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PRE-FLIGHT POLAR CODE PREDICTIONS FOR THE CHAWS SPACE FLIGHT EXPERIMENT

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13. ABSTRACT *(Maximum 200 words)*

The POLAR code is a 3D plasma simulation which has been used to design and predict the behavior of the Charge Hazards and Wake Studies (CHAWS) space flight experiment. The most recent results from the POLAR code are presented here prior to the launch of the Space Shuttle Discovery. CHAWS will measure the current-voltage (IV) characteristic of a high voltage probe mounted on the wake side of the Wake Shield Facility (WSF) free flyer. POLAR results indicate that ion currents to the negatively biased probe will be near "zero" only for potentials less than 30 to 300 Volts in magnitude. As the potential increases to the CHAWS limit of -5 kilo-Volts, the ion current will quickly rise to levels comparable to that which the probe would collect if orbiting unshielded.

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1. Introduction

The current-voltage (IV) characteristic of a charged object in the wake of another, larger body in Low Earth Orbit (LEO) is an issue that is relevant to spacecraft design and operation. In the wake of a space vehicle, the neutral gas and plasma densities are reduced to a tiny fraction of their values in the ambient stream creating conditions where for polar orbit, objects might become charged by auroral electrons, or where things could be 'hidden' from the plasma. Such things could be high voltage power equipment, or a contamination-sensitive space manufacturing facility.

The wake charging problem, as it is called, is difficult to analyze because plasma currents will remain small until the object potential is sufficient to pull charged particles from the dense plasma stream across an ion void and, in the case of ion collection, overcome a significant angular momentum barrier. The wake charging problem has received both laboratory (Enloe, 1993) and theoretical attention (Jongeward, 1986) but both approaches have been limited by the lack of in-situ measurements to validate the predictions.

In February of 1994, the Space Shuttle Discovery will carry, release, and recover the Wake Shield Facility (WSF) experiment. The WSF is a facility designed to explore the possible advantages of the space and wake vacuum for high purity epitaxy. The Charge Hazards and Wake Studies experiment (CHAWS) was designed by personnel at the Air Force Phillips Laboratory at Hanscom AFB, MA. to measure the interaction of a high voltage probe with the WSF wake as well as monitor the ambient plasma conditions during both WSF and CHAWS experiments.

The subject of this technical report is the prediction of CHAWS experimental results using the computer code, POLAR (Potential Of Large objects in the Auroral Region; Cooke, 1985; Lilley, 1989) POLAR is a steady-state Poisson-Vlasov code that models the interactions of large spacecraft with the LEO plasma, and the charging of spacecraft in polar orbit by auroral electrons. The velocity of a spacecraft in LEO is much greater than the thermal velocity of the ambient ions, but much less than that of the cold ambient electrons. Under these conditions, an ion void is formed just behind the spacecraft where the ambient electrons may still penetrate

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until limited by their own space charge. Energetic auroral electrons are sufficiently energetic as to be completely unaffected by the wake and will charge wake side surfaces until current balance is achieved by drawing in ions from outside the wake. The wake of an uncharged satellite is now reasonably well understood (Gurevich, 1966, Crow, 1978). The POLAR code's wake model agrees with existing wake theories and has been validated (Katz et.al., 1986) against measurements of the Shuttle wake made by the Plasma Diagnostics Package (PDP) on STS3 (Murphy, et.al., 1985). The process of ion collection from outside the wake is much less understood and is the subject of these simulations and the CHAWS experiment.

Early in the planning stages for the CHAWS experiment, a version of the POLAR code called POLAR II was used to design the probe and supporting power supplies (Tautz, 1992). POLAR II was a multi-nested grid enhancement to POLAR's single constant spaced grid, which allowed efficient simulation of the challenging dimension scales presented by the WSF-CHAWS experiment. The maximum WSF dimension is its 12 foot diameter, while the minimum CHAWS dimension is its 4 inch diameter. POLAR II, however, has not been further developed, while POLAR I has been improved to handle the large grid and object requirements of this simulation on a single grid. The simulations reported here were all performed using POLAR I.

A common and reasonable goal of a plasma simulation is to provide scientific and engineering data that can be scaled to other applications, or preferably, lead to the discovery of new laws and understanding. The simpler scaling approach will be limited in application to this problem because of the size of the parameter space that determines the current, *I*. The minimum set of dimensionless parameters needed to describe the WSF-CHAWS interaction are expressed,

$$I = I\,(\Phi_p, \Phi_d, R_p, R_d, M, D_{pd}, T_I/T_E, \Theta, C) \qquad (1)$$

where $\Phi = eV/kT$, e is the electron charge, k is Boltzman's constant, T is the plasma temperature, V is the potential on both the disk V_d and the probe V_p, and $M = Velocity\,/\,\sqrt{2kT/m}$ is the ion Mach speed of the flow. The R's are radii of the disk and probe normalized by the Debye length, $\lambda_D = e\sqrt{N/kT\varepsilon_o}$ and $D_{pd}=d/\lambda_D$ is the normalized separation distance. Θ is the tilt angle between the WSF disk and the velocity vector, and C represents the plasma composition. Certainly, if this list is complete, and each of the parameters are identical between two configurations, the currents should scale as well. Less trivial is the sort of scaling where one asks "how does *this* scale with *that*?", which is equivalent to knowing the physical law relating *this* and *that*. However, with a minimum of nine parameters, many two parameter laws would need to be convoluted to provide a complete description of the interaction. The resulting theory would likely be difficult to use even if known. One way to enhance the scalability of the space or laboratory data is to develop and/or apply a suitable computer model that can reproduce the experimental results, and provide predictions for problems that are not parametrically identical to measurements.

2. The WSF-CHAWS Mission

The CHAWS experiment consists of two major components. The wake side probe is a stainless steel cylinder 18 inches in length and 4 inches in diameter that will be biased to voltages ranging from 0.0 to -5000 Volts. The other component is a ram side sensor located on, (you guessed it) the ram side. This 'box' contains three new and innovative retarding potential analyzers (RPA) that employ Multi-Channel-Plates to provide single ion detection capability along with the possibility of wide angle particle direction imaging. (due to limited data band width, the RPAs entrance angle resolution will be limited to halves and quarters of the total field of view) The ram side detectors will provide data about the plasma density *N*, flow velocity **V**, composition, and ion temperature. In addition to measuring the total collected current, the wake side probe will also carry a suite of RPA's to measure the current collection at low voltages where it is anticipated that currents will be too low to be measured by the total current analog electrometer.

The STS60 Space Shuttle mission flight plan will present the opportunity to vary and study many of the parameters determining the CHAWS probe current. The WSF will be lifted from the Shuttle bay by the RMS manipulator arm and released after instrument check out and a ram cleaning procedure where the WSF wake side surfaces will be cleaned by facing them into atmospheric flow. The RPA's will be operated during this procedure in the hope of gathering data to support WSF contamination monitoring. After cleaning, the WSF will be released and separated from the Shuttle by about 70 kilometers, where the epitaxial experiments will be performed for about 3 days. At the end of that period, the CHAWS high voltage experiment will be activated. During this period the CHAWS will be free from any Shuttle induced effects, and will be able to study the HV-wake interaction under conditions where the actual probe and WSF potentials will be determined by global current balance. After retrivial, the WSF will remain on the RMS where CHAWS will become the prime experiment. While attached to the RMS arm, the shuttle will be piloted to numerous attitudes to study the effects of angle of attack, and WSF disk bias. Variation of the WSF bias will be accomplished by orienting the WSF at the maximum practical distance from the engine bells, measured by the vector, **L**, and then orienting the shuttle and WSF so as to maximize the $(\mathbf{V} \times \mathbf{B}) \cdot \mathbf{L}$ potential, where **B** is the local geomagnetic field. It is anticipated that when the WSF is *up*, the shuttle will float negative with the WSF floating slightly positive of the usual negative floating potential, due to the excess of the electron thermal current over the ion ram and thermal currents. When the WSF is *down*, the engine bells will be *grounded*, and the WSF will float to potentials of 5 to 10 volts negative. In addition, plasma parameters will vary over the orbits.

3. The POLAR Code

POLAR is a self-consistent three dimensional Poisson-Vlasov code, which provides steady state solutions by iterating between potential (Poisson) and density (Vlasov) solutions on a mesh of cubical volume elements A versatile set of building elements can be combined to form complex objects with a variety of surface materials and electrical connections. A surface charging module can be added to the iteration to provide the spacecraft charging response to both natural and active charge drivers. The Poisson solver uses a finite element conjugate gradient method, with a unique technique of filtering charge densities (charge stabilization) to suppress grid noise and produce stable solutions. POLAR calculates particle densities by a method that divides space into (one or more) sheath and non-sheath regions separated by a sheath edge(s), located as an equipotential, near *kT*. External to this surface the plasma distribution is presumed to be Maxwellian with possible flow. External densities are determined by geometric ray tracing with first order electric field corrections. This approach has been shown to correctly predict wake formation about the Space Shuttle Orbiter (Murphy, 1989). At the sheath edge, incoming fluxes are determined and assigned to macro-particles that are traced inwards. These fluxes are calculated at points on the sheath under the assumption that the point is on a spherical surface and that the potential falls as r^{-2}. This allows the moments of the flowing distribution to be calculated analytically assuming the usual constants of motion are conserved and a full hemisphere of orbits connect to infinity. POLAR either assigns the entire sheath flux associated with a point to a single trajectory aligned with the current moment of the distribution, or spreads the flux over 4 additional trajectories to better retain the thermal kinetic properties of the plasma. Internal sheath densities are determined from the time spent in each volume element, and surface currents from their final deposition. When particles are repelled, their density is assumed to be Boltzmann. Auroral electrons are assumed not to contribute significant space charge so they are decoupled from the P-V portion of the iteration. They and other sources of current are accounted for during a charging step that updates conductor and surface potentials. The Auroral electron flux is assumed to be isotropic, with no surface - surface shadowing, and secondary and backscatter currents are determined from surface potential and material properties. Photo-electron currents are also included.

POLAR's sheath model is very efficient and accurate in some respects. It is also the greatest source of uncertainty for the wake problem. Placing the (sheath) particle injection surface close to the interaction region minimizes both trajectory push time, and upstream streaming irregularities (Katz, 1987) that are caused by the discontinuous (transverse) electric fields inherent to any Poisson solver, such as POLAR's, that does not explicitly constrain the electric field to be continuous. The sheath of a stationary object that is at high potential compared to the plasma temperature, and large compared to the Debye length, is well described by Langmuir-Blodgett (1924) theory when combined with modern advances in understanding the presheath (Parrot, 1982). Under these circumstances, there is a well defined sheath edge located at the $0.45\,kT$ equipotential, which is totally adsorbing for attracted charged particles with thermal energies. At lower potentials and densities, with a super-sonic flowing plasma, particles could still be injected on any generalized sheath surface provided the particle distribution arriving at the surface were known. For the wake charging problem, this approach has not been fully investigated, so although the POLAR approach has been generally validated (Katz, 1989), the approach remains a source of uncertainty. Specificly, POLAR chooses for a (unsigned) sheath potential, the greater of $0.45\,kT$ and $kT * \ln(Sqalph * \lambda^2 / Dxmesh^2)$. This last choice is quite adhoc, but it is based on an understanding of the slight sheath expansion that is a result of the charge stabilization (Cooke, 1985). *Sqalph* is a parameter that is maximized to within limits of stability, and is usually set to about 3. It is anticipated that one major result of comparing POLAR predictions with CHAWS data will be the validation of this approach.

4. The Models

The POLAR model of the WSF and CHAWS is shown in Figure 1 where the WSF is the (12 foot diameter) disk, and the rectangular stack of 4 cubes represents the the CHAWS Langmuir probe (4 inches diameter, 18 inches length). Most of the WSF detail has been omitted from the model, with the exception of the central 'pedestal' which approximates the WSF wake side epitaxial source structure. Early runs indicated that this structure had a small but measurable effect on current collection.

Starting with the scaling dependence presented earlier,

$$I = I\,(\Phi_p, \Phi_d, R_p, R_d, M, D_{pd}, T_I/T_E, \Theta, C) \qquad (2)$$

R_p, R_d, and D_{pd} are reduced by the fixed spacecraft geometry to just one (any) dimension normalized by the Debye length, S. Further, POLAR assumes that $T_I = T_E$, thus the parameters that must be covered are,

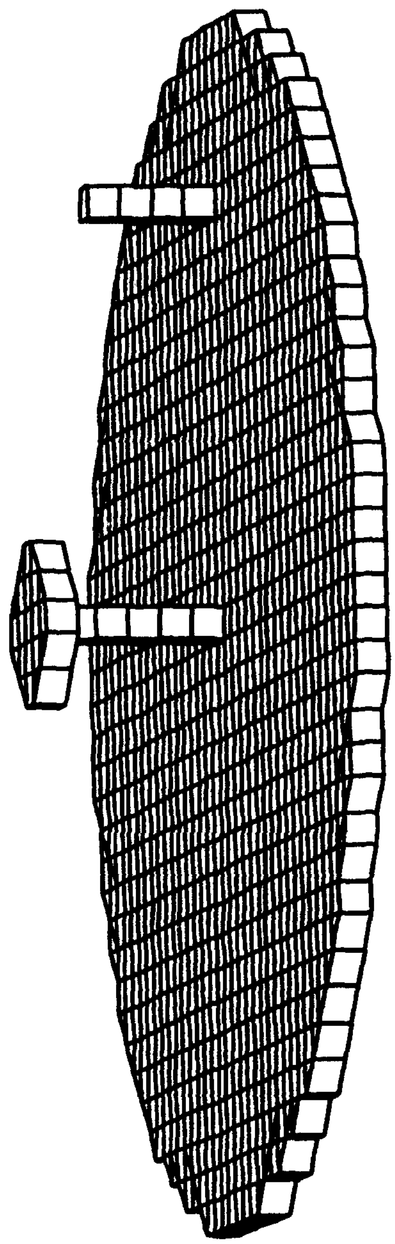

Figure 1. POLAR model of the WSF and CHAWS. The WSF is the (12 foot diameter) disk, the rectangular stack of 4 cubes represents the the CHAWS Langmuir probe (4 inches diameter, 18 inches length), and the central 'pedestal' approximates the WSF wake side epitaxial source structure.

$$I = I(\Phi_p, \Phi_d, M, S, \Theta, C) \quad (3)$$

Expressed as the actual inputs to POLAR, this becomes,

$$I = I(V_p, V_d, \mathbf{M}, T, N_i, C) \quad (4)$$

where it is important to recognize the over-specification since the temperature appears more than once, and **M** and T must be constrained to give orbital velocity, which is fixed along with the geometry. **M** is specified as a vector and thus also specifies Θ. N_i is the total ion or electron density, and for these calculations, the composition was taken to be all Oxygen. The runs reported here are a nearly complete matrix of parameter values listed below. The notations in parentheses are used later to label the IV curves.

SIMULATION PARAMETERS

V_{WSF} Volts	V_{probe} Volts	Density #/cc	Θ, Tilt Degrees	Mach # -
-10	-0.5 (L)	10^4 (d4)	+30 (t0)	7.1 (m7)
-30	-5.0 (V)	10^5 (d5)	0 (t1)	10.3 (m10)
-100		10^6 (d6)	-30 (t2)	
-300				
-1000				
-3000				
-5000				

Figure 2 is a 2D cut through one of the POLAR simulations in the study, showing the silhouette of the WSF and CHAWS, potential contours, the sheath edge marked by crosses, and a small sample of the trajectories used to determine the ion density and current. The parameters of this simulation are given in the figure caption. These runs typically run on a grid measuring $60 \times 50 \times 80 = 240{,}000$, and require about 12 CPU hours on a Silicon Graphics Indigo R4400 workstation to complete a voltage sweep. Figure 3 is similar cut through another simulation showing the sense of the tilt angle Θ.

The currents reported in this and following figures are only the collected ion currents with no secondary electron contribution. This is done because the exact secondary electron yields of the stainless steel CHAWS probe were not measured prior to flight. Further, there is evidence from laboratory simulations of wake current collection that secondary electron yields vary with the surface electric field (Enloe et.al., 1992), so that published values of secondary yields for energetic ion beams on an uncharged surface may not be correct. If the ion currents are reported without correction, the results may be adjusted for any possible secondary electron yield without complication.

Figure 4 shows the effect of Mach number at no tilt and a density of 10^5 */cc* while comparing the current collected to: a POLAR prediction when the WSF is removed and the probe is modeled orbiting alone, a POLAR prediction for the lonely probe in a stationary plasma, and Langmuir-Blodgett theory for a sphere of equal area with and without a presheath enhancement factor of 1.45 (Parrot, 1981). As can be seen, the WSF provides the best shielding for the probe at low voltage, but only minimal shielding at higher voltage. One can also notice the minimal effect of Mach number. This could represent a defect in the POLAR model, but it should be

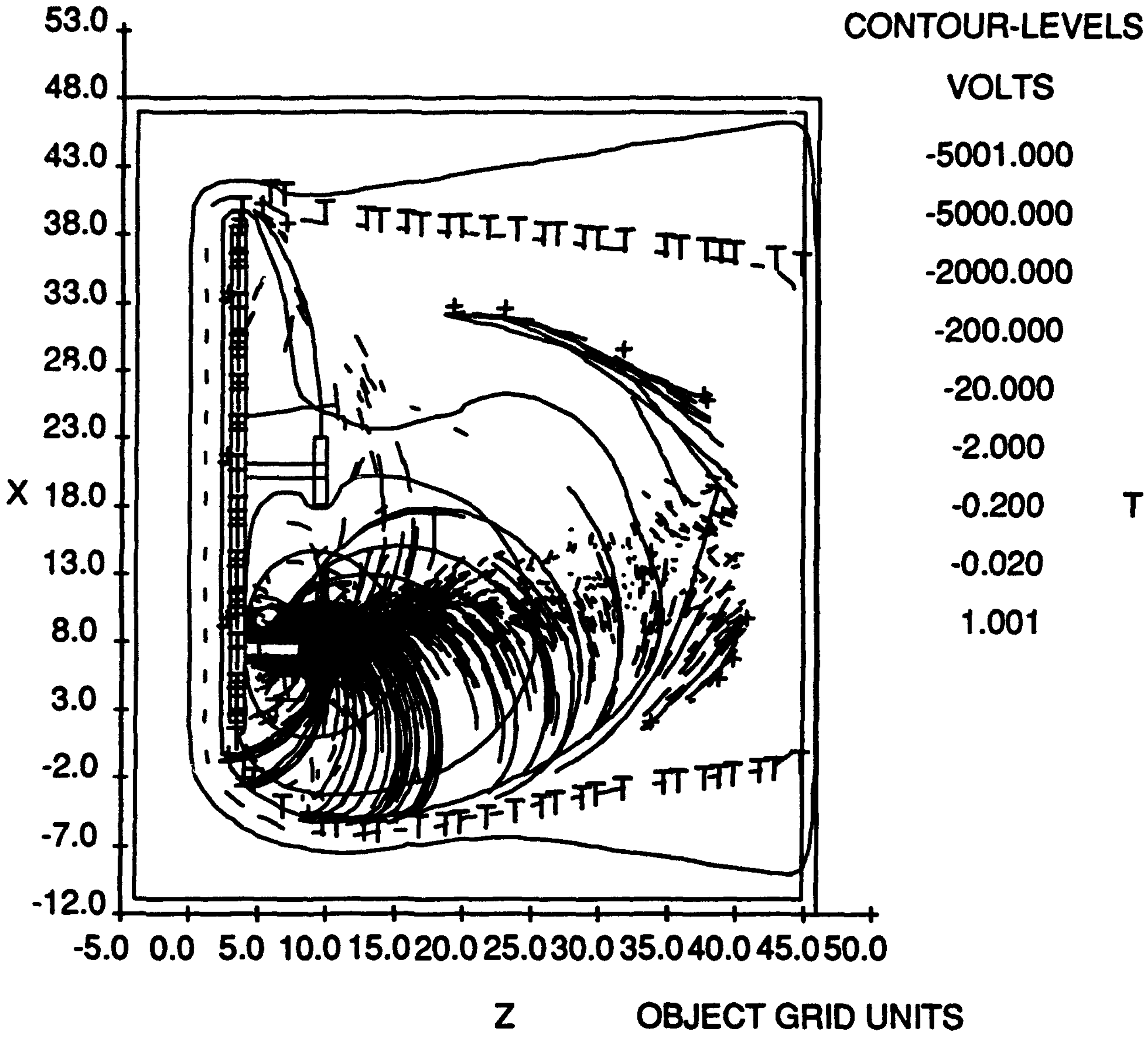

Figure 2. A 2D cut through a POLAR potential solution showing the potential contours, sheath, and a reduced set of ion trajectories. Only the $-0.2 Volt$ and the sheath contours are labeled. The sheath is marked by +. Parameters: no tilt, WSF potential = -5.0, N = 10^5 */cc*, and Mach = 7.1.

remembered that here, the variation in Mach number represents a cooling of the plasma from T = 0.2 eV to 0.1, while the orbital velocity is constant so the plasma sheath is presented with roughly the same ram ion flux.

Figure 5 shows IV curves for variations in WSF potential and density at $M = 7$ with no tilt. Notice that there is a threshold for significant current collection in the -30 to -300 Volt range. This has been anticipated by other researchers, (Besse 1983, Jongeward, 1986) and although it is difficult to compare predictions for other geometries, the computed thresholds here seem low compared to what was thought to lead to high auroral charging. One result of our laboratory simulations (Enloe, 1992) has been to show that the threshold given by conservation of angular momentum is much higher than that observed in the laboratory. We can also note that over most of the range, the currents do not scale linearly with plasma density, even near threshold. This indicates that above threshold, the probe does not collect from an undisturbed wake environment, where the tail of the ion distribution that is moving fast enough to catch the WSF would be expected to scale linearly with density. At higher voltage, the scaling appears to be roughly $N^{1/2}$. We can also see that the WSF potential has a profound effect on collected current at lower potentials.

Figure 6 show IV curves for density and tilt at constant WSF potential. Although this plot is crowded, it shows an interesting trend. At high potential, the curves are affected most by density, but at lower potential, they are seen to group themselves by tilt angle with the sense of the probe being tilted into the flow collecting the most current.

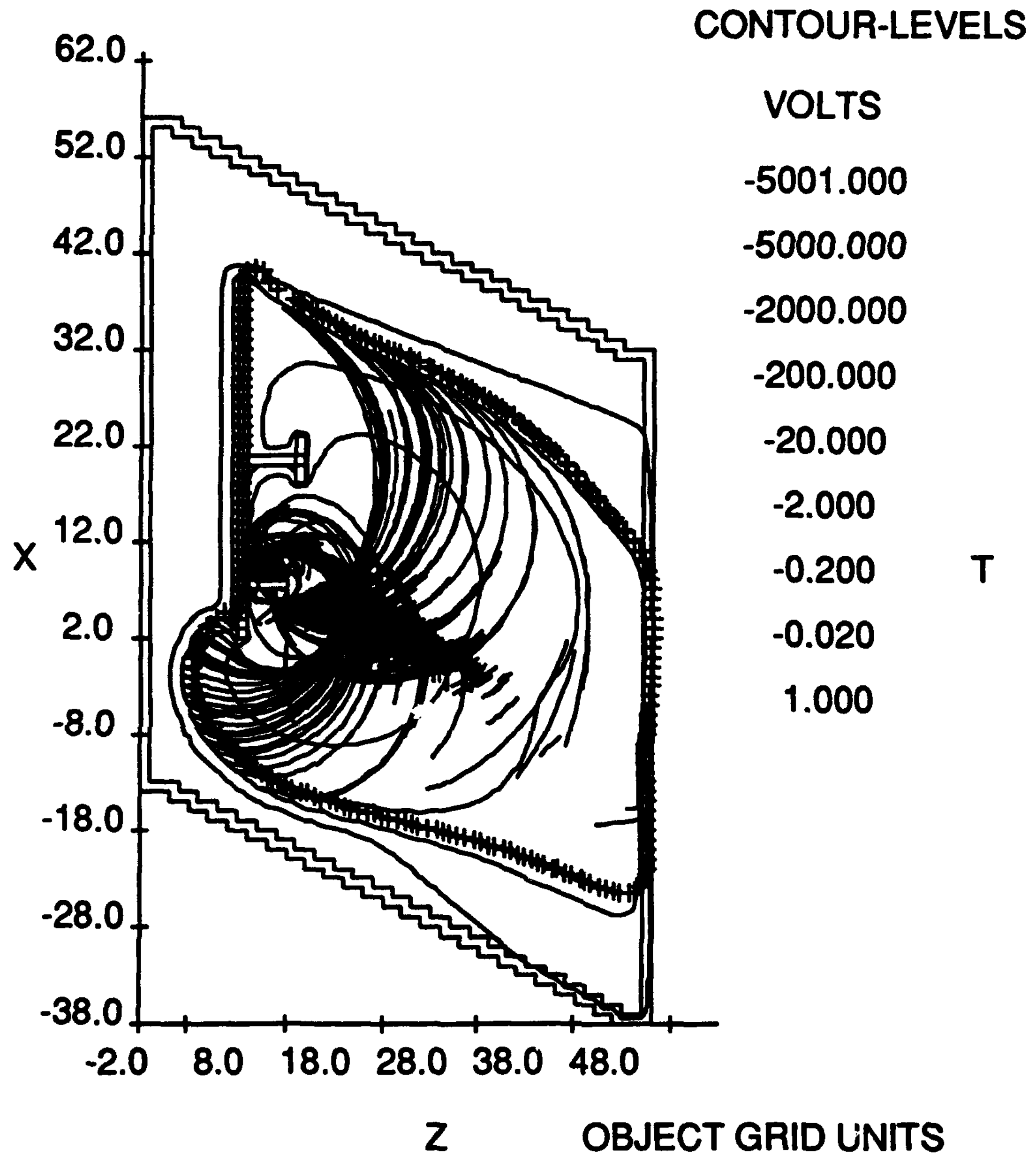

Figure 3. A 2D cut through a POLAR potential solution showing the potential contours, sheath (marked by +), and a small set of trajectories. Parameters: +30 degrees tilt, WSF potential = -0.5, N = 10^4 /cc, and Mach = 7.1.

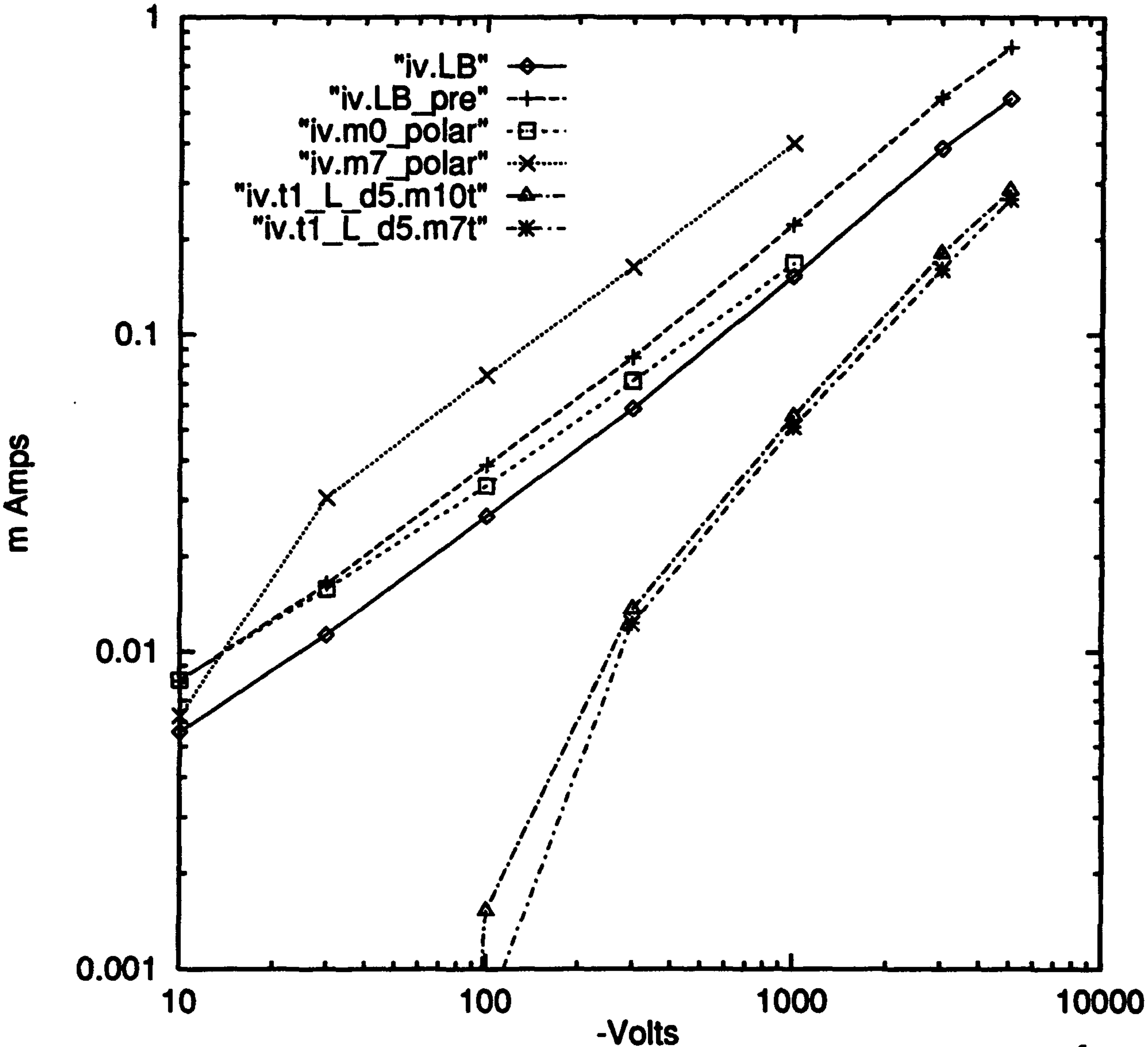

Figure 4. IV curves showing the the effect of Mach number at no tilt and a density of 10^5 */cc*, The Mach 7.1 run is designated by "iv.t1_L_d5.m7t", and the Mach 10.3 run by "iv.t1_L_d5.m10t". These runs are compared to the current collected by: a POLAR prediction when the WSF is removed and the probe is modeled orbiting alone (iv.m7_polar), a POLAR prediction for the lone probe in a stationary plasma (iv.m0_polar), Langmuir-Blodgett theory for a sphere of equal area with (iv.LB_pre) and without (iv.LB) a presheath enhancement factor of 1.45 (Parrot, 1981).

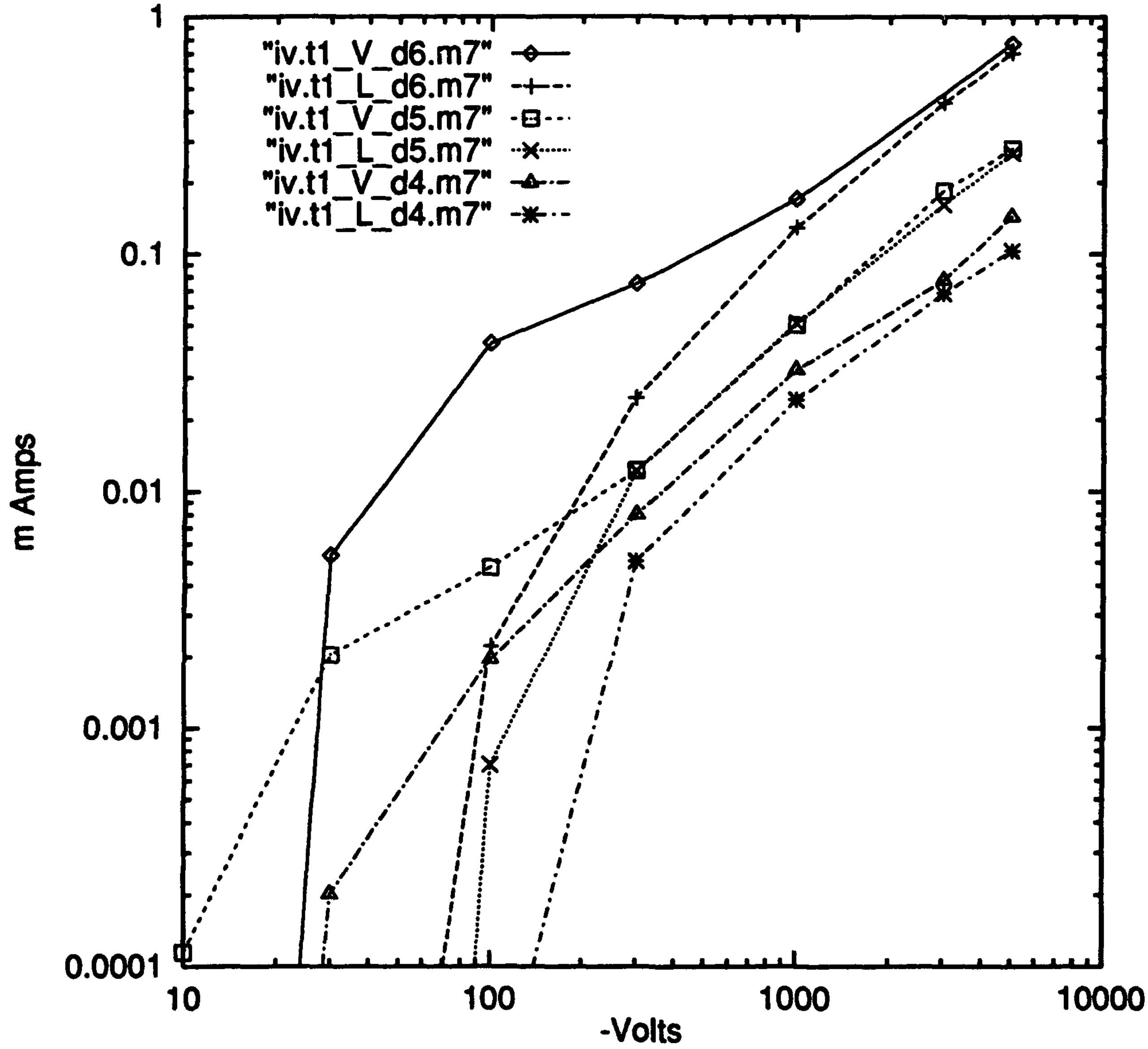

Figure 5. IV curves with variations in WSF potential and plasma density at Mach = 7 with no tilt. The curves are coded as follows: L, V = -0.5, -5.0 Volts; d4, d5, d6 = $10^4, 10^5, 10^6$ /cc; m7 = Mach = 7.

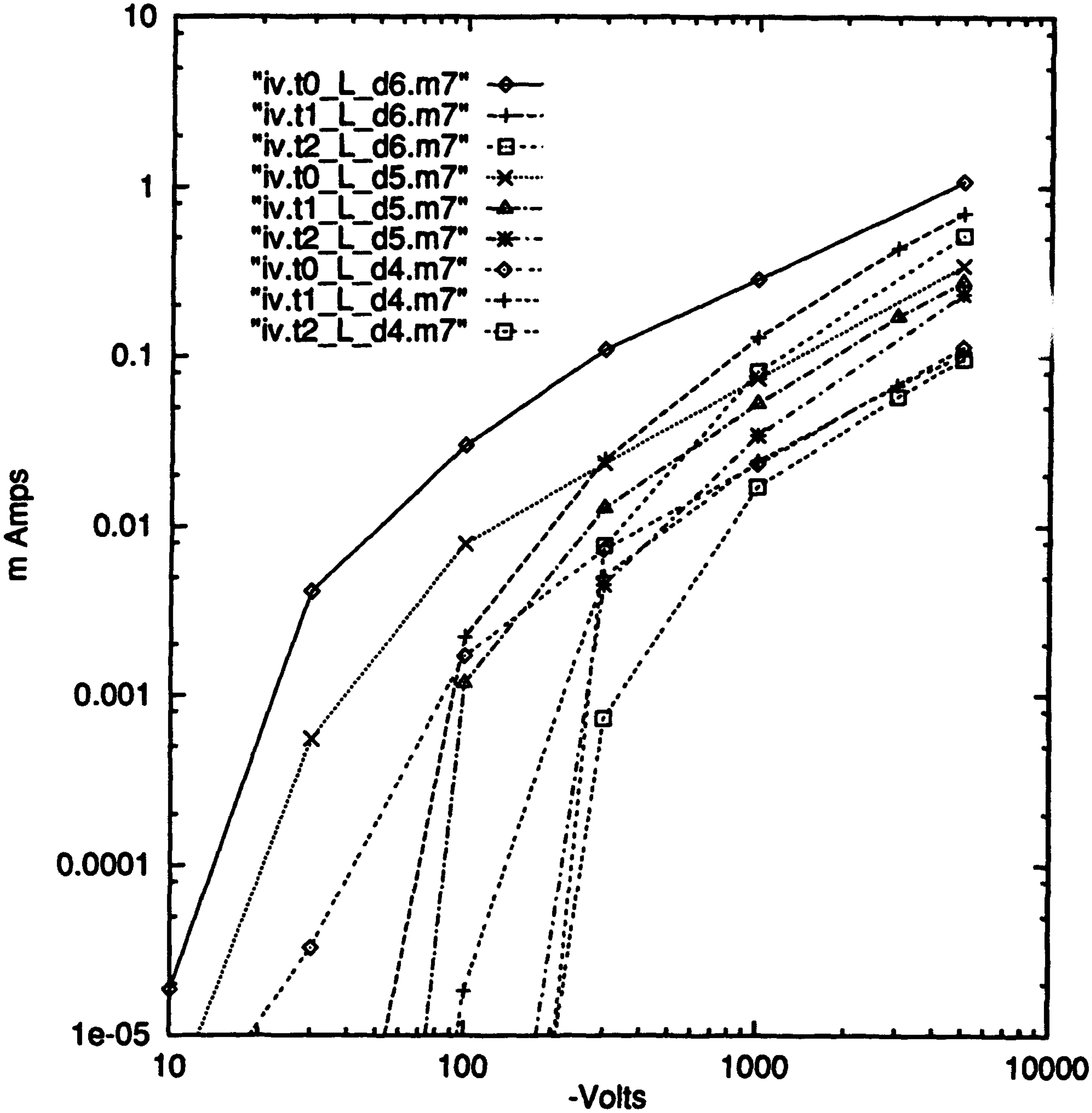

Figure 6. IV curves for density and tilt at a constant WSF potential of -0.5 Volts. The curves are coded as follows: t0, t1, t2 = -30, 0, +30 degrees; L = -0.5 Volts; d4, d5, d6 = $10^4, 10^5, 10^6$ */cc*; m7 = Mach 7. At high potential, the curves are affected most by density, but at lower potential they are seen to group themselves by tilt angle.

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