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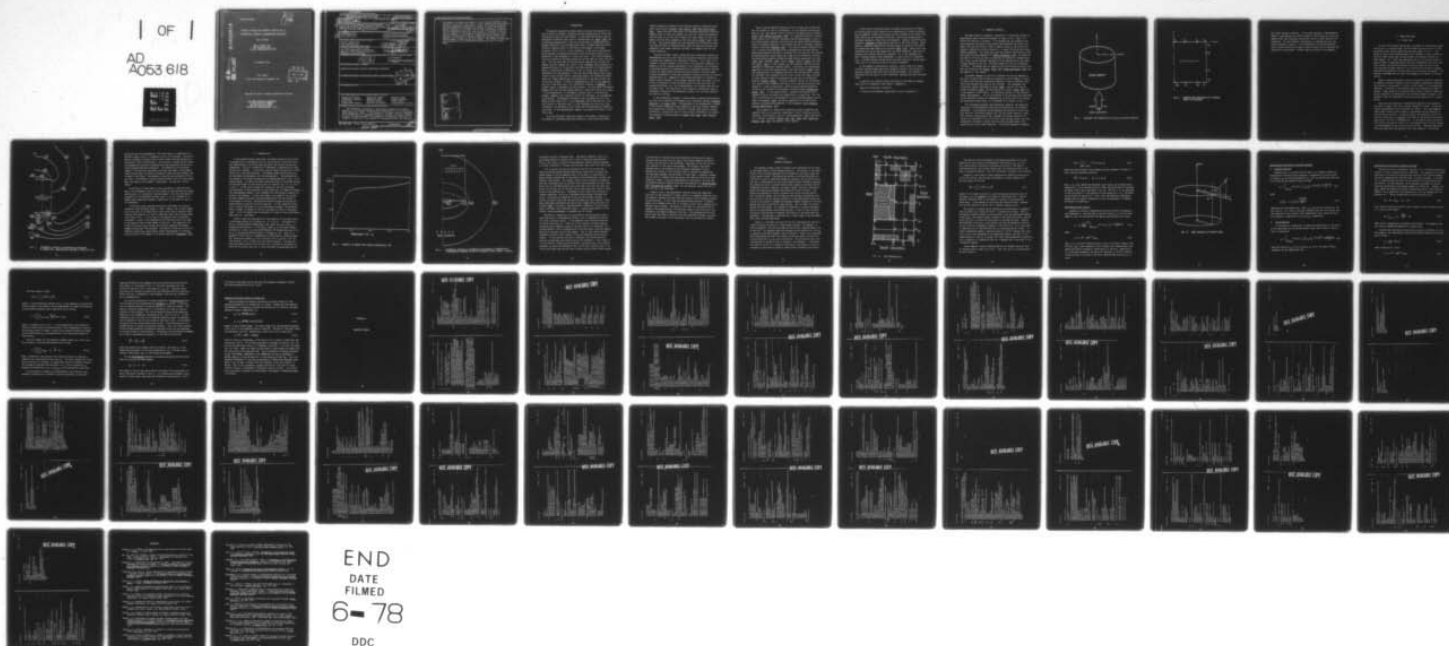
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POTENTIAL BARRIERS AND ASYMMETRIC SHEATHS DUE TO
DIFFERENTIAL CHARGING OF NONCONDUCTING SPACECRAFT

Lee W. Parker

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10 January 1978

Final Report

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The differential charging of a nonconducting spacecraft is modeled numerically by following charged-particle trajectories in a self-consistent space-charge-less sheath. In the presence of a plasma flow, but independent of any photoelectric or secondary emission, a potential difference between the front and wake surfaces of the spacecraft is generated, resulting in an asymmetric sheath and in the creation of a potential barrier for electrons.															

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The potential difference can amount to volts in the ionosphere, and kilovolts in the solar wind, that is, large compared with the potentials typically generated by photoemission alone. As in the more familiar case of photoelectric charging, the asymmetric sheath and potential barrier produced by the plasma flow can lead to erroneous interpretations of experiments measuring space electric fields and low-energy particle spectra. In an example of photoelectric emission, a sunlit area on an otherwise dark surface becomes positively charged by the emission, and is found to acquire a potential more than twice the emitted energy relative to the dark surface. This effect is associated with the physics of the terminator bounding the sunlit and dark areas.

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1. INTRODUCTION

Differential spacecraft charging takes place when the spacecraft surface is partly or entirely insulating and the charged-particle fluxes vary from point to point over the surface. In the relatively familiar case of photoelectric emission from a sunlit insulated area (cf. Grard, 1973), due to electrons escaping from it the sunlit area tends to become positively charged relative to the surrounding dark areas. Another mechanism of differential charging, which is less familiar and appears to have been discussed little if at all in the literature, is that due to the relative motion between a nonconducting spacecraft and the external plasma (e.g., a spacecraft in the ionosphere or in the solar wind). The fluxes of ambient ions and electrons on the wake surface are not the same as on the front surface. For high velocities of relative motion compared with the mean ion thermal velocity, whether this occurs in the ionosphere (due principally to spacecraft motion) or in the solar wind (due principally to plasma motion), there is a significant differential in the ion fluxes, but a negligible differential for the electrons. Since the net current density must vanish locally at each surface point in the steady state, this plasma-flow effect leads to a larger negative equilibrium potential on the wake surface than on the front surface. If there is photoemission as well on the front surface (as in the solar wind), this differential charging is enhanced. The present report is concerned with these effects. As shown below, differences between the front and wake surface potentials amounting to many kT/e (where T is the temperature, k is Boltzmann's constant, and e is the electron charge), together with a potential barrier for electrons, can be generated by the motion. The potential differential may be expected to be of the order of volts (tens of kT) in the ionosphere, and of the order of a kilovolt ($100 kT$) in the solar wind. In the ionosphere and solar wind, this differential can therefore be much larger than that generated by photoemission alone. In the magnetosphere, however, the plasma-flow effect is relatively weak.

As of the mid-1960's there was already a considerable literature on the subject of estimating spacecraft potentials, using simplified models

without considering trajectories and assuming perfectly conducting spacecraft (see reviews by Brundin, 1963; Whipple, 1965; Samir and Willmore, 1966). These relatively crude models for estimating spacecraft potentials assumed either (a) very thin sheaths such that the "planar approximation" could be used, or (b) very thick sheaths (for small objects in the ionosphere) but with radial symmetry so that the simple Langmuir theory could be used. The crude estimates were not concerned with differential charging; they sufficed for treating effects where the detailed structure and asymmetry of the sheath (potential barriers, for example) were not considered important.

From the mid-1960's onward, spacecraft have increasingly sampled the magnetosphere and solar wind, where the spacecraft conditions are altered in several ways important for differential charging. First, there is an increase of sheath thickness to the order of the spacecraft dimensions, as opposed to the thin sheaths encountered in the ionosphere; this thickness is governed essentially by photoelectrons and secondary electrons from the surface, the space plasma contribution being typically relatively weak. A second circumstance is that many spacecraft surfaces are partly or entirely nonconducting (e.g., composed of glass-covered photocells or insulating thermal control blankets), which becomes important when the sheath is thick. A third circumstance is that nonuniform particle fluxes occur over the spacecraft surfaces, e.g., due to photoelectron and secondary emission and to plasma flows. The combination of the foregoing circumstances leads to differential charging of the spacecraft surfaces, which can have deleterious effects as follows.

If the differential charging is severe enough, spacecraft malfunctions can occur due to electrical discharges on the insulating surfaces (Fredricks and Scarf, 1973; Rosen, 1976). The appearance of hot magnetospheric plasmas in the kilovolt temperature range impacting on the dark surface, combined with photoelectric emission on the sunlit surface, make possible intense differential charging such that tens-of-kilovolts differentials can appear (see spacecraft charging symposia by Grard, 1973; Rosen, 1976; Pike and Lovell, 1977).

Even if the differential charging is not so strong, say no more than tens to hundreds of volts of differential, it can interfere with measurements of, say, weak ambient electric fields or low-energy particle spectra (Grard, 1973; Whipple and Parker, 1969). An interesting feature of differential charging as it affects low-energy electron measurements is that it can create electron potential barriers which can return emitted photoelectrons or secondary electrons to the surface and lead to erroneous interpretations of the data (Fahleson, 1973). This type of electron potential barrier is distinct from and should not be confused with the more familiar space-charge potential minimum of the order of a volt which can be produced by emitted-electron space charge and is not due to differential charging. The space-charge potential minimum has been studied theoretically by Soop (1972, 1973), Schröder (1973), Parker (1976b), Whipple (1976a), and Rothwell et al. (1977); it can, however, be less important than the barriers produced by differential charging effects. Discussing a well-documented experiment on the ATS-6 geosynchronous satellite, Whipple (1976b) infers that photoelectrons and secondary electrons from the spacecraft surfaces are reflected from a potential barrier which is much too large to be due to space charge but must be associated with some kind of differential charging (Whipple, 1976ab). A similar potential barrier due to differential charge is that produced artificially by an attractive electron trap mounted on a repulsive spacecraft, which can cause secondary-emission currents to be incorrectly interpreted as plasma currents (Whipple and Parker, 1969). In the present report, a potential differential and a potential barrier are shown to be producible by a plasma flow. This can lead to difficulties of interpretation of solar wind measurements such as those of Rosenbauer (1973), and may be responsible for singularities observed by photoelectron detectors in the ionosphere (W. K. Peterson, private communication, 1977).

The procedure for theoretically predicting sheath asymmetries and potential barriers is generally complicated in that it requires particle trajectory calculations as well as a three-dimensional sheath description for a realistic treatment (Parker, 1970, 1973, 1976a, 1977; Parker and Whipple, 1967, 1970; and appendix of this report).

In this report we present results of sample calculations of differential charging due to both plasma flow and photoemission, primarily addressing the asymmetric sheath and potential barrier produced by the plasma flow. These results may be considered preliminary, because the photoemission is considered separately rather than simultaneously. However, the differential charging is enhanced by photoelectric emission on the front surface. Space charge is neglected compared with surface charges as sources of the field; this neglect has been shown to be justified (Soop, 1973). Hence, while the predictions may not be quantitative for an actual spacecraft, they are conservative and indicate what may be expected: (a) in the ionosphere for small insulated objects, small meteoroids, or small parts of a spacecraft (e.g., a painted antenna) located within the wake region of a moving spacecraft, and (b) in the solar wind for an entire spacecraft.

In the example of photoelectric emission, a sunlit area on an otherwise dark surface becomes positively charged by emission, and is found to acquire a potential more than twice the emitted energy. This effect is associated with the physics of the "terminator" bounding the sunlit and dark areas.

In Section 2 we indicate briefly the nature of the numerical methods used, which are presented in more detail in Appendix A.

Results are discussed in Section 3.

A listing of the computer program used is given in Appendix B.

2. NUMERICAL APPROACH

The model chosen to represent a spacecraft is a truncated cylinder of approximately equal height and diameter, as shown in Fig. 1 where it is called (for brevity) a "pillbox." It is assumed that the spacecraft surface charge and the electric field around the spacecraft are axially symmetric, and that the electric field in space is given by the solution of Laplace's equation on a grid of points in r - z space (including the pillbox-shaped spacecraft). This means that when the potential distribution on the grid points has been computed (cf. Parker and Whipple, 1970), the potential and electric field at any point in space may be obtained by interpolation. This allows ion and electron trajectories to be computed within the region of space spanned by the grid. The outer boundary of the grid represents "infinity." The method used for computing the field allows the use of variable grid intervals (see Parker, 1976a, 1977; Parker and Whipple, 1970; and the appendix of this report).

The normal component of the ion or electron flux may be computed at any point on the pillbox surface by evaluating a triple integral in velocity space, and following trajectories backward in time to determine their origin and therefore the value of the integrand. This represents the "inside-out" method originated by Parker (1964). Details are given by Parker and Whipple (1970), and more generally by Parker (1976a, 1977) and in the appendix of this report. An alternative approach is the outside-in method (see appendix). For the calculations to be discussed, the conditions at the spacecraft surface are represented by a discrete set of grid points and associated surface areas, as illustrated (by 12 points) in Fig. 2.

For the present purposes, the differential potential and charge distributions on the spacecraft surface may be determined by two different approaches. In one approach we may determine the potential at each local grid point by a relaxation process until the net current density is zero. This involves "cutting-and-trying", whereby the surface potentials (12 values as illustrated in Fig. 2) are first given assumed values, and later successively corrected in accord with the signs and magnitudes of the resulting set of net current densities. The surface potentials represent

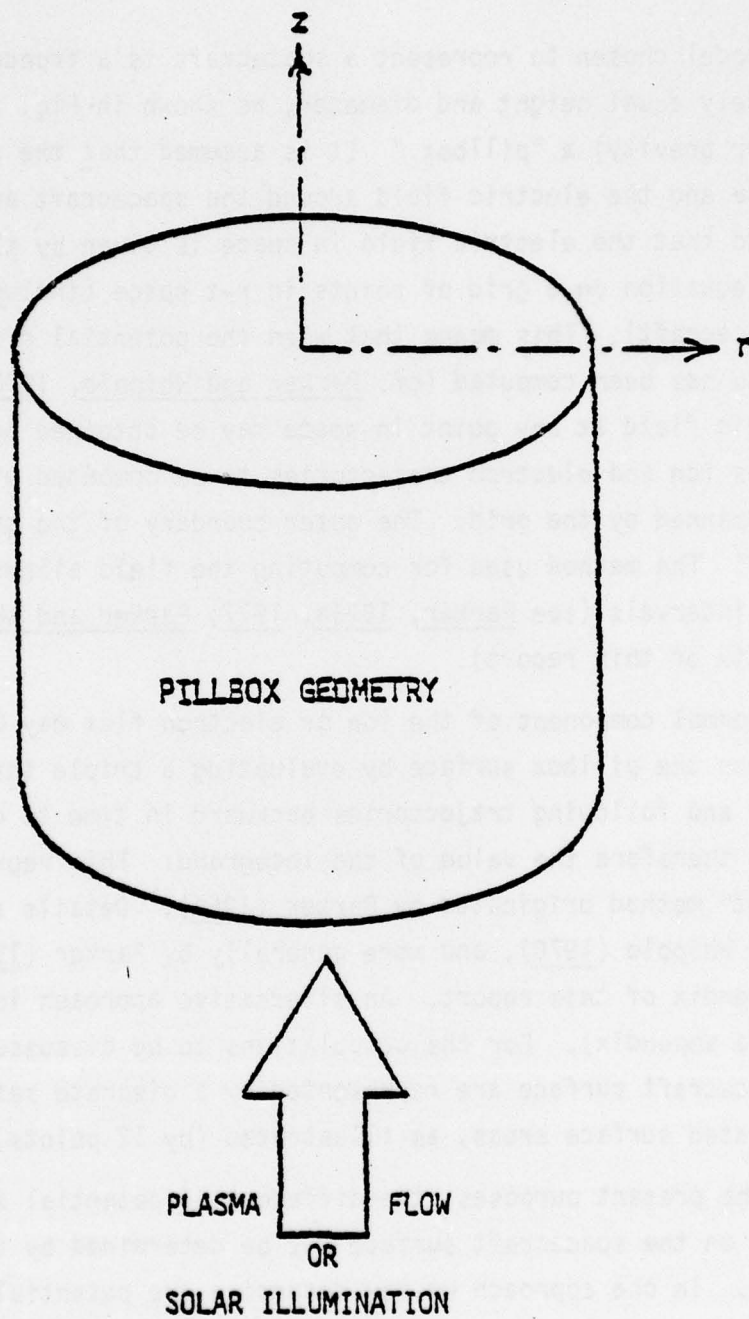


FIG. 1. SPACECRAFT AND PLASMA-FLOW OR SOLAR-ILLUMINATION GEOMETRY

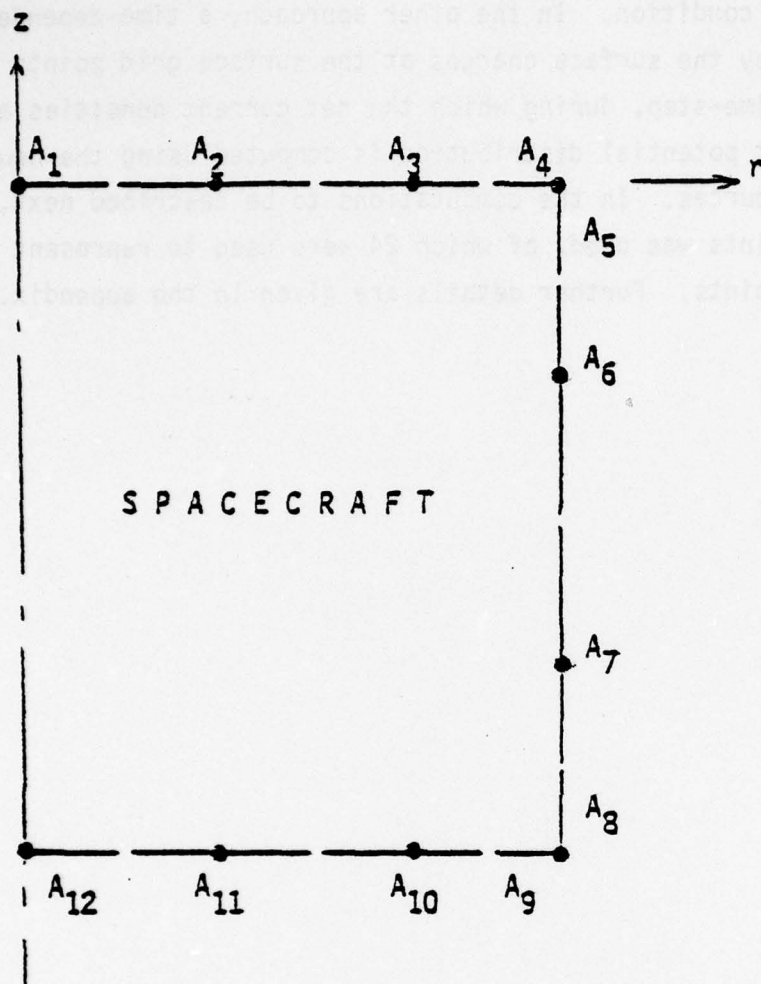


FIG. 2 . SURFACE AREAS ASSOCIATED WITH SURFACE POINTS ON SPACECRAFT

the "inner" boundary condition. In the other approach, a time-dependent method is used whereby the surface charges at the surface grid points are updated after each time-step, during which the net current densities are calculated. The next potential distribution is computed using the new surface charges as sources. In the computations to be described next, a grid of about 400 points was used, of which 24 were used to represent the spacecraft surface points. Further details are given in the appendix.

3. SAMPLE SOLUTIONS

A. Plasma Flow

In one of the problems treated here, we assume the nonconducting spacecraft to be in a flowing plasma, with the plasma flow along the axis, from the bottom (front region) toward the top (wake region) in Fig. 1. The plasma is taken to be ionized hydrogen and is assumed to have a velocity of flow four times larger than the most probable ion thermal velocity (ion "Mach number" = 4). Since the unperturbed ion flux to the wake surface is about 9 orders of magnitude smaller than the corresponding ion flux to the front surface, and since the electron fluxes are about the same to the front and wake surfaces, there will be a significant differential between the equilibrium potentials at the front and wake surfaces (see below). The effects of photoemission for the pillbox geometry are treated in the next section.

Figure 3 shows equipotential contours around the spacecraft, obtained by numerical solution, labeled by encircled numbers representing dimensionless values of the potential (in units of kT/e , where T is the plasma temperature). The errors in the solution shown are estimated to be under 10 percent. These potentials are obtained from Laplace's equation, where the surface potentials are obtained by the relaxation method discussed in the appendix, under the requirement of zero net current density at all surface points.

There are three regions of characteristic behavior of the potential, the "top" or "wake", the "side", and the "bottom" or "front". In the top region, the potentials are of the order of $-10kT/e$. This large negative value (about $-17kT/e$ at the surface) is associated with the reduction in ion flux due to the flow. In the side region, the potentials are of the order of $-3kT/e$; this is essentially the order of the equilibrium potential when there is no flow ($-\ln\sqrt{m_i/m_e} kT/e$). In the bottom region, the potentials are of the order of $-kT/e$, i.e., less negative than the side, because of the enhancement of the ion flux due to the flow. (Adding photoemission here would make the front potential still less negative.) The surface

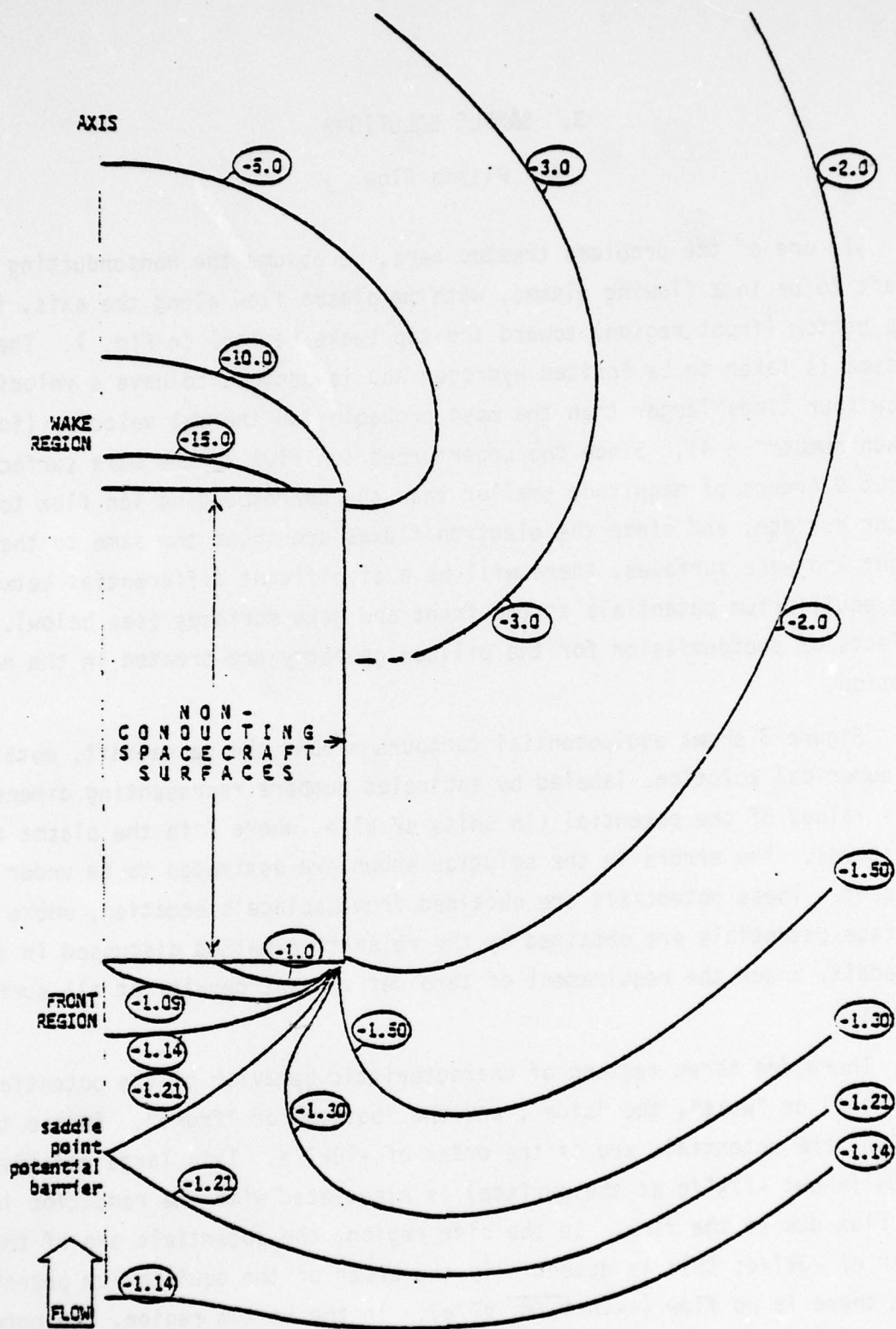


FIG. 3. DIFFERENTIAL CHARGING OF NONCONDUCTING SPACECRAFT BY PLASMA FLOW (EQUIPOTENTIAL CONTOURS IN UNITS OF kt/e)

points are thus not equipotential. Note that there is a saddle-point in the front region, that is, a potential barrier for electrons. The barrier height is between 10 percent and 20 percent higher than the potentials at the nearest (front) surface points. This feature is caused by the interaction between the relatively-large-magnitude wake potentials and the relatively-low-magnitude front potentials. The dashed part of the contour labeled "-3.0" near the side surface indicates that there is more complicated fine structure (variations of potential along the side surface) than is shown in the figure. The potentials along the top surface fall off to the right. The potentials along the bottom surface first fall with radius, then rise sharply as the corner is approached. This may be a "corner effect."

On the basis of these results, one would expect a relatively small body in the ionosphere, such as a thin antenna or boom painted with nonconducting paint, or a painted or insulated object in the very near wake of a spacecraft (or the spacecraft surface itself if it is a dielectric) to become highly negatively charged, to potentials of the order of volts in the ionosphere.

In the solar wind, the above calculation could apply to an entire spacecraft since the Debye length is large. However, the ion Mach numbers are of the order of 10 rather than 4, which would lead to negative dimensionless wake potentials an order of magnitude larger than the wake potentials shown in Fig. 3 (It is shown in the appendix that the potential difference in units of kT/e generated by the flow should be of the order of the square of the ion Mach number of the flow.) This means that for $T=10\text{ev}$ in the solar wind, one may have kilovolt potential differences between the wake and front surfaces. The electric fields due to this differential charging may significantly disturb measurements of low-energy plasma electrons, for example on the HELIOS spacecraft (Rosenbauer, 1973).

B. Photoemission

In the second problem treated here, the bottom surface of the pillbox is assumed to be illuminated by the sun (along the axial direction) and to emit photoelectrons, while the sides and top of the pillbox are dark and nonemitting. (The axial direction of illumination is appropriate for maintaining axial symmetry. In the solar wind the plasma flow and solar illumination are in the same direction.) The ambient plasma contributions are not considered simultaneously with the photoemission. The photoelectrons are assumed to be emitted isotropically and monoenergetically, with 1 ev of kinetic energy. All points and their associated areas on the bottom surface are emitting except for the corner point, for instance, Nos. 10, 11, and 12 in Fig. 2. In the actual problem the "terminator" was put at $R=0.95R_0$. (The terminator is not put exactly at the corner $R=R_0$, for numerical reasons.) The time-dependent method is used, together with the outside-in method discussed in the appendix. At zero time, there is no charge on any surface. As time increases from zero, emitted photoelectrons from the surface at first escape to infinity, leaving behind positive charge and causing the bottom surface to acquire a positive potential. As this potential builds up to a value of the order of a volt (the ejection energy), the photoelectrons no longer all escape to infinity, but begin to return to the spacecraft. (It is of interest that the potential is found to rise significantly above one volt - see below.)

Figure 4 shows the time-behavior of the potential of the center point on the bottom surface (for instance, No. 12 in Fig. 2). The potential in volts is plotted against dimensionless time, where the scale time t_0 in seconds may be written as $1.11 V_0 / (R_0 J_0)$, where V_0 is the kinetic energy of emission in volts, R_0 is the scale dimension of the emitting area in cm, and J_0 is the emitted current density in picoamp per cm^2 . Thus, for a spacecraft radius $R_0=50$ cm, photoemission current density $J_0=1000$ picoamp/ cm^2 , and emission energy $V_0=1$ volt, the scale time is $t_0=2.22 \times 10^{-5}$ sec. (The ordinate in Fig. 4 scales with the ejection energy.) The potential along the bottom surface is not uniform, but is maximum in the center and falls off with radius (see Fig. 5, which indicates an approximate drop of

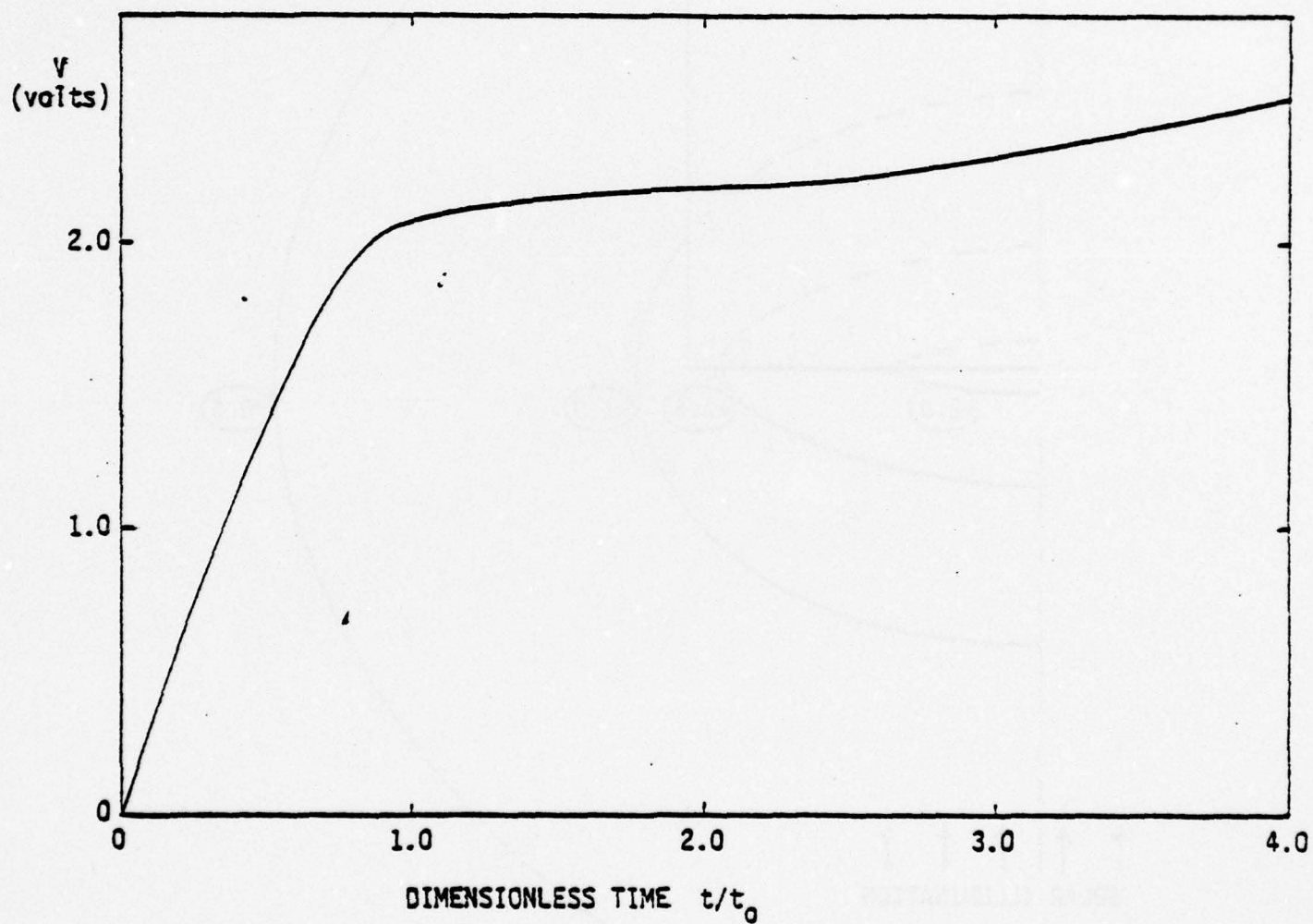


FIG. 4. POTENTIAL OF CENTER POINT VERSUS DIMENSIONLESS TIME

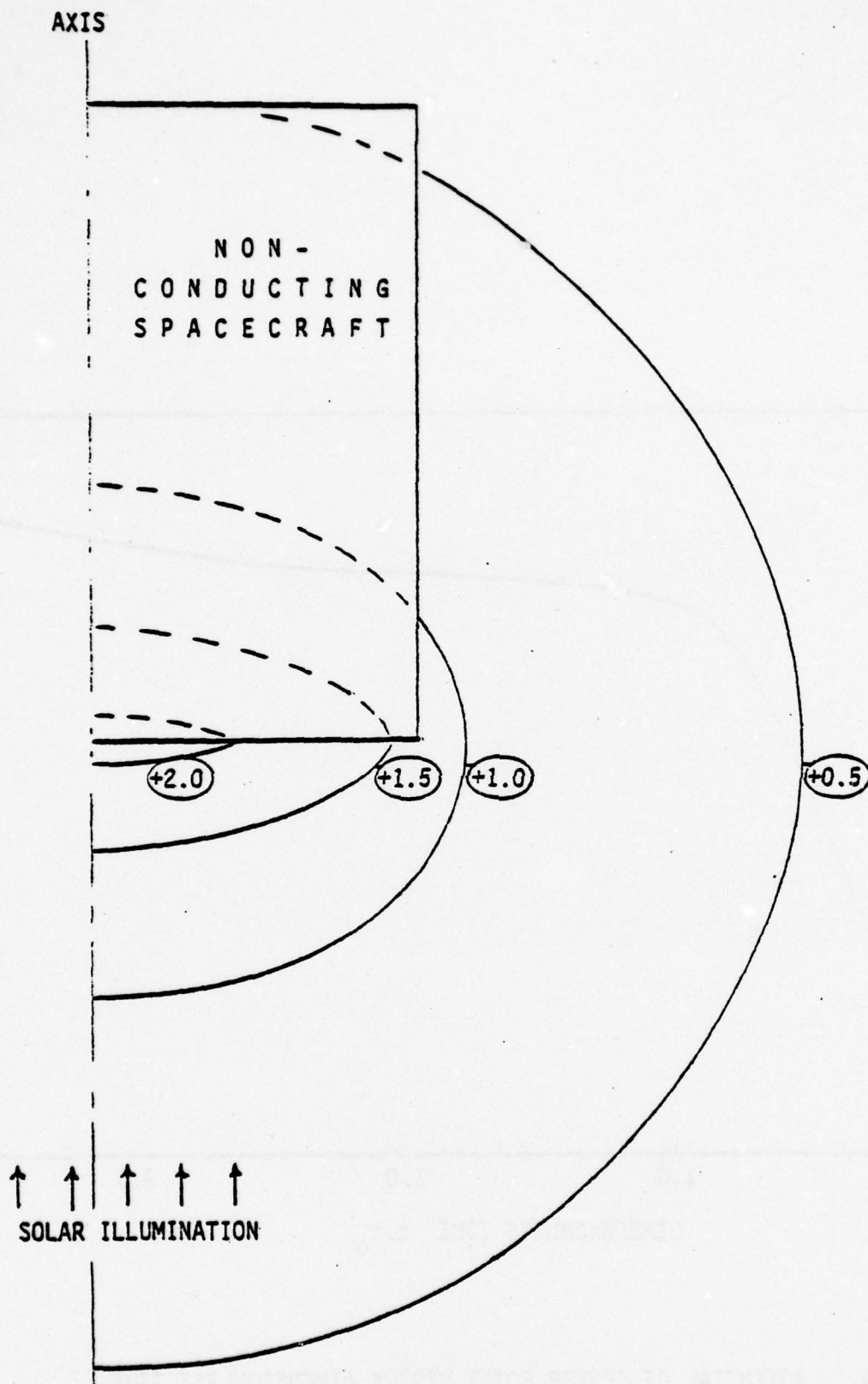


FIG. 5. DIFFERENTIAL CHARGING OF NONCONDUCTING SPACECRAFT BY PHOTOEMISSION
- EQUIPOTENTIAL CONTOURS IN UNITS OF EMISSION KINETIC ENERGY - $\text{time} = 2t_0$

30 percent over the illuminated area). The central potential rises to an approximate plateau of slightly over 2 volts in about one characteristic time t_0 , and, after an interval of approximately constant behavior between t_0 and $3t_0$, continues to increase but much more slowly than the initial rate.

It is a curious fact that the potential should rise to more than 2 times the ejected energy potential-equivalent, rather than to exactly the ejected energy as may be expected purely on the basis of conservation of energy without consideration of the nature of the trajectories, surface, and potential distribution. The computer results show a transfer of electrons from the illuminated areas to the small dark area associated with the corner point; that is, emitted electrons are pulled back, but cross the local terminator at $R=0.95R_0$ and hit the dark corner area rather than return to other points on the emitting area. The charge on this corner area continues to increase negatively, while the illuminated-surface charge increases positively. No charges are deposited on the top and side dark surfaces. A similar build-up to more than the ejection energy has been observed in computer experiments performed by De and Criswell (1977) and by Pelizzari and Criswell (1977) in studies of the photoelectric charging of locally-sunlit areas in the dark lunar terminator region. A possible explanation of this "excess" charging phenomenon is proposed here as follows.

The effect is appropriate to the problem of electron emission from a restricted area of a nonconducting surface, with no compensating electron flux from an external plasma. It also depends on the returning electrons "sticking" where they hit. After the initial potential buildup, despite the deposition of negative charge on the dark side of the terminator, the surface potential falls off monotonically from the central value but remains positive as one goes into the dark region. That is, the surface gradient (tangential electric field) remains finite and continuous across the terminator. (If the emitting area were a conductor, the surface gradient would be discontinuous and singular across the terminator.) Thus, there is a finite interval straddling the terminator, such that within this interval electrons can cross the terminator from a sunlit point (moving "uphill") to a dark point where they are held fast, without using up their kinetic energy.

A finite rate of transfer across the terminator from the sunlit area to the dark area can thus occur as long as the surface potential gradient is finite at the position of the terminator, regardless of how high the central potential of the sunlit area becomes. The transfer rate should approach zero as the gradient at the terminator approaches infinity. Whether this process is self-limiting, that is, whether the gradient at the terminator becomes infinite within a finite time, is presently unknown. The key point is probably that the sunlit area cannot be strictly an equipotential surface. It may be approximately so over most of its area, due to electron transport tending to maintain equipotentiality (De and Criswell, 1977; Pelizzari and Criswell, 1977), but the potential should fall off in the vicinity of the terminator.

Figure 5 shows a few equipotential contours around the spacecraft. (Only half of the spacecraft is shown, since it is symmetric about the axis.) The potential contours are taken from the solution of the foregoing problem, at the time $t=2t_0$. At this time the bottom-surface potential is approximately at its plateau value (Fig. 4) of about 2 volts, and is undergoing its smallest rate of change. The source of the field is a nonuniform disk of charge at the bottom surface, with positive charge on the left side of the terminator, and negative charge on the right. The equipotentials are symmetric about the plane of the disk since the spacecraft dielectric constant was assumed to be equal to the free-space value (no polarization effects).

APPENDIX A.

COMPUTER APPROACHES

The computer program listed in Appendix B was developed for the study of the sheath about a pillbox-shaped spacecraft. The sources of the sheath electric field include spacecraft surface potentials and space charge due to the ambient plasma. The program has options to include the effects of insulating as well as conducting spacecraft surfaces, and of electron emission due to photoelectric or (with minor modifications) secondary processes. The program can solve a coupled Poisson-Vlasov system of nonlinear partial-differential-integral equations, and uses a special iteration algorithm to obtain self-consistency between the Poisson and Vlasov solutions. This yields distributions of electric potential and ion and electron density. The "inside-out" method, which follows ion and electron trajectories backward to their origin at the body surface or in the undisturbed plasma, may be used as one option to compute the necessary moment-integrals for particle density and flux at arbitrarily chosen points. This is useful for contributions from the plasma. An "outside-in" approach is a useful alternative option for contributions from surface emission. A grid is used to define the spatial distributions of potential and density in the space about the spacecraft. The approach is applicable to a larger range of the parameters than other available approaches.

Figure A1 illustrates the nature of the grid representation used for a satellite having the form of a finite-length cylinder. The geometry is axially-symmetric, with the axis shown as the vertical dotted boundary line on the left. The boundary condition representing the condition at infinity is applied to the other boundary lines of the grid. There is an inner boundary representing the satellite surface, on the grid points of which the surface potentials (ϕ_a , ϕ_b , etc.) are defined. The grid points are at the intersections of the grid lines at constant r and constant z . Associated with each grid point is a volume of revolution in the shape of a torus of rectangular cross-section (shown as shaded boxes surrounding grid points).

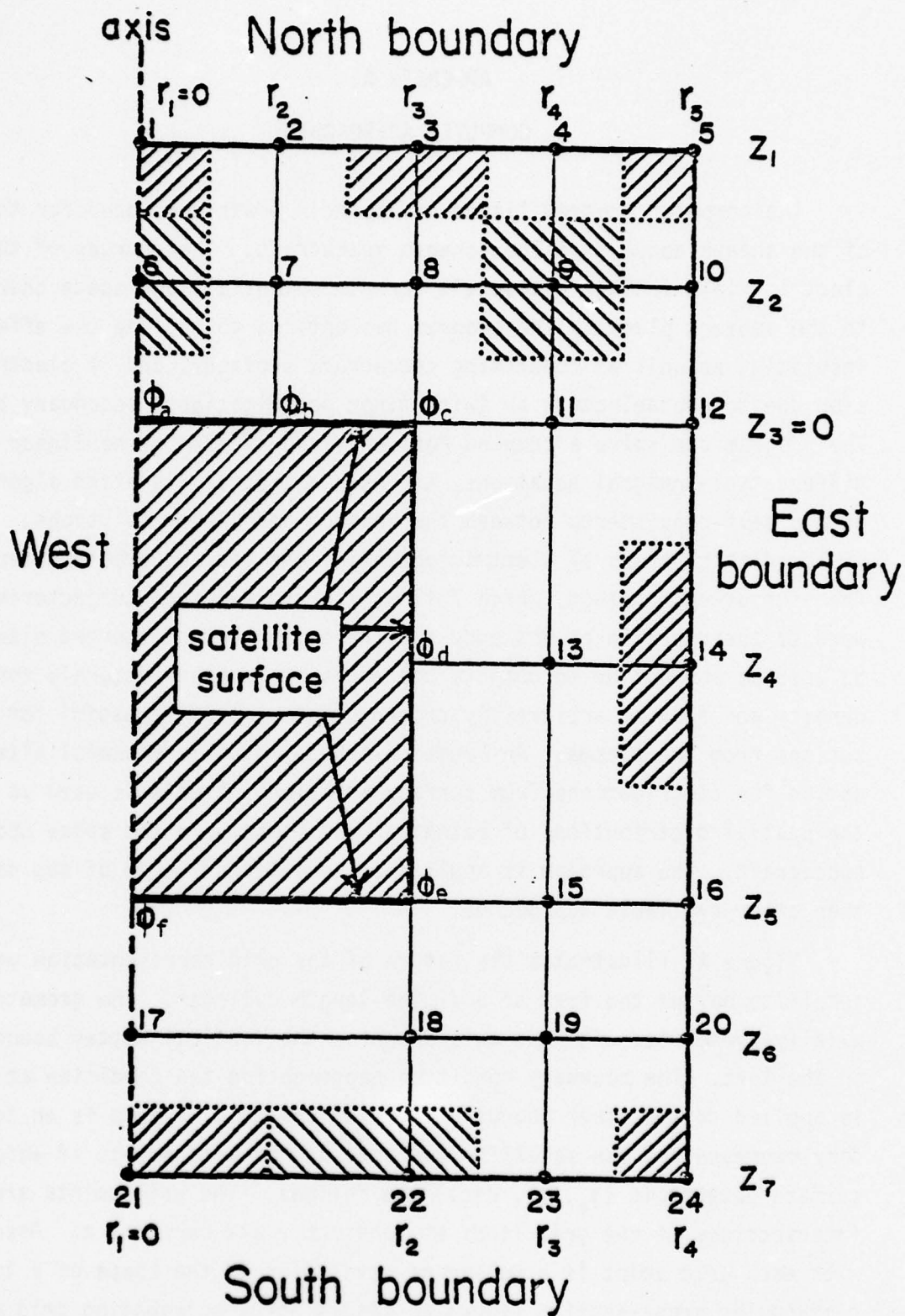


FIG. A1. GRID REPRESENTATION

The particle fluxes calculated at the satellite-surface grid points determine the equilibrium surface-potential distribution (ϕ_a , ϕ_b , etc.), with current density balance at individual grid points in the case of insulating sections, and current balance over the conducting areas in the case of conducting sections. The flux calculation is based on the following.

Assuming a fixed electric field configuration (potential-values given at all grid points), the flux may be written as a triple integral over velocity space, of the form

$$j(\vec{r}) = \int \int \int f(\vec{r}, \vec{v}) v_n d^3\vec{v} \quad (A-1)$$

where $\vec{v}$ is the vector velocity of a particle passing through the point $\vec{r}$, and where v_n is the component of $\vec{v}$ normal to the surface at $\vec{r}$. The distribution function $f(\vec{r}, \vec{v})$ is the density of points in six-dimensional phase space. In the absence of collisions and time-variations, f depends only on the constants of motion and is constant along any orbit.

The region of interest may be considered to be enclosed by a composite source surface on all points of which f is assumed to be known. There is an external boundary surface at infinity where f has the unperturbed ambient value $f_\infty(\vec{v}_\infty)$, and internal source surfaces on the spacecraft where f has the value $f_s(\vec{r}_s, \vec{v}_s)$ in accord with the emission from these surfaces. Separate contributions to the flux j from infinity and from the spacecraft surfaces can be written as independent integrals of the form of Eq. (A-1), where each is comprised only of contributions from its associated source surface. In order to determine whether a specified velocity $\vec{v}$ (at $\vec{r}$) connects with infinity or with a point elsewhere on the spacecraft surface, the orbit is followed backward in time to its source (all orbits being dynamically reversible). This is generally an appropriate task for a computer and is the heart of the "inside-out" method.

Since symmetric velocity distributions are of interest the polar form of velocity space is used in Eq. (A-1). Thus, the flux at a surface point $\vec{r}$ may be written as

$$j(\vec{r}) = \int \int \int_{\text{hemisphere}} f v^3 dv \cos \alpha d\Omega \quad (\text{A-2})$$

where the velocity-space volume element has been expressed in terms of a local velocity-coordinate system by

$$d^3\vec{v} = v^2 dv d\Omega, \quad d\Omega = \sin \alpha d\alpha d\beta \quad (\text{A-3})$$

Here, v , α , and β denote the magnitude, polar angle, and azimuthal angle, respectively, of the velocity-vector $\vec{v}$, where the definitions of the angle variables α and β are illustrated in Fig. A2. The flux j is the component of the flux vector $\vec{j}$ in the direction of the chosen axis, e.g., the normal to the surface at the point $\vec{r}$. In Eq. (A-2) the subscript "hemisphere" denotes that the angular integration is over the hemisphere of outgoing directions (2π steradians).

Contributions from Infinity

Assuming at infinity a Maxwellian-with-drift velocity distribution, with temperature T , particle mass m , particle density n_0 , and drift Mach number M , the flux contribution from ambient particles may be written:

$$j_\infty = n_0 \left(\frac{kT}{2\pi m} \right)^{1/2} \int_{\text{Max}(\phi, 0)}^{\infty} dE (E - \phi) \int \int e^{-U} \frac{\delta \cos \alpha d\Omega}{\pi} \quad (\text{A-4})$$

where

$$U = E + M^2 - 2ME^{1/2} \cos \theta_\infty \quad (\text{A-5})$$

Here, δ is a "cut-off" function which is unity if the orbit connects with infinity, and is zero otherwise; E and ϕ denote local dimensionless total energy and electric potential, normalized by kT and kT/e , respectively; θ_∞ is the angle between $\vec{v}_\infty$ and the drift direction at infinity, where $\vec{v}_\infty$ is the velocity at infinity of the orbit characterized locally by E , α , and β .

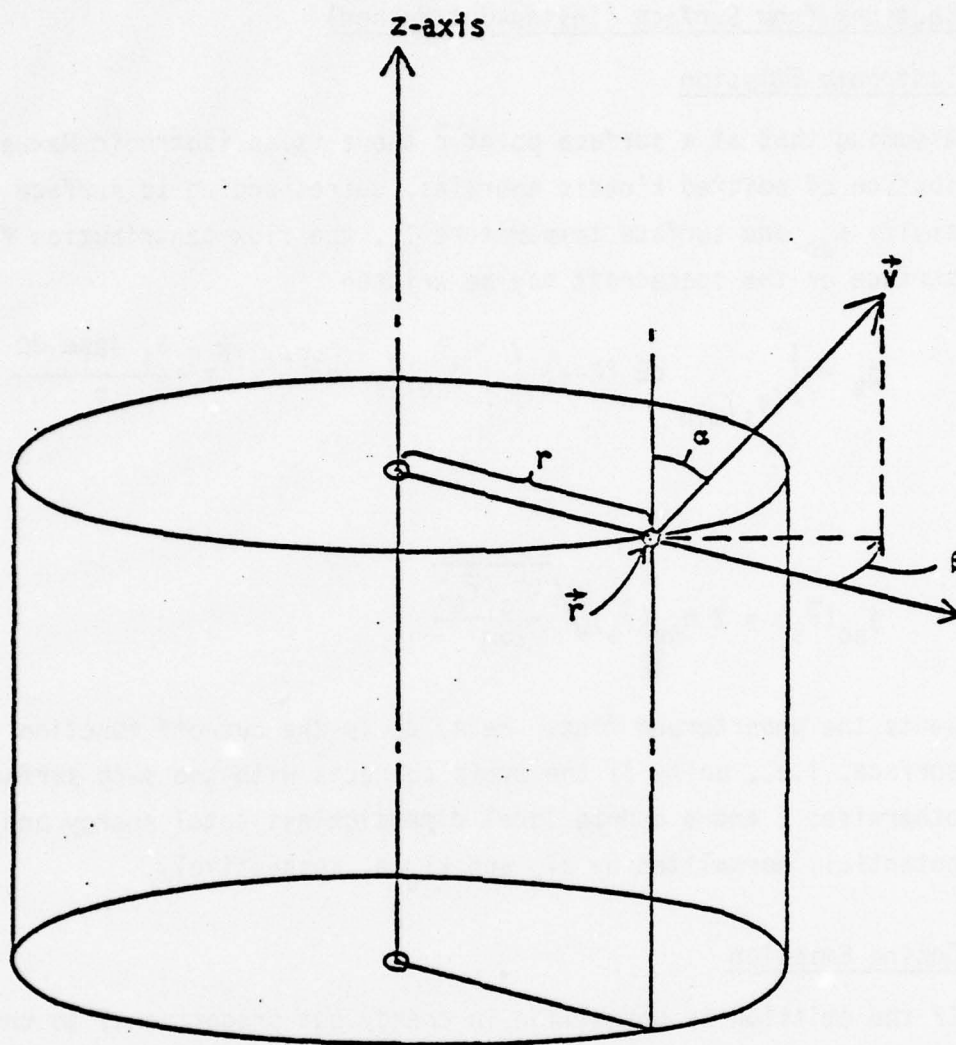


FIG. A2. ANGLE VARIABLES IN VELOCITY SPACE

Contributions from Surface (Inside-Out Method)

A. Isotropic Emission

Assuming that at a surface point $\vec{r}$ there is an isotropic Maxwellian distribution of emitted kinetic energies, corresponding to surface particle density n_{so} and surface temperature T_s , the flux contribution from the s -th surface on the spacecraft may be written

$$j_s = \int_{(\phi_s)_{\min}}^{\infty} dE (E - \phi) \int \int j_{so}(\vec{r}_s) e^{-E + \phi_s(\vec{r}_s)} \frac{\delta_s \cos \alpha d\Omega}{\pi} \quad (A-6)$$

where

$$j_{so}(\vec{r}_s) = 2 n_{so}(\vec{r}_s) \sqrt{\frac{kT_s(\vec{r}_s)}{2\pi m}} \quad (A-7)$$

represents the unperturbed flux. Here, δ_s is the cut-off function for the s -th surface, i.e., unity if the orbit connects with the s -th surface, and zero otherwise; E and ϕ denote local dimensionless total energy and electric potential, normalized by kT_s and kT_s/e , respectively.

B. Cosine Emission

If the emission is Maxwellian in energy but proportional to the cosine of the angle made with the surface normal rather than isotropic, then Eq. (A-6) is replaced by

$$j_s = \int_{(\phi_s)_{\min}}^{\infty} dE (E - \phi) \int \int \frac{4}{3} j_{so}(\vec{r}_s) e^{-E + \phi_s(\vec{r}_s)} \delta_s \frac{3 \cos^2 \alpha d\Omega}{2\pi} \quad (A-8)$$

where the function j_{so} is still given by Eq. (A-7), but where $(4/3)j_{so}$ represents the new unperturbed flux.

Contributions from Surface (Outside-In Method)

One can also use an "outside-in" approach, i.e., following trajectories forward in time, to compute fluxes or densities. This approach is of course equivalent to and would provide the same results as the inside-out method, but may be computationally more efficient in certain problems. In particular, it should be more efficient for calculating flux contributions from the surface. For this approach, let dA represent an element of surface receiving contributions from another element of surface dA' . Moreover, let $dF_{AA'}$ denote the fraction of emitted trajectories from dA' which reach dA . Moreover, let j_A denote the flux received at A , while $j_{A'}$ denotes the flux emitted at A' . Then by conservation of particles we may write

$$dj_A \cdot dA = dF_{AA'} \cdot j_{A'} \cdot dA' \quad (A-9)$$

Thus, the flux received at point A due to emission from all emitting points A' is given by the integral

$$j_A = \int_{\text{all } A'} j_{A'} \cdot \frac{dF_{AA'}}{dA} \cdot dA' \quad (A-10)$$

where dF/dA is determined by trajectory calculations. The foregoing integrals may be implemented numerically as shown below.

Assuming that the ambient plasma flows along the z -direction with ion Mach number M , the dimensionless velocity-distribution function at infinity may be written:

$$f_0 = \frac{1}{\pi^{3/2}} \exp(-U) \quad (A-11)$$

where (repeating Eq. (A-5))

$$U \equiv E + M^2 - 2ME^{1/2} \cos\theta_\infty \quad (A-5)$$

The flux integral, namely,

$$j(\vec{r}) = \int \int \int f(\vec{r}, \vec{v}) v_n d^3\vec{v} , \quad (A-1)$$

where f is the distribution function and v_n is the component of the particle velocity normal to the surface, may be approximated for numerical evaluation by the inside-out method using a quadrature sum as follows:

$$j \approx \sum_i \sum_j \sum_k A_{ijk} \delta_{ijk} \frac{(E_k - \phi)}{\pi^{3/2}} \exp(-U_{ijk}) \quad (A-12)$$

where U is defined by Eq. (A-5), ϕ is the dimensionless local potential, and the 3 indices refer to discrete values of the 3 components of velocity. The discrete values are chosen in accord with a Gaussian quadrature scheme, and the coefficients A_{ijk} are proportional to the associated weights and other factors.

The flux integral for the outside-in method, namely, Eq. (A-10), may be evaluated by a four-fold quadrature sum as follows:

$$j \approx \sum_i \sum_j \sum_k \sum_a B_{ijka} \cdot j_a \cdot \frac{F_a}{A} \cdot A_a' \quad (A-13)$$

Here, in addition to the sum over the 3 velocity indices, we indicate a summation over contributing finite areas A_a' . The area A denotes the finite area at the point of interest; F_a denotes the fraction of emitted trajectories (assumed all emitted from the center of A_a') which intersect A ; j_a denotes the emitted flux at A_a' ; and B_{ijka} is the appropriate coefficient.

For the purpose of computing surface-potential distributions over a spacecraft surface with a variation of surface properties, we associate

separate differential area segments with the surface grid points defining the surface, as illustrated in Fig. 2. The areas associated with the surface grid points in Fig. 2 are labeled A_1, A_2 , etc. These may represent areas with different conductivities and different emission properties, either intrinsic or depending on their geometric position and orientation (as in photoemission).

For a given distribution of surface properties, the equilibrium potential distribution may be determined by relaxation as follows. A distribution of surface potentials (at the grid points) is initially assumed. This leads by trajectory computations to a distribution of fluxes of ions and electrons at the surfaces. The ion and electron fluxes can be determined numerically using summations represented by Eq. (A-12) or (A-13). On each conducting area (or collection of connected conducting areas) the potential must be adjusted so that the net current to the area is zero. At nonconducting points the net current density must be zero. These adjustments can be accomplished by an iterative relaxation procedure. Thus, the initial guesses for the surface potentials are modified according to the sign and magnitude of the net current or current density. The essence of the relaxation procedure, for a totally nonconducting spacecraft, is the iterative algorithm:

$$\phi_k^{N+1} = \phi_k^N + \alpha \cdot CD_k^N \quad (A-14)$$

where the superscript N denotes the N -th iteration, and where ϕ_k is the dimensionless potential at the k -th surface point, CD_k is the net current density at that point, and α is the relaxation parameter.

For the time-dependent approach, the charge associated with the finite area A is given by the time-integral:

$$Q_A = \int j \cdot A \cdot dt \quad (A-15)$$

This charge is used as the source term at the center of the associated volume of revolution indicated in Fig. A1. In a step-by-step procedure, during one half of each cycle, the fluxes are evaluated in accord with Eq. (A-12)

or (A-13); in the other half of the cycle the charges are updated in accord with the discretized form of Eq. (A-15).

Charging of the Wake Surface in Plasma Flow

One may estimate the potential acquired by the wake surface of a non-conducting spacecraft in a plasma flow, as follows. Assume that the dimensionless potential ϕ is negative, and that the electron and ion fluxes to the wake surface are given, respectively, by

$$j_e \approx n_0 \sqrt{kT/2\pi m_e} \exp(+\phi) \quad (A-16)$$

and

$$j_i \approx n_0 \sqrt{kT/2\pi m_i} \{ \exp(-M^2)/2M^2 \} \quad (A-17)$$

where M is the ion Mach number. For large values of M , the bracketed expression in Eq. (A-17) is the asymptotic form of $\{ \exp(-M^2) - \sqrt{\pi} M \operatorname{erfc} M \}$, the exact factor for the neutral ion flux. Equating Eqs. (A-16) and (A-17), we may write:

$$-\phi \approx M^2 + \ln 2M^2 + \ln \sqrt{m_i/m_e} \quad (A-18)$$

This will yield an overestimate, since the ion flux is actually larger than that given by Eq. (A-17). For $M=4$ and $m_i/m_e \approx 1836$ for hydrogen, we obtain $\phi \approx -23$, versus the self-consistent value $\phi \approx -17$ presented in Section 3. For $M=10$, the potential is $\phi \approx -109$. Hence, for large M we may obtain a good estimate by keeping only the first term on the right-hand side. Then the potential difference generated by the flow becomes independent of the temperature and may be estimated by $m_i v^2 / 2e$, where m_i is the ion mass and v is the velocity of the flow. Thus, the potential difference in volts may be estimated by $0.00519 \cdot m(\text{au}) v^2 (\text{km/sec})$ where $m(\text{au})$ is the ion mass in atomic units and $v(\text{km/sec})$ is the flow velocity in km/sec. Thus, in the ionosphere, assuming $m(\text{au})=16$ (O^+ ions) and $v=7$ km/sec (orbital velocity), the potential difference is about 4.0 volts. In the solar wind, with $m(\text{au})=1$ (protons) and $v=440$ km/sec, the potential difference becomes 1.0 kilovolt.

APPENDIX B.

COMPUTER PROGRAM


```

00 55 I=2,IIS
00 56 I=1,IJS
      INX=INX+1
      PHIS(I,J)=X(INX)
90 CONTINUE
      IF(NGO.EQ.2) GO TO 500
      NG0=2
      ARTE(M,120) IT,NG2
      FORMAT(//,1X,23HPOTENTIAL ARRAY - NORTH,5V,4HTT =,13,7X,5HNGR =,
      1 13)
      WRITE(M,2004) (RHT(J),J=1,JJN)
      00 91 I=1,IIN
      ARTE(M,123) I,ZNT(I),(PHIN(I,J),J=1,JJN)
91 CONTINUE
      WRITE(M,122)
      122 FORMAT(//,1X,35HPOTENTIAL ARRAY - SOUTH.
      1 13)
      WRITE(M,2004) (RST(J),J=1,IJS)
      2004 FORMAT(//,1X,2HP=,16F9.4/(//1X,16F9.4))
      70 93 I=1,IIS
      WRITE(M,123) I,ZST(I),(PHIS(I,J),J=1,JJS)
93 CONTINUE
      123 FORMAT(//5H LINE,14,5X,2H2=F8.4/(//7F16.9))
      C
      GO TO 11
500 CONTINUE
      IF(PUNCH.GT.0)
      IF(IPUNCH.GT.0.AND.OFAYE.EQ.0.) PUNCH 52,IT,NSS
      IF(IPUNCH.GT.0.AND.OFAYE.EQ.0.) PUNCH 221,(PHIN),N=(1,NSS)
      IF(IPUNCH.GT.0.AND.OFAYE.EQ.0.) PUNCH 221,TIME
      IF(IPUNCH.GT.0.AND.OFAYE.EQ.0.) PUNCH 221,(CHARGE(N),N=1,NSS)
      IF(IT.GT.ITMAX) GO TO 1
      IF(OE9YL.EQ.0.) GO TO 11
      C FIRST NO DENSITIES
      C
      NP0INT=NP0INT+1
      40=MC1
      MC=MC1
      MA=MA1
      40=MC1
      ME=ME1
      STEP=STEP+1
      C STOP IN DENSITY IF STEP LT ZERO.
      ZSAVE=ZSAVE1
      ZSAVE=ZSAVE1
      ALPHA=ALP0+441
      RETA=RETA1
      FE=FE1
      XMSAVE=XMSAVE1
      CALL DENSITY
      WRITE(M,664) NP0INT,40,MC,MA,MP,MC,STFC,ZSAVE,ZSAVE,ALPHA,DETA,CF,

```

9

```

1 XMSAVE
664 FORMAT(1X,22HNP0INT,40,MC,MA,MP,MC,STFC,ZSAVE,ZSAVE,ALPHA,DETA,CF,
1 1X,37HSTEP,ZSAVE,ZSAVE,ALPHA,DETA,CF,X40CH=,7F10.6)
      WRITE(M,660) IT
      IF (ITFIRST.EQ.0.OF.NGR.EQ.0) GO TO 31
90 CONTINUE
91 CONTINUE
      C THEN DO CURRENTS
      C
      NP0INT=NP0INT+1
      C
      IF (ITFIRST.GT.0) NP0INT=0
      C
      40=MC2
      MC=MC2
      MA=MA2
      MP=MP2
      ME=ME2
      STEP=STEP+1
      C STOP IN DENSITY IF STEP LE ZERO.
      ZSAVE=ZSAVE2
      ZSAVE=ZSAVE2
      ALPHA=ALP0+42
      RETA=RETA2
      FE=FE2
      XMSAVE=XMSAVE2
      CALL DENSITY
      WRITE(M,664) NP0INT,40,MC,MA,MP,MC,STFC,ZSAVE,ZSAVE,ALPHA,DETA,CF,
1 XMSAVE
      IF(MC2.GT.0) WRITE(M,5070) IT
      IFIRST=ITFIRST+1
      IT=IT+1
      C
      IF(IT.GT.0.AND.IVMAX.GT.0.AND.MOD(IT,IVITS).EQ.0) GO TO 600
      GO TO 10
800 CONTINUE
      C
90 STOP
      END

```

10

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```

SUBROUTINE ROOT(A,X)
COMMON JJN,TIN,JJS,IIS,NTOT,RNT(50),ZNT(50),ZST(50),
1 KZ( 500,2),PHIN(20,20),PHIS(20,20),CNC( 500),IFIRST,M
C = IND = OUT OF X*EXP(X)=A. 3Y NEWTON METHOD.
KPOB=0
KPRB=0
EPS=1.E-5
XOLD=X
KMAX=1000
DO 100 K=1,KMAX
XOLD=X
KPRB=K
F=X + R*EXP(X) - A
FF=1. + R*EXP(X)
XX=0.
IF(FP.GT.0.) DX=F/FP
X=XOLD + DX
DELTA=DX
IF(ABS(X).GT.1.E-8) DELTA=DX/X
IF(KPPA.GT.0) WRITE(M,1000) K,A,R,X,DX,DELTA,F,FP
FORMAT(IX,22HK,A,B,X,DX,DELTA,F,FP=,15,127E14.4)
IF(ABS(DELTA).LT.EPS) GO TO 200
CONTINUE
WRITE(M,9999) KMAX
FORMAT(//IX,9H MORE THAN,15,
1 40H ITERATIONS IN ROOT. HENCE PROGRAM STOP.)
STOP

```

33

```

200 CONTINUE
DELTA=100.*DELTA
IF(FP.GT.0) WRITE(M,2000) EPS,X,DELTA,KPR
FORMAT(IX,35H CONVERGENCE IN ROOT WITHIN EPSILON=,10E9.1,1H.,10X,
1 3HY =,12.4,7H WITHIN,10.2,11H PERCENT IN,14,12H ITERATIONS.)
RETURN
END

```

11

SUBROUTINE FELD

UNSYMMETRIC DISK FIELD
SFIELD METHOD

```

COMMON JJN,TIN,JJS,IIS,NTOT,RNT(50),ZNT(50),ZST(50),
1 KZ( 500,2),PHIN(20,20),PHIS(20,20),CNC( 500),IFIRST,M
COMMON/FLD/NCOLSM,NCOLSF,NCOLSS,NPQMSM,X(500),NPQMS,PEBYE,DEBYE2,
1 RHONH(50),RHOH(50),RHOS(50),7N(50),ZS(50),PHI(50),NGAP,HUISK
COMMON/A/CN,CS,CE,CM,CV, INDH,JSAT,RH,Z,INDXH( 500),INDXS( 500)
1,INDEX( 500),INDXH( 500),CONST( 500,6)
COMMON/CFH/IT,MAH,HEMPH,ISAVE,NGR,NGRNUF( 500),OSAVE( 500)
1, 7FCNT,NSS,NPOWS,NPHOTO,AREA(100),EFF_UY(100)

```

C ASSUME ASYMMETRIC MONOPOLE

```

ALPHA(R,27)=-27/(22**2 + R3**2)
BTA(R,27)=-R/(22**2 + R3**2)

```

```

C
IF(IFIRST.EQ.0) GO TO 45
IF(NEAP.LT.EQ.0.AND.DEBWE.GT.0.) WRITE(M,222) DEBYE,IT,MGR,
1 CN,RHANN(ND,N=1,NTOT)
IF(NEPH.GT.0.AND.DEBYE.GT.0.) WRITE(M,223) DEBYE,IT,MGR,
1 CN,RHANN(ND,N=1,NTOT)

```

```

222 FORMAT(14/16H FIELD CALCULATION, 10X,
1 41HNFJ=CHARGE DENSITIES WITH DEBYE NUMBER=,F10.5,
2 10X,WHIT =,13,3X,SHNGP =,13,
3 (28X,13,1PE15.4))

```

```

223 FORMAT(14/16H FIELD CALCULATION, 10X,
1 41HNFJ= ION DENSITIES WITH DEBYE NUMBER=,F10.5,
2 10X,WHIT =,13,3X,SHNGP =,13,
3 (28X,13,1PE15.4))
NORTH + NORTHEAST REGION

```

FIRST POINT, FIRST LINE

CONTINUE

JSAT=0

I=1

IF(IFIRST.EQ.0) WRITE(M,333)

333 FORMAT(//IX,25H NORTH + NORTHEAST REGION//)

IF(IFIRST.EQ.0) WRITE(M,334) I

746 FORMAT(//5H LINE,13,93H

1 J=1

INDX=J

INDXH(INDX)=0

INDXS(INDX)=J*JJN

INDXCF(INDX)= INDX + 1

INDXH(INDX)=0

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```

Z=ZNT(I)
PHO=ZNT(J)
HN=0.
HS=Z-7N(I+1)
HE=ZNT(J+1)-PHO
HM=0.
ALPHA=ALPHA*(RHO,Z)
CN=0.
CS=0.125*HE**2/HN
CE=HS/HN.
CM=0.
C=0.125*HE*(HE/HN+2.*HS/HE-ALPHA*HF)
V=HS*HE**2/16.
CALL PRINT

```

C C C

MIDDLE POINTS, FIRST LINE

```

JMAX=JN-1
DO 5 J=2,JMAX
  INDX=J
  INDXM(INDX)=0
  INDXS(INDX)=J*JN
  INDXC(INDX)=INDX+1
  INDX4(INDX)=INDX-1
  Z=ZNT(I)
  PHO=ZNT(J)
  HN=0.
  HS=Z-7N(I+1)
  HE=ZNT(J+1)-PHO
  HM=PHO-ZNT(J-1)
  ALPHA=ALPHA*(RHO,Z)
  CN=0.
  CS=0.125*HE*(HE/HN+2.*HS/HE-ALPHA*HF)/HN
  CE=HS/HN*(RHO*HE/2.)
  CM=0.125*HS*(HE/HN+2.*HS/HE-ALPHA*HF)/HN
  V=0.25*HS*(HE/HN+2.*HS/HE-ALPHA*HF)/HN
  CALL PRINT

```

C C C

LAST POINT FIRST LINE

```

J=JN
INDX=J
INDXM(INDX)=0
INDXS(INDX)=J*JN
INDXC(INDX)=0
INDX4(INDX)=INDX-1
INDXS(INDX)=0
INDXM(INDX)=INDX-1
INDXC(INDX)=INDX-1
INDX4(INDX)=0
INDXS(INDX)=INDX-1

```

13

```

Z=ZNT(I)
PHO=ZNT(J)
HN=0.
HS=Z-7N(I+1)
HE=0.
ALPHA=ALPHA*(RHO,Z)
BETA=ZNT(J+1)-PHO
HM=PHO-ZNT(J-1)
CN=0.
CS=0.5*44/HS*(PHO-HM/4.)
CE=0.
CM=0.5*45/HN*(PHO-HM/2.)
C=0.5*(44/HS+HS/HN-ALPHA*HM)*(PHO-HM/4.)-HS*(BETA*CM/4.0+0.25)
V=0.25*HS*(44/HS+HS/HN-ALPHA*HM/4.)
CALL PRINT

```

C C C

MIDDLE LINES

```

DO 10 I=2,NROWSN
  IF (IFIRST.EQ.0) WRITE (N,314) I
  DO 10 J=1,JN
    INDX=J*(I-1)+JN
    INDXM(INDX)=INDX-JN
    INDXS(INDX)=INDX+JN
    Z=ZNT(I)
    HN=ZNT(I-1)-Z
    HS=Z-7N(I+1)
    PHO=ZNT(J)
    JCO=2
    IF (J.EQ.1) JCO=1
    IF (J.EQ.1) JCO=3
    GO TO (5,7,8),JCO
    6 INDXM(INDX)=INDX+1
    INDX4(INDX)=0.
    HE=ZNT(J+1)-PHO
    HM=0.
    CALL LEFT (PHO,HN,HS,HE,HM,CN,CS,CE,CM,C,V)
    GO TO 9
    7 INDXM(INDX)=INDX+1
    INDX4(INDX)=INDX-1
    HE=ZNT(J+1)-PHO
    HM=PHO-ZNT(J-1)
    CALL RIGHT (PHO,HN,HS,HE,HM,CN,CS,CE,CM,C,V)
    GO TO 9
    8 INDXM(INDX)=0
    INDX4(INDX)=INDX-1
    HE=0.
    HM=PHO-ZNT(J-1)
    BETA=ZNT(J+1)-PHO
    CALL RIGHT (PHO,HN,HS,HE,HM,CN,CS,CE,CM,C,V)
    9 CALL PRINT

```

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10 CONTINUE

7 = 0 PLANE

IF (FIRST.EQ.0) WRITE(M,444)
444 FORMAT(////1X, 9H2=0 PLANE ///)

I=1

IF (FIRST.EQ.0) WRITE(M,444) I

DO 26 J=1,JJN

INDEX=J*PPOMSS*JJN

INDEX(INDEX)=INDEX-JJN

INDEX(INDEX)=INDEX+JJN

PHO=INT(J)

Z=0.

JGO=2

IF (J.EQ.1) JGO=1

IF (J.EQ.1) JGO=3

HN=Z*PPOMSS*JJN

HN=Z*PPOMSS*JJN

HN=Z*PPOMSS*JJN

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HN=Z*PPOMSS*JJN

HN=Z*PPOMSS*JJN

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SOUTH + SOUTHEAST REGION

000000000000

0

IF (FIRST.EQ.0) WRITE(M,555)
555 FORMAT(//1X, 9H2=0 SOUTH + SOUTHEAST REGION///)

DO 41 I=1,PPOMSS

IF (FIRST.EQ.0) WRITE(M,333) I

DO 41 J=1,JJN

INDEX=J*PPOMSS*JJN

INDEX(INDEX)=INDEX-JJN

INDEX(INDEX)=INDEX+JJN

PHO=INT(J)

Z=ZST(I+1)

JGO=2

IF (I.EQ.1) JGO=1

IF (I.EQ.1) JGO=3

HN=Z*PPOMSS*JJN

HN=Z*PPOMSS*JJN

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HN=Z*PPOMSS*JJN

HN=Z*PPOMSS*JJN

PROGRAM PARKOC

43 110N / (CALI4,1PEI2,4)))
 CONTINUE
 IF (IFIRST.GT.0) CALL STIOFL
 RETURN
 END

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PROGRAM PARKOC

CALL MIDTLE (PHO,HN,IS,HE,HM,CH,CS,CE,CM,Z,V)
 GO TO 40
 C LAST POINT
 C
 76 INDXE(IYXX)=0
 INDXE(IYVY)=INDX-1
 HE=0.
 HM=PHO-Z*ST(J-1)
 HETA=ACTOF(RHO,Z)
 IF (IIO.EQ.3) GO TO 13
 CALL RIGHT(RHO,HN,IS,HE,HM,HETA,CH,CS,CE,CM,Z,V)
 GO TO 40
 33 GO TO (37,39,34),J50
 C LAST LINE, FIRST POINT
 C
 37 CN=0.125*HE**2/HM
 CS=0.
 CE=HM/4.
 CM=0.
 C=0.125*4E*(HE/HN + 2.*HM/HE - ALPHA*HE)
 V=HN*HE**2/16.
 GO TO 40
 C LAST LINE, MIDDLE POINTS
 C
 38 CN=0.5*(HE*HM/HN*(RHO*(HE-HM)/4.))
 CS=0.
 CE=0.5*4N/HE*(RHO*HE/2.)
 CM=0.5*4N/HM*(RHO-HM/2.)
 C=0.5*HN*(HE+HM)*(RHO/HE/HM + (1.-ALPHA*HN)*(RHO*(HE-HM)/4.)/HM**
 12)
 V=0.250*HN*(HE+HM)*(RHO + (HE-HM)/4.)
 GO TO 40
 C LAST LINE, LAST POINT
 C
 39 CN=0.5*4N/HN*(PHO-HM/4.)
 CS=0.
 CE=0.
 CM=0.5*4N/HM*(PHO-HM/2.)
 C=0.5*(HM/HN*HN/HM-ALPHA*HM)*(RHO-HM/4.)- HM*(HETA*2HO + 0.25)
 V=0.25*HN*HM*(PHO-HM/4.)
 40 CALL PRINT
 41 CONTINUE
 IP=INT=0
 IF (IP=INT.EQ.0) GO TO 43
 IF (IFIRST.EQ.0.AND.II.EQ.0.AND.NPHOTO.GT.0.AND.OFCYC.EQ.0.)
 1 WRITE(4,777)(N,PHANT(N),N=1,NTOT)
 777 FORMAT(//1X,54H)AND ARRAY FOR INVERSE CAPACITANCE MATRIX CALCULAT

17


```

SUBROUTINE LEFT(RHO,HN,HS,HE,HM,CN,CS,CF,CH,C,V)
  ZN=0.125*(HE**2/HS)
  CS=LN*HN/HS
  CE=0.25*(HN*HS)
  CM=0.
  C=0.25*(HN*HS)*(1.09.54E**2/HS/HS)
  V=4E**2*(HN*HS)/16.
  OF TURN
  END

```

19

```

SUBROUTINE MIDDLE (RHO,HN,IS,HT,HM,CN,CS,CF,CH,C,V)
  CN=0.5*(HE*HM)/HN*(RHO*(HE-HM)/4.)
  CS=CN*HM/HS
  CF=0.5*(HN*HS)/HF*(RHO*HC/2.)
  CM=0.5*(HM*HS)/HM*(RHO-HM/2.)
  C=0.5*(HN*HS)*(HE*HM)*(RHO/HF/HM*(RHO*(HE-HM)/4.)/HM/HS)
  V=0.25*(HN*HS)*(HE*HM)*(RHO*(HE-HM)/4.)
  RETURN
  END

```

20

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```

SUBROUTINE RIGHT (PHO,HN,HS,HE,HM,BETA,CN,CS,CF,CW,C,V)
  CM=0.5*44/IN*(PHO-HM/4.)
  CS=CM*HN/HS
  CE=0.
  CH=0.5*(IN+45)/HM*(240-HM/2.)
  C=0.5*(HN+HS)* (HM+HN/HS*(PHO-HM/4.)+(RHO-HM/4.)) - (ETA*RHO)
  V=0.25*(HN+45)*HM*(RHO-HM/4.)
  RETURN
END

```

21

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```

SUBROUTINE PRINT
  COMMON JIN, IIN, JJSAT, IISAT, IOT, RNI(50), ZNI(50), RST(50), ZST(50),
  1 KZ( 500,2), PHIN(20,20), PHIS(20,20), PHAN( 500), IFRST, M
  COMMON/FLU/NCOLSN,NCOLSF,NCOLSS,NCOLSM,X(500),HROWSS,IRVVF,OTBYE2,
  1 PHONI(50),PHOF(50),PHOS(50),PHI(50),ZS(50),PHI(50),NGAP,NOISK
  COMMON/VCN,CS,CF,CW,C,V, INDX,JSAT,RHO,7,INDXH( 500),INDXS( 500)
  1,INDEX( 500),INDXM( 500),CONST( 500,6)
  CP=0.
  CONST(IYDX,1)= CN
  VF(INDXN(INDX),FO,0 ).AND.(CM.NF.0.) CP=CM
  CONST(INDX,7)= CS
  IF(INDXS(INDX).EQ.0 ).AND.(CS.NF.0.) CP=CS
  CONST(INDX,3)= CF
  CONST(INDX,4)= CW
  IF(INDX4(INDX).EQ.0 ).AND.(CW.NF.0.) CP=CM
  C ***** TEMPORARY --- HELMHOLTZ EQUATION
  IF(DEVF2.GT.0.) C=C* V/(DEVF2**2)
  C ***** TEMPORARY --- HELMHOLTZ EQUATION
  CONST(INDX,5)= C
  CONST(INDX,6)= V
  IF (CP.GT.0..AND.OTBYE.GT.0.) KHAM7(INDX) = 2/HAM7(INDX)*V/DEVF**2
  1 + CP*P4(JSAT)
  IF (CP.EQ.0..AND.OTBYE.GT.0.) PHAN7(INDX) = PHAN(INDX)*V/DEVF**2
  IF (IFIRST.GT.0) GO TO 3
  WRITE (M,1) INDX, ICHN(INDX), CONST(INDX,1), INDXM(INDX), CONST(
  1 INDX,4), INDX,CONST(INDX,5), INDXE(INDX), CONST(INDX,3), INDXS(EN
  2 DX), CONST(INDX,2), CONST(INDX,6)
  1 FORMAT / 6H POINT,14, 3H/C(,14,2H)=,10F10.4,3H/C(,14,2H)=,
  1F10.4, 3H/C(,14,2H)=,10F10.4, 3H/C(,14,2H)=,10F10.4, 3H/C(,14,2H)=,
  2F10.4, 5H/VOL=E10.4)
  IF (CP.NF.0.) WRITE (M,2) JSAT, CP
  2 FORMAT(31M COEFFICIENT OF POTENTIAL NO. (,13, 4H) IS,F10.5)
  3 P7(INDX,1)=RHO
  RZ(INDX,2)=Z
  RETURN
END

```

22

```

C ***** MODIFICATION FOR FINITE DIFF THICKNESS
C SFT PHI TO BODY POTENTIAL AT ADDITIONAL BODY POINTS IF ANY
IF (K1K,11,GT,999999.99,RTK,21,LT,ZFRONT,99,RTK,21,GT,99.9)
  1 GO TO 20
  IF (IFIPSI,GT,0.0,AND,IT,EQ,0,AND,NPHOTO,GT,0,AND,DERIV,EQ,0.0)
    1 GO TO 20
  IF (PZK,21,LT,0.0) GO TO 5
  IF (K1,11,GE,1,AND,K1,11,LT,NCOLSN) X(K)=PHI(K-11)
    GO TO 20
  3 CONTINUE
  NO OVERLAP IF NONCONDUCTING BODY
  IF (NONCON,ST,0) GO TO 20
  K1=K1+1
  NSSIK2=0
  INTARG=1+NCOLSN+K1/NCOLSS
  X(K1)=0.
  IF (PZK,21,EQ,ZFRONT) GO TO 5
  MODFUN=MOD(K1,NCOLSS)
  IF (MODFUN,EQ,0) X(K1)=PHI(INTARG)
  GO TO 20
  5 K2=K2+1
  IF (K2,FL,NCOLSS) X(K2)=PHI(NSS+2)
  IF (K2,EL,NCOLSS) GO TO 20
  NSSIK2=NSS+1-K2
  X(K2)=PHI(NSSIK2)
  3 CONTINUE
  WRITE(M,1111) K1,K2,MODFUN,INTARG,NSSIK2
  C
  1111 FORMAT (/1X,3HK1, K2, MODFUN, INTARG, NSSIK2 = ,515)
  1112 X(K1)=OMEGA*X(K1)+1.-OMEGA)*X1
  DELTA=ABS(X(K1)-X1)
  IF (X1,NE,0.0) DELTA=ABS(X(K1)-X1)/X1
  IF (DELTA,GT,DELTA) DELTA=DELTA
  3 CONTINUE
  IF (ITCOJN,GT,ITMAX) WRITE(M,11) ITMAX
  IF (ITCOJN,GT,ITMAX) GO TO 9
  11 FORMAT(//10H MORE THAN 14,10HITERATIONS)
  IF (IPR,LT,IPPOLO) GO TO 15
  IF (QLO,LT,IPR)
    GO TO 10
  15 IF (DELTA,GT,EPS) GO TO 2
  11 IF (ITCOJN,GT,ITMAX)
  10 IF (EPS,LT,1E-10) + 1
  9 IGO=2
  10 IF (EPS,LT,1E-10) + 1
  C
  C
  C

```

```

C ***** MODIFICATION FOR FINITE DIFF THICKNESS
C SFT PHI TO BODY POTENTIAL AT ADDITIONAL BODY POINTS IF ANY
IF (K1K,11,GT,999999.99,RTK,21,LT,ZFRONT,99,RTK,21,GT,99.9)
  1 GO TO 20
  IF (IFIPSI,GT,0.0,AND,IT,EQ,0,AND,NPHOTO,GT,0,AND,DERIV,EQ,0.0)
    1 GO TO 20
  IF (PZK,21,LT,0.0) GO TO 5
  IF (K1,11,GE,1,AND,K1,11,LT,NCOLSN) X(K)=PHI(K-11)
    GO TO 20
  3 CONTINUE
  NO OVERLAP IF NONCONDUCTING BODY
  IF (NONCON,ST,0) GO TO 20
  K1=K1+1
  NSSIK2=0
  INTARG=1+NCOLSN+K1/NCOLSS
  X(K1)=0.
  IF (PZK,21,EQ,ZFRONT) GO TO 5
  MODFUN=MOD(K1,NCOLSS)
  IF (MODFUN,EQ,0) X(K1)=PHI(INTARG)
  GO TO 20
  5 K2=K2+1
  IF (K2,FL,NCOLSS) X(K2)=PHI(NSS+2)
  IF (K2,EL,NCOLSS) GO TO 20
  NSSIK2=NSS+1-K2
  X(K2)=PHI(NSSIK2)
  3 CONTINUE
  WRITE(M,1111) K1,K2,MODFUN,INTARG,NSSIK2
  C
  1111 FORMAT (/1X,3HK1, K2, MODFUN, INTARG, NSSIK2 = ,515)
  1112 X(K1)=OMEGA*X(K1)+1.-OMEGA)*X1
  DELTA=ABS(X(K1)-X1)
  IF (X1,NE,0.0) DELTA=ABS(X(K1)-X1)/X1
  IF (DELTA,GT,DELTA) DELTA=DELTA
  3 CONTINUE
  IF (ITCOJN,GT,ITMAX) WRITE(M,11) ITMAX
  IF (ITCOJN,GT,ITMAX) GO TO 9
  11 FORMAT(//10H MORE THAN 14,10HITERATIONS)
  IF (IPR,LT,IPPOLO) GO TO 15
  IF (QLO,LT,IPR)
    GO TO 10
  15 IF (DELTA,GT,EPS) GO TO 2
  11 IF (ITCOJN,GT,ITMAX)
  10 IF (EPS,LT,1E-10) + 1
  9 IGO=2
  10 IF (EPS,LT,1E-10) + 1
  C
  C
  C

```

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```

1 IF (FIRST.EQ.0.AND.IT.EQ.0.AND.NPHOTO.GT.0.AND.0FIVE.FO.0.0)
2 GO TO (15,4), IGO
3 DO 51 I=1,NFPP
4 WRITE(M,P2) TICOUNT,EPS,DELTA,OMEGA
5 DO 51 I=1,60
6 K1=I + 300*(IP-1)
7 K2=K1 + 60
8 K3=K2 + 60
9 K4=K3 + 60
10 K5=K4 + 60
11 IF (K5.LE.NTOT) WRITE(M,3333)K1,X(K1),K2,X(K2),K3,X(K3),K4,X(K4),
12 K5,X(K5)
13 IF (K5.LE.NTOT) GO TO 51
14 IF (K4.LE.NTOT) WRITE(M,3333)K1,X(K1),K2,X(K2),K3,X(K3),K4,X(K4)
15 IF (K4.LE.NTOT) GO TO 51
16 IF (K3.LE.NTOT) WRITE(M,3333)K1,X(K1),K2,X(K2),K3,X(K3)
17 IF (K3.LE.NTOT) GO TO 51
18 IF (K2.LE.NTOT) WRITE(M,3333)K1,X(K1),K2,X(K2)
19 IF (K2.LE.NTOT) GO TO 51
20 IF (K1.LE.NTOT) WRITE(M,3333)K1,X(K1)
21 CONTINUE
22 3333 FORMAT(5I0,F16.8)
23 GO TO (15,4), IGO
24 22 FORMAT(15)SOLUTION AFTER,16,2X,25HITERATIONS WITH TOLFRANCE,F12.3
25 1,8X,18HMAXIMUM DIFFERENCE,F12.8,4X,6HONCE,5X,F9.5)
26 4 RETURN
27 END

```

```

SUBROUTINE DFNSTY
COMMON JIN,IIN,IJS,IIS,IND,INLEO,Z(1050),ZS(50),ZSV( 500),
1 ZSV( 500),OMHIT(20,20),OMHIS(20,20),CNSV( 500),IFIRST,M
COMMON/C/N/NPRINT,M0,MC,MA,MB,MC,STC0,R3AVE,ZSAVE,ALPHA,BETA,FC,
2 XNSAVE,FADIOS,FLUYIT(,20),FLUYE(13,20),F_UXFM(13,20),CNSAVE(100)
COMMON/C/M/IT,MAHE,NFMHIT,ZSAVE,NG2,NG3DUP( 500),ZSAVE( 500)
1 ZERONT,HSS,NPOMS,NPHOTO,ARFA(100),CFF_UX(100)
COMMON/OMIT/JIGM,J=4,IJS,JCS
COMMON/OMIT/RA(50),RA(50),Z(150),Z(150),IJA,JJA,IIJ,JJM
COMMON/C/3/3DOT,7DOT,AMS,NTI4E,RI,2,71,22,3,7,PHI,PSAV,ZSAV
COMMON/2/2/PI,XMACH,KEMAX,JEKAX,KPMAX,JBMAX,KAMAX,JAMAX,
1 FEE(16,2),SKA(16,2),CSA(16,2),JTA(16,2),COFFA(15,2),COEFF(16,2)
2 THEUSION ONORTH(2,2),JCSA(16,2),JCSOUTH(20,20)
3 DIMENSION PARTCL(2),PART1(2),PART2(2),FATE(2),ENH1(2),ENH2(2)
4 DIMENSION FRAC(100),FLUX(100),ADFLUX(100),INCEX(10),KMHIT(13,50),
5 DIMENSION(13,50),KMHIT(13,50),JMHIT(13,50),JNSTEP(100)
6 DATA PART1/6H IOM ,6H /,PART2/6H ELECT,FARON /
7 DATA ENH1/6H ANSOR,6HRED /,FEND2/6H ESCAP,6HES /
8 PI = 3.1415926536
9 INDX4Y=50
10 NSTEP=10*0
11 ROUNO=1.E-12
12 REPEAT=0.
13 COMIN=0.
14 NORMALIZATION FACTOR FOR HYDROGEN ION /LUX
15 FACTOR=1./SDPT(1A36.)
16 IPPRINT=1
17 IF (MC.GT.0.OP,MSR.GT.1 ) IPRINT=0
18 NTOT=ND
19 NPIS=ND
20 NDP=ND+1
21 IYIN=IIN-1
22 IIS4=IIS-1
23 I1=I100*IJM
24 N2=NTOT-IIS4*JJS
25 NCOLSN=(IIS4-MONS-1)/2
26 IF (NRMS.EQ.0) NCOLSN=NSS
27 NCOLSN=NCOLSN
28 DO ONE CHARGE DENSITY OR CURRENT DENSITY, OR 00 ALL
29 IF (D.EQ.0) NPIS=1
30 IF (D.EQ.0) RSV(1)=RSAVE
31 IF (D.EQ.0) ZSV(1)=ZSAVE
32 IF (MC.EQ.0) WRITE(M,566) IT,NGR
33 IF (MC.GT.0) WRITE(M,667) IT
34 WRITE(M,664) HPRINT,MD,MC,MA,MB,ME,STC0,ZSAVE,ZSAVE,
35 1 ALPHA,BETA,FC,XNSAVE
36 1 ALPHA,BETA,FC,XNSAVE
37 665 FORMAT(1H/10HDEFINITIONS,5X,4HIT =,I3,3X,3HNSF =,I3)
38 667 FORMAT(1H/10HDEFINITIONS,5X,4HIT =,I3)
39 664 FORMAT(11,22HPRINT,MD,MC,MA,MB,ME,STC0,ZSAVE,ZSAVE,
40 1 X,XHSTEP,ZSAVE,ZSAVE,ALPHA,BETA,FC,XNSAVE,ZSAVE,7F10.5)

```

```

IF (HP-INT.EQ.0) WRITE(M,660) NPOINT
IF (HP-INT.EQ.1) WRITE(M,661) NPOINT
IF (HP-INT.EQ.2) WRITE(M,662) NPOINT
IF (HP-INT.EQ.3) WRITE(M,663) NPOINT
560 FORMAT(1X,8HPOINT =,I2,38H YEARS NO TRAJECTORY PRINTING
661 FORMAT(1X,8HPOINT =,I2,38H INDICES OF ESCAPING TRAJECTORIES ONLY)
662 FORMAT(1X,8HPOINT =,I2,38H FIRST & LAST STEPS OF EACH TRAJECTORY)
663 FORMAT(1X,8HPOINT =,I2,38H EVERY STEP OF ALL TRAJECTORIES
1
333 FORMAT(1X,14HLINE,14,5X,2H2Z=,F8.4//7F16.8)
3000 FORMAT(1X,1X,24H POTENTIAL ARRAY - SOUTH//1X,2H2Z=,16F8.4/
1 (/3X,15F8.4))
5000 FORMAT(1X,24H POTENTIAL ARRAY - SOUTH//1X,2H2Z=,16F8.4/
1 (/3X,15F8.4))
C
WRITE (M,3000) (R(I),J=1,JUN)
DO 5 I=1,IIN
WRITE(M,333) (I,7HII), (PRINT(I),J=1,JJN)
DO 5 J=1,JJN
DO 6 I=1,IIS
WRITE(M,333) (I,7HII), (PRINT(I),J=1,JJS)
DO 6 J=1,JJS
NSOUTH(I,J)=0.
NOSTPS=0
5 DO 95 LOOP ENDS AT END OF PROGRAM
IF (IND.GT.0.AND.MC.EQ.0) NPTS=ND*1
NSURF=0
IF (IND.GT.0.AND.MC.GT.0) NPTS=ND*NS
IF (IND.GT.0.AND.MC.GT.0) NSURF=1
NFI=NCOLSN
NF2=NCOLSN
NF3=NCOLSN
NC1=ND+NCOLSN
NC2=NC1+1
NC3=NPTS-NCOLSN
NC4=NC3+1
IP4IN=1
IP4AX=1
IF (IPHOIO.EQ.1) IPMIN=2
IF (IPHOIO.GT.0) IPMAX=2
DO 950 IP=IPMIN,IPMAX
DO 95 N=1,NPTS
IF (NSURF.GT.0) COS(VIN)=0.
IF (INSURF.GT.0.AND.N.LF.NO) GO TO 35
IF (IP.EQ.2.AND.EFFLUX(9-HUB.EQ.0)) GO TO 86
IF (IPHOIO.EQ.1) WRITE(M,3995)N
95AVE=RSV(H)
7SAVE=7SV(N)
HUB=N-N
IF (INSURF.GT.0.AND.IFIRST.EQ.0) COSAVE(N-ND)=93.

```

```

1P=0
JN=0
IS=0
JS=0
IF (INSURF.EQ.2.AND.NDONS.LF.0) NSURF=1
IF (INSURF.GT.0) GO TO 19
IF (N.LF.NO) GO TO 7
IF (N.GT.N2) GO TO 4
DO 1 I=1,IIN
IF (ZSAVE.EQ.ZN(I)) IN=I
CONTINUE
DO 2 J=1,JJN
IF (ZSAVE.EQ.PN(J)) JN=J
CONTINUE
DO 3 I=1,IIS
IF (ZSAVE.EQ.ZS(I)) IS=I
CONTINUE
DO 4 J=1,JJS
IF (ZSAVE.EQ.PS(J)) JS=J
CONTINUE
CONTINUE
IF (N.LF.N2.AND.IM.GT.0.AND.JN.GT.0) NMOUTH(I,N,J)=DSAVE(N)
IF (N.GT.N1.AND.IS.GT.0.AND.JS.GT.0) NSOUTH(I,S,J)=DSAVE(N)
IF (N.GT.0) GO TO 15
IF (N.GT.0) GO TO 15
IF (N.GT.0.AND.N.LF.NPTS.AND.NGROUP(N).N.NGRD COS(VIN)=DSAVE(N)
IF (N.GT.0.AND.N.LF.NPTS.AND.NGROUP(N).N.NGRD) GO TO 35
15 CONTINUE
***** MODIFICATION FOR FINITE DISK THICKNESS
IF (ZSAVE.LF.RADIUS.AND.ZSAVE.GF.ZFRONT.AND.ZSAVE.LI.0.) COS(VIN)=0.
IF (ZSAVE.LF.RADIUS.AND.ZSAVE.GF.ZFRONT.AND.ZSAVE.LI.0.) GO TO 95
IF (N.GT.0.AND.ISAVE.EQ.0) DSAVE(N)=0.
CONTINUE
13 IF (INSURF.GT.0.AND.IFIRST.GT.0.AND.ANSICUSAVE(N-ND)).LI.COMIN)
GO TO 96
4ASAVE=14
NRSAVE=13
NFSAVE=12
STEPS=STFP
INCPFA=0
IF (IP.EQ.2) MF=0
IF (N.GT.0.OP.MAME.EQ.0) GO TO 20
***** INCREASE ACCURACY NEAR AXIS
IF (ZSAVE.LF.PN(2).AND.ZSAVE.GT.0.) MA=MF+16
IF (ZSAVE.LF.PN(2).AND.ZSAVE.GT.0.) STEP=.05
IF (ZSAVE.LF.PN(2).AND.ZSAVE.GT.0.) INCPFA=1
20 CONTINUE
C TEST WE DO THE IONS
SCALE=1.
PARTCL(1)=PARTI(1)
PARTCL(2)=PARTI(2)

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```

IF (IP.EQ.2.AND.NPHOTO.EQ.1) SCALE=-1.
2 RETURN FROM END OF PATH FOR ELECTRONS
C
237 CONTINUE

```

```

IF (SCALE.GT.0.) XMAX=XMSAVE
IF (SCALE.LT.0.) XMAX=0.
POWER=1/(XMAX)
PHMAX = 0.
DO 11 I=1,IIN
DO 10 J=1,JIN

```

```

10 PHINT(J)=SCALE*PHIN(I,J)
IF (PHMAX.LT.PHINT(I)) PHMAX = PHINT(I)
11 CONTINUE
C

```

```

DO 13 I=1,IIS
DO 12 J=1,JJS
PHST(J)=SCALE*PHS(I,J)
13 CONTINUE
C

```

```

2 SET UP SUMS OVER TRAJECTORIES
C

```

```

IF (MA.EQ.0) GO TO 32
JMAX=2
JMAX=2
KMAX=4
KMAX=4
NUMBER=4*4*4*4

```

```

C DO ONLY ONE SET ON AXIS (SYMMETRY)

```

```

IF (SAVE.EQ.0.) KMAX=1
IF (PSAVE.EQ.0.) NUMBER=4*2
IF (PSAVE.EQ.0.) JMAX=1

```

```

IF (SCALE.GT.0.AND.N.EQ.1) WRITE (M,664) 'A,M',NUMBER
168 FORMAT(IX,16,16H ALPHA-INTERVALS,IX,16,15H OPTA-INTERVALS,IX,16,
1 24H TRAJECTORIES FOR ENERGY)
C

```

```

IF (ME.EQ.0) GO TO 31
JMAX=2
KMAX=4

```

```

IF (SCALE.GT.0.AND.N.EQ.1) WRITE (M,670) 4E
670 FORMAT(IX,16,47H ENERGY INTERVALS, WITH 2 ENERGIES PER INTERVAL//)
C

```

```

GO TO 33
C

```

```

C SINGLE ENERGY
C

```

```

31 JMAX=1
KMAX=1

```

```

IF (SCALE.GT.0.AND.N.EQ.1) WRITE (M,673) 3E
673 FORMAT(IX,31H MONOENERGETIC CASE WITH ENERGY,10.5//)
C

```

```

GO TO 33

```

```

C SINGLE TRAJECTORY ONLY
C

```

```

32 JMAX=1
JMAX=1
JMAX=1
KMAX=1
KMAX=1
KMAX=1
NUMBER=1

```

```

WRITE (M,663) ALPHA, BETA, EE
569 FORMAT(11H SINGLE TRAJECTORY/ 7H ALPHA=F20.19, 8H JCGREES/
1 6H BETA=F20.19, 3H DECFES/ 3H ENERGY=F10.6)
C

```

```

ALPHA=ALPHA*PI/180.
ALTA=BETA*PI/180.

```

```

WRITE (M,665) ALPHA, BETA
665 FORMAT(IX, 31H, 6H ALPHA=F11.9, 94 PAUANS/ IX, 5H BETA=F10.6)
1.0, 8H RADIANS)
C

```

```

SYN=SIGN(ALPHA)
COS=COS(ALPHA)
C

```

```

C SUM OVER ALPHA, BETA, AND ENERGY
C

```

```

33 CONTINUE
CALL COARS
DEFST=0.

```

```

NOSTEP(NVD)=0
DO 349 NAF=1,NSS
INDEX(NAF)=0
EPAG(NAF)=0.

```

```

CONTINUE
DO 1001 KE=1,KFMAY
DO 1001 JE=1,JFMAY
DENS=0.

```

```

NOST=0
DO 1000 K3=1, KFMAY
DO 1000 J3=1, JFMAY
DO 1000 K4=1, KFMAY
DO 1000 J4=1, JFMAY

```

```

C INITIAL POSITION
C

```

```

23 CONTINUE
IF (IP.EQ.2.AND.II.EQ.0) GO TO 1001
READSAVE
7=7SAVE
X=2
Y=0.

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```
INT=0  
CALL YHTRQP  
INT=1  
PHISAV=P+I  
***** ASSUME DELTA MAIN FACTOR FOR DENSITY OF ELECTRONS (OVERPOIDE)  
IF (ABS(PHI),GT,.500) GO TO 96  
IF (MC.E3.O.AND.SCALE.LT.0.) DENST=XPI-PHI  
IF (MC.EO.O.AND.SCALE.LT.0.) GO TO 96  
IF (MC.E3.O.AND.ISAVE.GT.0) DENST=OSAVE(M)  
IF (MC.E3.O.AND.ISAVE.GT.0) GO TO 96  
  
C INITIAL VELOCITY  
IF (STEP.LE.0.) WRITE(M,111)  
FORNAT(//,'IX,4-HPOT DMF TO STEP LC. 7FRD *****  
IF (STEP.LE.0.) STOP  
  
C INITIAL VELOCITY  
SPEED=0.  
IF (MF.NE.0) GO TO 41  
P=FF  
TF (IP.EQ.2) E=L+PHI  
IF (LT.PHI) WRITE(M,674) KE,JF,KJ,JB,KA,JA,DTAI,ALPHA1,E,PHISAV  
IF (LT.PHI) GO TO 1001  
GO TO 40  
CONTINUE  
E=E*(KE,JF)+AMX1(PHI,0.)  
IF (LT.0.) WRITE(M,674) KE,JF,KJ,JB,KA,JA,DTAI,ALPHA1,E,PHISAV  
IF (LT.0.) STOP  
  
C 40 SPEED=SQR(TF - PHI)  
IF (MA.E3.0) GO TO 79  
JVA=SNR(KA,JA)  
GSA=CGR(KA,JA)  
BETA=BTA(KA,JB)  
IF (EQ,P.) BETA=0.  
  
C 39 XDOT=SPEED*SINA*COS(BETA)  
YDOT=SPEED*SINA*SIN(BETA)  
ZDOT=SPDF*CGSA  
IF (INSURF.EQ.3) ZDOT=-ZDOT  
IF (INSURF.EQ.2) ZDOT=-XDOT  
IF (INSURF.EQ.2) XDOT=SPEED*CGSA  
ROOT=XDOT  
AMS=(R*YDOT)**2  
  
THEYA=0.  
ATAN1=0.  
ATAN2=0.  
ANSPT=4*5*(R*YDOT)  
TF (ANSPT.GT.0.) ATAN1=ATAN(R*DOY/AMS*Y)
```

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```

      SLEP4=SIGN(THETA)
      XDOT=RDOT/COSTH
      YDOT=RDOT*SINTH
      IF (R.GT.0.) XDOT=XDOT - (ANSRT/R)*SINTH
      IF (R.GT.0.) YDOT=YDOT + (ANSRT/R)*COSTH
      X=R*COSTH
      Y=R*SINTH
      CONTINUE
  18 C
      IF (NPINT.EQ.3)
        IMPITE(M,AAA) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,R,T,H,JCH,I65,J65
        Z,NTIME
        IF (KSTEP.LT.HSTEP) GO TO 15
        ARTIE (4,999) HSTEP
        APITE(M,17) KSTEP,M,KE,JE,KR,J8,KA,JA
        999 FORMAT(10M MORE THAN,110,5HSTEPS)
        IF (NPINT.EQ.3) REPEAT.GT.0:1 STOP
        REPEAT=1
        NPINT=3
        GO TO 29
  19 C
      PHIOLQ=PI
      QP=R
      77=Z
      IF (ZDOT.NE.0.) R=R + ROUND*SIGN(1.,ZDOT)
      IF (ZDOT.NE.0.) Z=Z + ROUND*SIGN(1.,ZDOT)
      IF (Z.LT.RADIUS.AND.SIGN(1.,Z).NE.SIGN(1.,ZOLD)) GO TO 16
      ***** MODIFICATION FOR FINITE DISK THICKNESS
      IF (R.LT.RADIUS.AND.Z.GE.7EPOUT.AND.7.LT.0:1 GO TO 16
      IF (R.GT.NCJ.M) OR (Z.GT.ZN(1) OR (Z.LT.ZN(1))) GO TO 17
      ZOLD=Z
      IF (R.LT.9..AND.RR.EQ.0.) RDOT=-RDOT
      IF (R.LT.0..AND.PR.EQ.0.) P=P.
      CALL INTERP
  20 C
      D=DR
      7=Z2
      IF (KST=P.EQ.0) GO TO 34
      VFLSQ=PHIOLQ-PHI
      IF (INTIME.LL.4) VELSQ=VELSQ + RDOT**2
      IF (INTIME.LL.4) AND.VELSQ.GE.0.) ZDOT=SQRT(VFLSQ)*SIGN(1.,ZDOT)
      IF (INTIME.GT.4) VFLSQ=VELSQ + ZDOT**2
      IF (INTIME.GT.4) AND.VELSQ.GE.0.) ZDOT=SQRT(VFLSQ)*SIGN(1.,ZDOT)
  21 C
      IF (VELSQ.GE.0.) GO TO 30
      IF (INTIME.LL.4) RDOT=-RDOT
      IF (INTIME.LL.4) NCHP=NCHP+1
      IF (INTIME.LL.4) AND.ZDOT.NE.0.1K=P+ROUND*SIGN(1.,ZDOT)
      IF (INTIME.GT.4) ZDOT=-ZDOT
      IF (INTIME.GT.4) NCHZ=NCHZ+1
      IF (INTIME.GT.4) AND.ZDOT.NE.0.1Z=Z+ROUND*SIGN(1.,ZDOT)

```

33

```

  22 C
      IF (NCHP.LT.NCHMAX) OR (NCHZ.LT.NCHMAX) GO TO 25
      WPIIE (4,777) NCHP,NCHZ,NCHMAX
      FORMAT(1X,5NCHP=,13,10H AND NCHZ=,13, 12H HAVE ATTAINED THE MAXI
      1MUM ALLOWED NUMBER=,13, 30H AND THE TRAJECTORY IS ABORTED)
      WPIIE(M,97) KSTEP,M,KE,JF,KR,J8,KA,JA
      WPIIE(M,PP3) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,RDOT,P,IGN,JCH,I65,J65,
      1 NTIME
      GO TO 1000
  25 CONTINUE
      CALL INTERP
      P=PR
      Z=Z2
      CONTINUE
  26 C
      IF (NPINT.LT.2) GO TO 34
      IF (ANSRT.GT.0.) ATANZ=ATAN(P*RDOT/ANSRT)
      ATANI=ATANZ
      COSTH=COS(THETA)
      SINTH=SIN(THETA)
      XDOT=RDOT*COSTH
      YDOT=RDOT*SINTH
      IF (R.GT.0.) XDOT=XDOT - (ANSRT/P)*SINTH
      IF (R.GT.0.) YDOT=YDOT + (ANSRT/P)*COSTH
      X=R*COSTH
      Y=R*SINTH
      IF (NPINT.EQ.3)
        IMPITE(M,384) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,RDOT,P,IGN,JCH,I65,J65
        Z,NTIME
      GO TO 34
  27 C
      C PARTICLE IS ABSORBED
      36 CONTINUE
      Z=RR
      7=Z2
      IF (ANSRT.EQ.0) OR (P.LT.2) GO TO 360
      CALL INTERP
      NAR=0
      IF (Z.EQ.0.) NAR=NCH
      IF (R.EQ.PADTUS) NAR=NCOLN+IGS
      IF (Z.EQ.7EPOUT) NAR=NSS+1-J65
      INDEX(NAR)=INDEX(NAR)+1
      INDEXY=INDEX(NAR)
      IF (INDEXY.GT.INDEXX) WPIIE(M,155) NAR,IND,INDEXX
      IF (INDEXY.GT.INDEXX) WPIIE(M,12) IND,INDEXX,NAR,14*OR3,KORBIT(NAR,14)
      IF (INDEXY.GT.INDEXX) WPIIE(M,12) IND,INDEXX,NAR,14*OR3,KORBIT(NAR,14)
      IF (INDEXY.GT.INDEXX) STOP
      IF (INDEXY.GT.INDEXX) STOP
      355 FORMAT(1X,1X,INDEX OF ORBIT HITTING AREA=,13, 5 FROM AREA=,14,

```

34

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577 FORMATTION AT X=,E13.6, 7H AND 7E,F13.6, 19H. THE POTENTIAL IS=,
1E13.3/1V,204 AND THE NORMALIZED 2A6,204 CURRENT DENSITY IS=,1DE13
2.4/1)

C

```

IF (INSURF.EQ.0) GO TO A9
IF (INSURF.EQ.1) NSEF=N-1
IF (INSURF.EQ.2) NSEF=N-NO-NF1
IF (INSURF.EQ.3) NSEF=NPTS-N+1
IF (SCALE.GT.0) FLUX(INSURF,NSEF)=DENST*FACTOR
IF (SCALE.LT.0) FLUX(INSURF,NSEF)=DENST
CONTINUE
IF (SCALE.LT.1) AND (MC.EQ.0) GO TO 91
IF (SCALE.LT.0) AND (NSURF.GT.0) GO TO 31
IF (SCALE.LT.1) AND (MC.GT.0) GO TO 90
SCALE=-1.
PARTCL(1)=PART2(1)
PARTCL(2)=PART2(2)
DENSA=NF*ST
VFINSURF.GT.0) GO TO 237
IF (MC.EQ.0) AND (ISAVE.EQ.0) DSAVE(N)=DENSA
IF (MC.EQ.1) AND (ISAVE.EQ.0) AND (JN.GT.0) DNOPTH(TN,JN)=DENSA
IF (MC.EQ.1) AND (ISAVE.EQ.0) AND (JS.GT.0) DSOJTH(JS,JS)=DENSA
IF (MC.GT.0) AND (MC.EQ.1) AND (N.EQ.NPTS) DNOPTH(TN,1)=DENSA
GO TO 237

```

A9

C RETURN TO BEGINNING OF TRAJECTORIES FOR ELECTRONS

C CONTINUE IF IONS AND ELECTRONS COMPLETEN

```

91 C=DENSA-DENST
IF (INSURF.GT.0) C3=FACTOR*DENSA-DENST
IF (INSURF.GT.0) CDSAVE(N-NO)=C0
CDSV(N)=C0

```

IF (MC.EQ.0) AND (NFWPHI.EQ.0) DSAVE(N)=C0

C SAVE ION DENSITY ONLY IF EXP(PHI) IS TO BE INCLUDED IN POISSON SOLUTION

IF (MC.EQ.0) AND (NFWPHI.GT.0) CDSV(N)=DENSA

PHISAVE=-PHISAV

IF (MC.EQ.0) WRITE (M,672) N,RSAVE,ZSAVE,PATSAV,DENSA,FNST,C0

IF (INSURF.GT.0) WRITE (M,672) N,RSAVE,ZSAVE,PATSAV,DENSA,DENST,C0

FORMAT(1,5HAT N=,16,9H F,7,PHI=,1P,10.2,E12.6,

1 40H, THE ION/ELECTRON/CHARGE DENSITIES ARE=, 3E13.4)

IF (MC.EQ.1) WRITE (M,672) N,HA,MB,MF,STEP

FORMAT(11,12HFOR POINT N=, 17,4X,

1 3HHA,MB,ME, AND STEP ARE CHANGED TO, 1E5,4H AND,1E5,

2 23H FOR INCREASED ACCURACY/)

C

90 DO 92 I=1,IIN

DO 92 J=1,IJN

92 PHIN(I,J)=SCALE*PHI(I,J)

DO 93 I=1,IIS

DO 93 J=1,IJS

93 PHIS(I,J)=SCALE*(PHISAT,I,J)

***** RESTORE IAMB,ME,STEP

17

MA=MASAV
MD=MDSAVE
MF=MFSAVE
STEP=STEPSV

A6

```

CONTINUE
IF (INSURF.EQ.1) AND (CSAVE.EQ.0) AND (RADIUS.AND.7SAV.EQ.0) HSHF=2
IF (INSURF.EQ.2) AND (CSAVE.EQ.0) AND (RADIUS.AND.7SAV.EQ.0) HSHF=3
96 CONTINUE
IF (IP.LT.2) GO TO 950
DO 940 N=1,NPTS
IF (N.LE.NO) GO TO 940
MD=N-NO
IF (INSURF.GT.0) AND (IPST.GT.0) AND (RSCSAVF(N-HJ)).LT.COMIN)
1 GO TO 940
CDSV(N)=CDSV(N)+EFFLUX(N-NO)-FLUX(N-NO)
IF (INSURF.GT.0) CDSAVE(N-N)=CDSV(N)
IF (N.LE.(MD+NF1)) GO TO 941
IF (N.GT.(MD+NF1+NF2)) GO TO 943
GO TO 942
941 NSURF=1
HSEF=N-NO
HSEF=N-NO
GO TO 944
942 NSURF=2
HSEF=N-NO-NF1
GO TO 944
943 NSURF=3
HSEF=NPTS+1-N
944 FLUX(N)=UPF,HSEF)=FLUX(N-NO)
940 CONTINUE
950 CONTINUE

```

C

C

IF (MD.GT.0) WRITE (M,666) IT,HCR

IF (INSURF.EQ.0) WRITE (M,94) (H,PSV(N),7SV(N),CDSV(N),N=1,NPTS)

IF (INSURF.EQ.0) GO TO A5

CORN1=.5*(CDSV(NC1)+CDSV(NC2))

CORN2=.5*(CDSV(NC3)+CDSV(NC4))

CDSV(NC1)=CORN1

CDSV(NC2)=CORN1

CDSV(NC3)=CORN2

CDSV(NC4)=CORN2

CDSAVE(NC1-NO)=CORN1

CDSAVE(NC2-NO)=CORN1

CDSAVE(NC3-NO)=CORN2

CDSAVE(NC4-NO)=CORN2

CONTINUE

IF (INSURF.GT.0) WRITE (M,940) (N,CDSV(N),7SV(N),CDSV(N),CDSAVE(N-NO),

1 MOSTEP(N-NO),N=NPTS)

FORMAT(4X,10H,N=,12Y,1H2,12Y,1H4HET CURRENT DENSITY,5X,10HMOST

1 STEPS /,11X,16,0P,13.5,1P,2E13.6,5X,15 1)

9401

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PROGRAM PARKING

E W N

04

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С. 206-207

```

0001  FORMAT(//X,1H,AX,140,12X,1M,12X,4HD/C0/(1X,16,3F13.5))
0002  C TPA=COPY WITH MOST STEPS, PRINT INDICES,IN0 K AND I INDICES)
0003  WRITE(M,971) M0STPS,NSAVC,KFS,JFS,KAS,MS,KAS,JAS
0004  97  FORMAT(1X,15,16,113,12),14H=401STEPS,N,VF,JF,KQ,JR,KA,JA,I
0005  IF(NSUP=.GE.0) TPOINT=1
0006  IF(INSUP.EC.0) GO TO 98
0007  IF(IPRINT.EC.0) GO TO 99
0008  WRITE(M,9091)
0009  IF(ISAVE.EC.0) WRITE(M,2001)
0010  FORMAT(11/1X,21HD=DENSITY ARRAY - NORTH )
0011  WRITE(M,2004) (RNL(J),J=1,JNJ)
0012  FORMAT(1X,2HFC=16F8.4/(1X,16F8.4))
0013  FORMAT(1X,40HD=DENSITIES READ IN RATHER THAN CALCULATED //)
0014  DO 100 I=1,IIN
0015  WRITE(M,333) I,ZN(I),CONORTH(I),J,J=1,JNJ)
0016  CONTINUE
0017  WRITE(M,2002)
0018  FORMAT(11/1X,21HD=DENSITY ARRAY - SOUTH//)
0019  WRITE(M,2004) (RSL(J),J=1,JJS)
0020  DO 101 I=1,IIS
0021  WRITE(M,333) I,7S(I),IDSOUTH(I),J,J=1,JJS)
0022  CONTINUE
0023  GO TO 99
0024  CONTINUE
0025  WRITE(M,2005)
0026  FORMAT(11/1X,21HD=CURRENT DENSITY ARRAY)
0027  WRITE(M,2004) (RNL(J),J=1,NF1)
0028  ZOUT=0.
0029  WRITE(M,334) ZOUT,(FLUXI(I),J,J=1,NF1)
0030  WRITE(M,335) (FLUXE(I),J,J=1,NF1)
0031  WRITE(M,336) (FLUXE(I),J,J=1,NF1)
0032  FORMAT(1X,2H7=16F8.4,7H (10MS),14F8.4/(1X,14F8.4))
0033  FORMAT(1X,12H (ELECTRONS),14F8.4/(1X,14F8.4))
0034  FORMAT(1X,12H (E-MISSI0N),14F8.4/(1X,14F8.4))
0035  IF (MF2.EC.0) GO TO 102
0036  IF (MF2.EC.0) GO TO 102
0037  ZOUT=7F30
0038  WRITE(M,336) ZOUT,(FLUXI(I),J,J=1,NF1)
0039  WRITE(M,337) (FLUXE(I),J,J=1,NF1)
0040  WRITE(M,330) FLUXE(I),J,J=1,NF1)
0041  CONTINUE
0042  FORMAT(11/1X,12HD=RAJ10S, 2=16F8.4,94X,7H (10MS),F8.4)
0043  FORMAT(10X,12H (ELECTRONS),F8.4)
0044  FORMAT(110X,12H (E-MISSI0N),F8.4)
0045  WRITE(M,2004) (PS(I),J=1,NF3)
0046  ZOUT=7F30
0047  WRITE(M,336) ZOUT,(FLUXI(I),J,J=1,NF3)
0048  WRITE(M,335) (FLUXE(I),J,J=1,NF3)
0049  WRITE(M,336) (FLUXE(I),J,J=1,NF3)
0050  CONTINUE
0051  RETURN

```

SUBROUTINE COAPS

C
C PRECALCULATION OF COEFFICIENTS AND ANGLESSAS FOR FNEQCV AND ANGLE
C QUADRATURES

C
C COMMON JIN, LIN, JJS, IIS, MO, RM(50), ZM(50), RS(50), ZS(50), PSV(500),
1 ZSV(500), PHIP(20,20), PHIS(20,20), COSV(500), IFTIRST, 4
C
C COMMON/JEN/HPRTAT, MO, MC, MA, MJ, ME, STEP, PSAVE, ZSAVE, ALPHA, NTA, EE,
1 XMSAVE, ADTUS, FLUX(13,20), FLUVE(13,20), F-URFM(13,20), CPSAVE(100)
C
C COMMON/2A/PI, XNACH, KEMAX, JEMAX, KBNAY, JBNAY, KAMAX, JAMAX,
1 ECE(16,2), SNA(16,2), CSA(16,2), NTA(16,2), COEFA(16,2), COEFF(16,2)
C
C DIMENSION A(2)
A(1)=-1./SQRT(3.)
A(2)=-A(1)
POWER=433*(XWACH)
YM=1.
DO 100 J=1, KEMAX
CE=TA(JE)+1./JEMAX
E=(1.+CE)/(1.-CE)
IF(POWER.GT.XM) E=POWER**2*E
CEE(KE, J)=E

C
C IF(MC.GT.0) CCF=2./(1.-CE)**2/FLOAT(KEMAX)
C IF(MC.EQ.0) CCE=CCF**2/SQRT(PI)
C IF(POWER.GT.XM) CCF=CEE*XWACH**2

C
C COEFE(KE, J)=CCE

C
C CONTINUE

DO 300 J=1, KEMAX
C
C CETA=(3.(JN)+1./JBNAY)
JETA=PI*(1.+CETA)/2.
JTAKE(JN)=BETA
CONTINUE

DO 200 CA=1, KAMAX
C
C CA=TA(JA)+1./JAMAX
C IF(MC.FT.0) COSA=CA

C
C FOR LARGE MACH NO. FIPHASIZE VELOCITY DIRECTIONS TOWARD UPWIND

C
C IF(MC.EQ.0.AND.XWACH.GT. YM) COSA=-1.+2.*(1.+CA)/2.**POWER
C IF(MC.EQ.0.AND.XWACH.LT.-XM) COSA=1.-2.*(1.-CA)/2.**POWER

C
C IF(MC.EQ.0) SINB=SQRT(1.-COSA**2)

C
C IF(MC.GT.0) SINB=SQRT(1.-CAB)

41

C
C IF(MC.GT.0) COSA=SQRT(1.-SINB**2)

C
C SNA(KA, JA)=SINB
C CSA(KA, JA)=COSA

C
C CCA=1.

C IF(MC.EQ.0.AND.XWACH.GT. XM) CCA=CCA*POWER**((1.+CA)/2.)**POWER-1.)
C IF(MC.EQ.0.AND.XWACH.LT.-XM) CCA=CCA*POWER**((1.-CA)/2.)**POWER-1.)
C COEFA(KA, JA)=CCA

C
C CONTINUE

DO 700 J=1, JEMAX
C
C WRITE(N, 700) (T, J, FEF(T, J), SNA(I, J), CSA(I, J), JTAKE(J), COEFA(I, J),
1 COFFE(I, J), J=1, JEMAX), I=1, KEMAX
C
C FORMAT(1/20X, 3HFPE, 11X, 3HNSA, 11X, 3HCSA, 11X, 3HTAQ, 10X, 5HCOFFFA, 10X,
15HCOFFE/(1X, 14, 16, 3V, 1P6E14.5/ 1X, 14, 16, 3X, 1P6E14.5//))
C
C RETURN
C
C END

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```
IF (ZROOT,GE.,Z1.AND.ZROOT2,LE.,Z2) TIME(NR)=T22
```

```
GO TO 60
```

```
00 TIME(NR-1)=T21
```

```
TIME(NR)=T22
```

```
GO TO 60
```

```
0 CONTINUE
```

```
DO 100 NR=5,6
```

```
TIME(NR)=T00M
```

```
IF (ZROOT,EO.,N.) GO TO 100
```

```
0 S-INTERSECTION ALONG Z1-LINE
```

```
0 IF (NR,EL.,5) Z12=Z1
```

```
0 T-INTERSECTION ALONG Z2-LINE
```

```
0 IF (NR,EL.,6) Z12=Z2
```

```
TS=Z12-Z1/ZROOT
```

```
SPOOT=5 + SDOOT*TS + TS**2/4./H
```

```
IF (NOUT,GT.,0)
```

```
1MRTE(M,706)NR,Z12,TS,SPOOT
```

```
705 FOPRAT(IX,16)NR,Z12,TS,SPOOT=,IA,1P2E25,15)
```

```
0 ACCESS POOT FOR SIGNIFICANCE
```

```
0 IF (SPOOT,GE.,S1.AND.SROOT,LE.,S2) TIME(NR)=TS
```

```
100 CONTINUE
```

```
IF (NOUT,GT.,0)
```

```
1MRTE(M,707) (N,TIME(NR),N=1,6)
```

```
707 FOPRAT(IX,16)NR,TIME(NR)=,3(10,1PF25,15)/11X,3(10,1E25,15)
```

```
0 END SHORTEST SIGNIFICANT TIME
```

```
0
```

```
NTIME=-1
```

```
TTIME=T00M
```

```
DO 200 NR=1,6
```

```
IF (TIME(NR),EO.,T00M) GO TO 200
```

```
IF (TIME(NR),GT.,ROUND.AND.TIME(NR),LT.,TIME(NR) NTIME=NR
```

```
IF (TIME(NR),GT.,ROUND.AND.TIME(NR),LT.,TIME(NR) TTIME=TIME(NR)
```

```
200 CONTINUE
```

```
IF (NOUT,GT.,0)
```

```
1MRTE(M,708)NTIME,TTIME
```

```
708 FOPRAT(IX,12)NTIME,TTIME=,IA,1P2E25,15)
```

```
0 ADVANCE TO APPROPRIATE END-POINT
```

```
0
```

```
IF (NTIME,LT.,0) RETURN
```

```
Z=7 + 7001*TTIME
```

```
S=5 + 501*TTIME + .25*TTIME**2/H
```

```
49
```

```
SNOI=SNOI + .5*TTIME/H
```

```
Z=N
```

```
IF (S,GT.,ROUND) R=SNOI(S)
```

```
IF (NOUT,GT.,0)
```

```
1MRTE(M,709)Z,S,SNOI,R
```

```
709 FOPRAT(IX,11)Z,S,SNOI,R=,1P4E25,15)
```

```
0 SAV=Z
```

```
ZSAV=Z
```

```
IF (NTIME,EO.,1.0Z.NTIME,EO.,2) R=X1
```

```
IF (NTIME,EO.,1.0Z.NTIME,EO.,4) R=R2
```

```
IF (NTIME,EO.,5) Z=Z1
```

```
IF (NTIME,EO.,6) Z=Z2
```

```
OR=P-ZSAV
```

```
Z=Z-ZSAV
```

```
IF (ABS(NR),GT.,ROUND.AND.NTIME,LE.,4) NTIME=-2
```

```
IF (ABS(Z),GT.,ROUND.AND.NTIME,GT.,4) NTIME=-3
```

```
IF (ABS,EO.,0.,.0P.,0.,EQ.,0.) RETURN
```

```
RROOT=.5*SNOI/R
```

```
RETURN
```

```
END
```

```
50
```

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