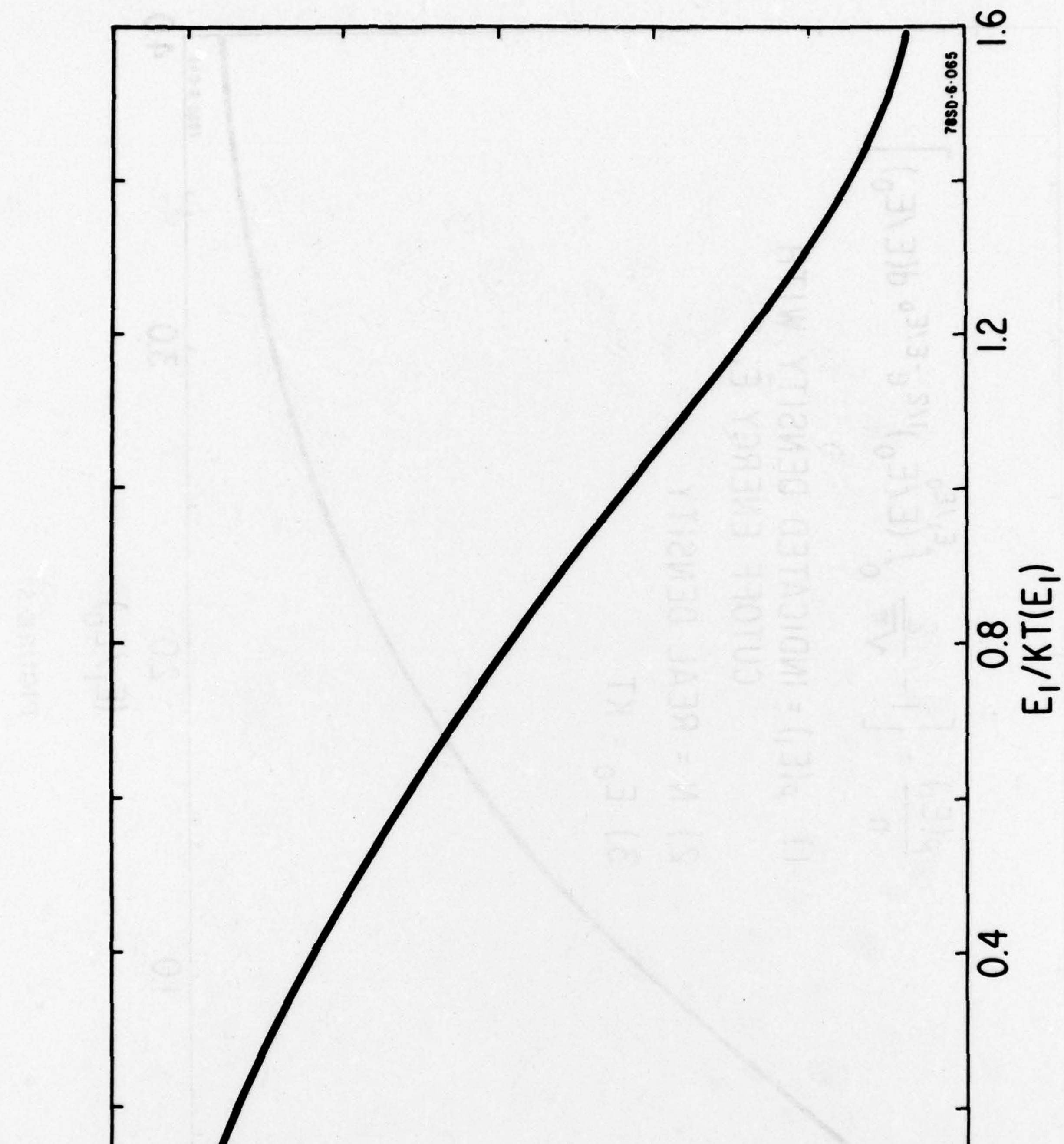

FIGURE 4

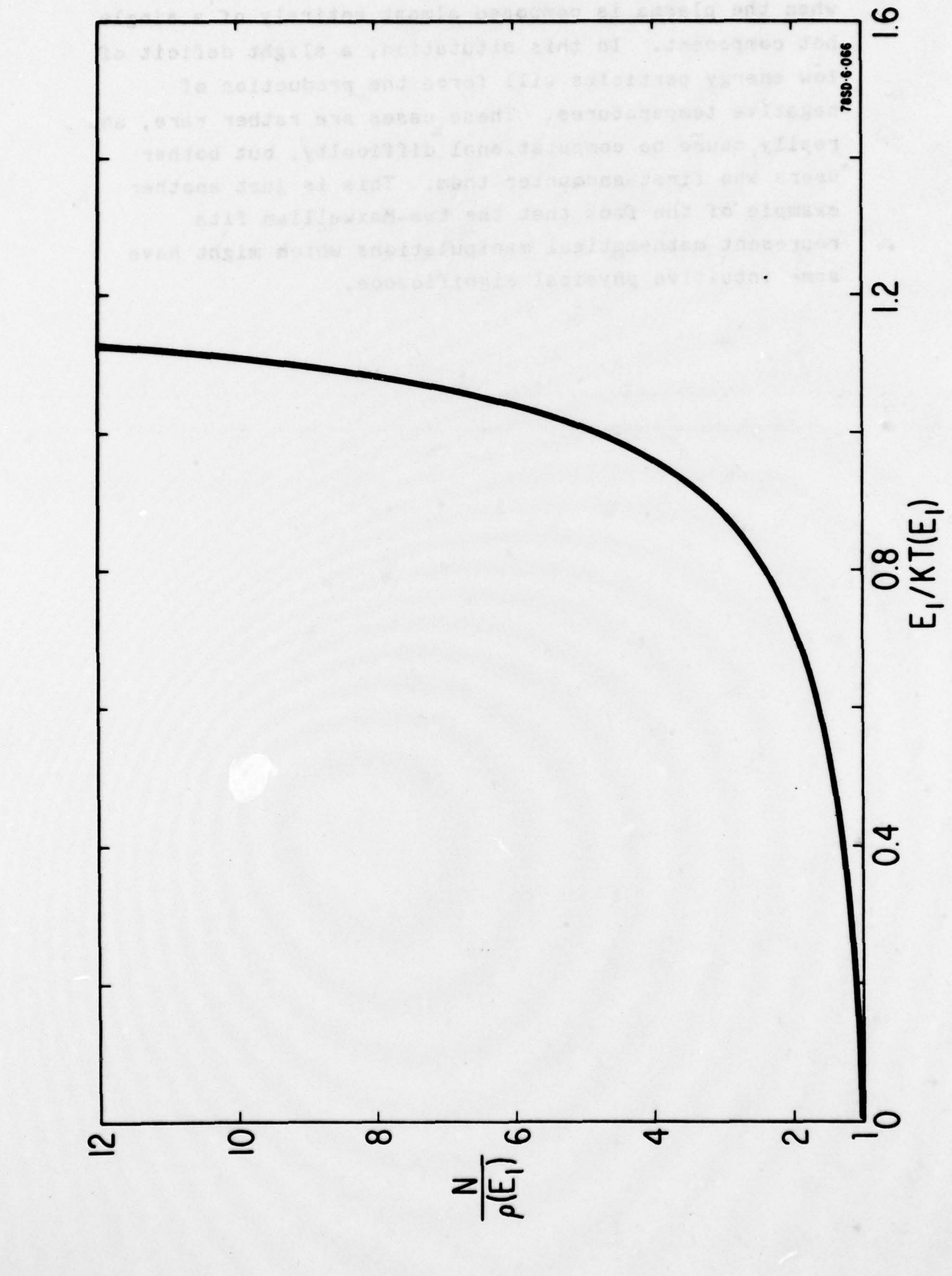

FIGURE 5

when the plasma is composed almost entirely of a single hot component. In this situtation, a slight deficit of low energy particles will force the production of negative temperatures. These cases are rather rare, and really cause no computational difficulty, but bother users who first encounter them. This is just another example of the fact that the two-Maxwellian fits represent mathematical manipulations which might have some intuitive physical significance.

III. KINETIC MODELLING

In contrast to the magnetospheric modelling efforts which essentially present the user with a time-ordered series of particle spectra for given orbit, we have been attempting to develop a kinetic theory which would be useful in specifying the environment within the magnetosphere with a minimum of ad hoc assumptions. The impetus for this work has been twofold. The availability of a large data base from the plasma instruments onboard ATS-5 and 6 and the work of McIlwain (1974) in developing an electric field based on this data. The data obtained by the ATS satellites at GEO show that the plasma exhibits complicated structures and behavior patterns. A theoretical understanding of such particle distributions requires a kinetic treatment. If such a treatment can also simplify the environmental specification, then it should be very useful.

In his paper on magnetospheric convection, McIlwain also pointed out that mapping the equitorial plane into a new coordinate system given by the electric potential (U) and the magnetic field intensity (B) could simplify the problem of obtaining particle trajectories. If such a mapping procedure could then be extended to all particles, this would simplify the kinetic approach which by its very nature requires detailed particle trajectory calculations.

We have therefore developed a generalized coordinate system using the adiabatic invarient, K, as the third coordinate. This new modelling technique is still being developed, but has already shown its usefulness in several ways.

Progress to Date

The advantage of using U and B coordinates in the magnetic equator is that the locally mirroring particles follow a straight line trajectory in this representation. Thus, the problem of finding the particle path is trivial. This property of the particle trajectories follows directly from the assumption of the conservation of energy and the first adiabatic invariant: $E=eU + uB$, where E is the total energy, and e and u are the particle charge and magnetic moment respectively. The first term on the right is the potential energy, and the second is the particle kinetic energy, since all the kinetic energy is assumed perpendicular to the magnetic field line in this case.

This feature of the particle trajectory has been shown to be true for all particles if one follows their mirror points. In the absence of electric fields parallel to the magnetic field lines, the modified longitudinal invariant, K, which is defined by $K = \oint \left[B_M - B(s)\right]^{1/2} ds$ defines a surface in space in which a particle mirror point moves. Within each such surface, the coordinates U and B can be used to map to real space. The particle mirror points follow straight lines, just as in the equatorial (K=0) case just described.

In order to exploit this simplification of the specification of the particle trajectories, one must first derive the equation of motion in the new coordinate system. This has been done, and the results are again surprisingly simple. The equations are given by:

$$dB/dT = W$$

$$dU/dt = -(u/e)W$$

$$dK/dt = 0$$

where W is a generalized velocity function given by

$$W = \left[(\nabla\vec{U} \times \nabla\vec{B}) \cdot \vec{uK}\right] / (\vec{B} \cdot \vec{uK})$$

and n_k is a unit vector perpendicular to the local constant K surface. The velocity function W depends only upon position in the magnetosphere, independent of any particle properties. However, W is also an energy function which gives the rate at which potential energy is being transformed into particle kinetic energy. The surface space on which W vanishes form natural boundaries in the magnetosphere between accelerator regions (W>0) and dynamo regions (W<0). The occurrence of forbidden zones for particles and the distinction between various types of particle trajectories are determiend by the topology of these boundaries and can easily be visualized.

We feel that this work is an important contribution to the understanding of magnetospheric processes. The system is in a sense a natural system in that connections between different regions can be readily seen. It should become possible to distinguish between effects which depend upon particle sources or sinks. Then we might be able to specify the time history of particle spectra encountered by a spacecraft anywhere within the magnetoshpere with only a description of the magnetic disturbances and the input plasma. Eventually one might be able to make detailed predictions of the magnetospheric response to solar disruptions without resorting to ad hoc semi-empirical formulae.

Two papers have alredy been written and accepted for publication on this topic (Whipple, 1978, and Whipple and Greenspan, 1978). In the coming year, we intend to extend the analyses to solve the problem of a dipole field exposed to a uniform solar wind. We also will attempt to add the facility of handling electric fields parallel to the magnetic field. If this is successful, then perhaps a more realistic model of the complete magnetosphere is possible.

IV. DATA

Since the primary output of this contract is the construction of a model of the environment at GEO which will be of use to a variety of disciplines, we have tried to make presentations to the various communities as we completed work that would be of use to them, (see publication list). However by far the most important single output has been the series of AFGL publications on Modeling of the Geosynchronous Orbit Plasma Environment -- Parts 1-3. The third part contains the pictorial atlas which is the heart of the data reduction effort. That atlas has already been completed at the writing of this report. It was done by personnel at both AFGL and UCSD working in cooperation. The introduction to that report stands as an excellent introduction to the plasma data and will therefore not be repeated here. The reader is referred to that report (Reference 20) for the detailed presentation of the ATS-5 and ATS-6 data in their entirety. We also feel that the value of the atlas is greatly enhanced by having the entire output at ones' disposal. Therefore we have also elected not to select special events or otherwise abstract the data base.

Further work of this type with the ATS spacecraft will probably become unnecessary with the forthcoming launch of SCATHA which was especially designed to gather information that is more readily useful for this kind of study.

Comments on the Ion Measurements

We have emphasized throughout this report and throughout the study that the ATS instruments were not designed to perform ion composition measurements. The sensors respond to a given energy per unit charge. No mass separation is done. Recently the results from the European Spacecraft GEOS have been available, and we hope that the mass spectrometers on SCATHA will also add to the store of knowledge.

At the present time, the effects on spacecraft charging of large fractions of oxygen ions in the plasma is unknown. One could speculate on several physical processes that would be affected such as waves in the sheath and surface erosion. However, the overall charge balance equations will not be greatly affected even if the plasma is ultimately shown to consist of 30% heavy ions instead of being predominately protons.

In principal, the same comments hold for the electrons. The so-called electron channels could be measuring heavier negative ions. However, the spectrum of likely candidates for such confusion is much smaller than for the positive ion case. While the presence of negative ions might very well become important for the scientific study of the magnetosphere and its dynamics, we feel that they could only play a very minor role in any charging or other spacecraft hazards.

V. FUTURE WORK

When looking at the spectrograms of the ATS plasma data, one is struck by the fact that much of time spacecraft-induced artifacts dominate. Removal of these artifacts is difficult, time-consuming and sometimes impossible. On SCATHA for the first time, we might be able to control the state of the vehicle charge so that such corrections might be unnecessary. This means that we might be able to measure in detail the spectrum of the very lowest energy particles which are frequently excluded from view on ordinary spacecraft.

The orbit of SCATHA is slightly eliptical in order to allow measurements of the average gradient on plasma conditions. This information should be of use in the next generation of models.

While the two-Maxwellian description has already proven to be useful, it might not be the best description in the long run. Future work on the kinetic modelling might lead to a better method of specifying the environment with even fewer parameters.

As we understand more about magnetospheric dynamics, we might be able to specify certain key measurements which could give a reliable prediction of charging events. If these key measurements involved only the detection of relatively high energy particles (say greater than 25 KeV), then the instrumentation and data analysis for such a program would be greatly simplified and reduced in cost over such programs as SCATHA.

The magnetospheric modelling effort as concerns spacecraft design and operations is definitely a closed end program with a final product. All of the scientific concerns of the magnetosphere will not be solved in the near future by SCATHA or any other proposed spacecraft system. In this program we have tried to serve the end of helping to produce that final product while simultaneously adding to the knowledge of the magnetosphere. The twin goals of providing engineerig input "right now" while at the same time producing scientifically meaningful results have been difficult to accomplish. We feel that with the aid of the personnel at AFGL, we have made much progress through this contract, and that further advances will be made during the coming year with SCATHA.

PAPERS RESULTING FROM MODELING EFFORT AT UCSD

1. DeForest, S. "The Plasma Environment at Geosynchronous Orbit," Proceedings of the Spacecraft Charging Technology Conference (AFGL-TR-77-0051) and NASA TMX-73537), 1977.

2. DeForest, S. "Environmental Model Needs for Spacecraft Interactions," to be published in the Proceedings of the Symposium "Quantitative Modeling of Magnetospheric Processes" by AGU, 1978.

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FINANCIAL STATEMENT

Of the total funds of $116,000 authorized for 22 months, approximately 99% has been expended after 22 months. 100% of the work has been completed.

CUMULATIVE COST DATA AS OF 30 SEPTEMBER 1978

LABOR ELEMENTS	PLANNED %	ACTUTAL %
Assoc. Res. Phys.	27.3	26.6
Research Phys.	12.7	14.3
Research Asst.	63.6	56.7
2 Research Assistants	0	65.6
Programmer	20	2.5
Sr. Programmer	0	15.9
Draftsman	5	2.0
Coder	10	1.3
Secretary	14.5	16.5
Management Officer	5	4.0
Administrative Asst.	5	3.3

TOTAL LABOR	$57,115	64,947
TRAVEL	6,177	5,173
COMPUTER	13,695	1,773
SUPPLIES & EXPENSE	12,936	8,780
OVERHEAD	26,077	28,873
EQUIPMENT (COMPUTER)	---	10,308
GRAND TOTAL	116,000	114,854