Using Computer Simulation to Understand Active Experiments

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Outline

• Early years, electron beam rockets and big balloons
• SPEAR, Space Power Experiment Aboard Rockets
• Wake Shield
• NASCAP, POLAR, DynaPAC, Nascap-2k
• DSX
• TSS
• Momentum coupling in plasmas
Passive communication reflector satellites, 1960, 64

- High LEO (1000 km+) 47° & 80° inclination
- Successful voice (big bounce) transmission
- Led to first considerations of Alfven J x B drag
- No plasma drag reported, but photon pressure was measured
- More later

Electron Beam Rockets

- Broad interest in electron beams for field line mapping, artificial aurora (Hess, 68), and perhaps plasma physics in space.

- Linson (69) review of electron collection
  - I-V characteristics of space platform and environment will determine charging.
  - Beard & Johnson (similar to Langmuir & Blodget, Langmuir & Mott-Smith)
    - Ignore B, compute the sheath, plasma electron current to/thru sheath
    - Quasi-analytic sheath model
  - Parker & Murphy
    - Analytic dynamical limit on electron collection based on conservation of canonical angular momentum
  - Suggested turbulence
    - $Q = \omega_p^2 / \omega_{ce}^2 = c^2 / v_A^2 > \frac{1}{2}$, conductive
    - $Q < \frac{1}{2}$, magnetic insulation

- The question of would beam emitting rockets collect enough current was replaced by why did they sometimes collect so much?

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Fig. 3. Comparison of the predictions of the three models discussed in the text. Their asymptotic behavior for large $\phi$ is shown. The dot-dash curve represents the absolute upper limit to the current which the satellite can attract and, for constant potential, scales like $I_0^{-1/6}$. The normalized voltage $\phi_n$ defined in equation 8 has been taken to be 178 volts. A change in the constant $q_0$ displaces the solid curve horizontally by the appropriate factor.
Electron Beam Rockets

Hess (71) Artificial Aurora Experiment

• Taking no chances with insufficient return current

• First e-beam rocket?
  – Aerobee rocket, Wallops Island, Jan 69
  – 9 KV, 490 mA electron beam
  – 290 km altitude
  – Faint “aurora” streaks were observed for the highest power beams
  – Possible, but inconclusive VLF detected
  – Collector partially deployed, ultimately wrapped around payload
  – No apparent beam instability
  – No serious charging (details unpublished)
ECHO Rocket Series, 1-7

• By 1980, there had been an about 25 particle beam rockets including ECHO 1-5 (mostly electrons)
  – Artificial aurora, conjugate returns, other effects observed
  – Beam currents up to 800 mA, 40 keV
  – Quiescent return currents to bodies 1-10 mA
  – Observed and estimated body potential < 40 V
  – Mostly below 300 km
  – Suggested puzzle solutions: Beam plasma discharge, Control gas ionization. No definitive models or measurements.
  – Negative charging showed accelerated ion spectrum
  – Electron spectra always hot and down to 0 eV.

• ECHO 7
  – Launched Feb 9, 1988, at from the Poker Flat, Alaska
  – Apogee of 292 km, 3 payload sections
  – 40 keV, 250 mA (AFGL built) electron gun beam
  – 5 kV (inst. limit) charging observed at 300km
  – Reduced to few 100V by ACS gas release


Onboard observation of ECHO 7 beam
100 km, 36 kV, 180mA, 150 ms
• The low charging potential of electron beam rockets seemed related to low altitudes, RSC gas jets
  – But the ionization rates did not work.
• Two independent efforts showed that ions born in the electron collecting sheath move out slowly
  – Positive space charge destabilizes sheath (explodes).
  – \(8 \times 10^{16} \text{ m}^{-3} \approx 10^{-8} \text{ Torr} \approx 160 \text{ km}\)
  – 1% of density needed for Paschen breakdown
• Even above 200 km, and w/o gas jet operation, outgassing can provide enough neutral density to discharge a sounding rocket

And then there was MAIMIK
14 kV charging with 8 keV e-beam

Mother-daughter tethered sounding rocket, launched Nov. 1985 from Norway
- Mother-daughter potential measured during electron beam emission
- Potential as high as 14 kV measured during emission of 8 keV, 0.8A electron beam
- Low plasma density measured by EISCAT (< $10^4$ /cc)
- Estimated plasma thermal current integrated over a L-B type sheath < 2% $I_{beam}$

• 2D axisymmetric PIC simulation (Mandell & Katz)
  - Dipole oscillation of trapped electron beam cloud, above-below-above... the rocket
  - Broadened electron distribution with energized fraction sufficient to escape and maintain supercharged potential


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SPEAR-1,2,3 was an SDIO science program to pioneer high voltage and current technology for space

- Insulated & pressurized systems would be too heavy
- Use the vacuum (with conductive plasma)
- The terrestrial insulation and rocket communities were brought together to develop guidelines for plasma engineering
  - Design of insulator bushings to hide triple points
  - Sheath physics, including bi-polar sheath
  - Still mysterious neutralization
  - Neutral gas effects, both outgassing & RCS jets
  - Paschen type breakdown between spheres

**SPEAR-1**

- Launched Dec 1987, Wallops Island, 370 km.
- 46 kV between probes and/or rocket body
- No breakdown in space (common in chamber testing)
- A hollow cathode failed, and did not hold rocket V≈0
- Neutral pressure stayed above 10⁻⁵ Torr
- Plasma currents were linear with Voltage and effected by angle to B, but never magnetically insulated
• The boom insulators worked as designed
• The current-voltage characteristic was linear
  – Both PM & PB currents should grow less than linear with Voltage.
  \[ I_{PM} = \frac{1}{2} I_{LB} \frac{\omega_{pe}}{\omega_{ce}} \left( \frac{kT_e}{eV} \right)^{1/4} \]
  \[ I_{LB} = 4\pi I_{th} R_O \lambda_D \frac{\omega_{pe}}{\omega_{ce}} \left( \frac{eV}{kT_e} \right)^{3/4} \]
  \[ 3/4 < \beta < 6/7 \]
• POLAR II simulation
  – Bipolar distorted sheath limits symmetry and magnetic shielding, increasing collection efficiency w larger V
  – Angular momentum, canonical or otherwise is a property of field symmetry, not the particle.
  – As the ion energy impacting the body increases, ion generated secondary yield increases
  – Linear finite-element, multi-grid, charge stabilized. Trajectories tracked from sheath edge
  – Steady State, electrons behave classically and turbulence not need
• NASCAP-LEO Analytic space charge formula, sheath edge particle tracking for currents
DynaPAC Applications

SPEAR - II
- Pulsed power components in space, 100 KV
- No oil, no water, no pressurized gas, no foam
- It will breakdown, but after how long? Long enough?
- Launch failure
  - Extensive chamber testing & model agreement validated designs

DynaPAC (Dynamic Plasma Analysis Code)
- Evolved from POLAR II, Full explicit & hybrid PIC, extended CAD capability

**DynaPAC Applications**

**SPEAR-II PIC Simulation**

- Ion macroparticles 3 μs into simulation. Original distribution represented constant ion density.
- Calculated ion currents to the SPEAR-II high voltage components.

SPEAR-II was lost on launch, but (CAD aided) designs to hold off breakdown were developed and validated in chamber testing.

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DynaPAC Applications

DynaPAC multi-sub-grid resolution enables the simulation of the CHAWS high voltage probe experiment on the Wake Shield Facility (STS60 and STS69)

DynaPAC simulation of the 3D ion sheath surrounding the SPEAR-III sounding rocket experiment
Non-linear finite element interpolants yield continuous electric field

Linear Finite Elements lead to piece-wise continuous potential, piece-wise discontinuous electric field and unphysical beaming
Nascap-2K Replaces Earlier Spacecraft-Plasma Codes

**Code: NASCAP/GEO (1976-1984)**
- **Applications:** GEO S/C Charging
- **Sponsors:** NASA, Air Force

- **Applications:** High Voltage Current Collection in Dense Plasma
- **Sponsor:** NASA

- **Applications:** Auroral Charging, Wakes
- **Sponsor:** Air Force

- **Applications:** Complex dense plasma phenomena
- **Sponsor:** AFRL
Boundary Element Method
Equations & Implicit Charging

In GEO, where space charge may be neglected, rather than a global gridded field solution, the BEM uses Coulomb’s law to sum over all sources of surface charge for the field at a specific point (grid-less).

\[ V = \frac{q}{4\pi\varepsilon_0 r} \quad \rightarrow \quad (4\pi\varepsilon_0)V_i = \sum_j \int d^2r_j \frac{\sigma_j}{r_{ij}} \]

\[ E = \frac{q}{4\pi\varepsilon_0 r^2} \quad \rightarrow \quad (4\pi\varepsilon_0)E_i = \sum_j \int d^2r_j \frac{\sigma_j}{r_{ij}^3}(r_i - r_j) \]

\[ V_i = [C^{-1}]_{ij}\sigma_j \quad \quad E_i \cdot n_i = F_{ij}\sigma_j \quad \quad E_i \cdot n_i = F_{ik}C_{kj}V_j \]

\[ q_i = A_i (E \cdot n)_i + C_{ic} (V_i - V_c) \quad \text{(insulators)} \]

\[ I_i (V_i, (E \cdot n)_i) = A_i F_{ik}C_{kj}\dot{V}_j + C_{ic} (\dot{V}_i - \dot{V}_c) \quad \text{(insulators)} \]

Discretize and Implicitize:
\[ I(t + \Delta t) \approx I(t) + dI / dV (V(t + \Delta t) - V(t)) \]

A bit more Math:
\[ V(t + \Delta t) = V(t) + I(t) / [G - I'] \]

Where \( G \) is a ‘round-up’ of all the capacitance-like terms (all the math) and the current derivative, \( I' = dl/dV \), contains all the physics.
**DSX Spacecraft**

**A really big VLF antenna**

**Largest unmanned self-supporting structure ever flown in space**

**Payload Module (PM)**
- Wave-particle Interactions (WPIx)
  - VLF transmitter & receivers
  - Loss cone imager
  - DC Vector Magnetometer
- Space Weather (SWx)
  - 5 particle & plasma detectors
- Space Environmental Effects (SFx)
  - NASA/Goddard Space Environment Testbed
  - AFRL effects experiment
- NASA/JPL deployable structures payload

**Avionics Module (AM)**
- Attitude Control System
- Power
- Thermal Control
- Communications
- Computer/Avionics
- Experiment Computer
- Space Weather (HEPS)

- 80 m Y-axis boom
  - VLF Tx & Rx
- 16 m Z-axis boom
  - VLF Rx
  - DC magnetic field
- ~ 500 kg
- 3-axis stabilized
- ~ 5 kV amplitude

**First spacecraft design with integrated ESPA Ring**

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Dynamic Sheath Simulation with Nascap

Sheath physics is key to antenna performance
- Investigation with Nascap
- 3D finite element PIC and hybrid PIC simulations
- Full scale, 5 kV, nested grids 15 cm – 5 m, \( \lambda_D = 0.2 \) m
- **Plasma power loss:** < 1 W (preliminary)
- Antenna + volume/shielding currents hand off to cold-plasma EM solver

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Phase shift at 2 kHz, 1 kV, \( 10^9 \) m\(^{-3} \)
Numeric models in Nascap-2k

- Environment integrals (*NASCAP/GEO* & *POLAR*)
- Implicit charging algorithm (*NASCAP/GEO*)
- Finite element method (*NASCAP/GEO*)
- Multiply nested grids (*NASCAP/LEO*)
- Space charge stabilization (*POLAR*)
- Matrix elements for “special elements” (*NASCAP/LEO*)
- Strictly continuous electric fields (*DynaPAC*)
- Third order particle tracking (*DynaPAC*)
- Boundary element method (*Nascap-2k*)
- Moment conserving particle injection, splitting, chemistry (*Nascap-2k*)
- Object Toolkit (*Nascap-2k*)
- Orbit Averaging blends, PIC → Cloud in Cells → Steady State Trajectory (*Nascap-2k*)

Where we started and still very efficient

- Pseudopotential fluid current calculation (for DSX)
Electrodynamic Tethers

The TSS1 (1992) and TSS-1R (1997) space shuttle missions demonstrated:

- Viable concept for extracting or adding orbital energy
- Space Shuttle charging
- Techniques for electron emission and ion collection at shuttle (and tether) end
- Enhanced magnetized probe collection
- There was and still is no theory for the positive bias Langmuir probe in a flowing plasma
- Electrodynamic plasma coupling theory was not adequate for experiment prediction
- Much more
TSS-1R Current Collection During Electron Gun Emission

- TSS-1R data showed enhancement over Parker-Murphy, P-M, canonical angular momentum conservation theory, ranged from 2.2 to 2.9.
- Data does not show dependence on Alfvén speed or D region conductivity
- Results do scale like P-M.

- Data groups best when normalized to local plasma parameters

TSS-1R data normalized by thermal current and electron temperature [Thompson et al., 1998]

Early TSS-1R data by Wright et al. [1997]
Heated pre-sheath model, Cooke & Katz [‘98]
\[ I = \frac{1}{2} I_{P-M} \left( 1 + \left( 1 + 2E_{\text{Ram}}/5T_O \right)^{1/2} \right) \]
The (Alfvén) Wing model (Drell et al.)
Recall ECHO I-II & TSS-1R

Current closure through polarization current

\[ j_p = \left( \frac{\rho}{B^2} \right) \left( \frac{dE_y}{dt} \right) = \frac{dE_y}{dt} = \frac{dE_y}{dy} \frac{dy}{dt} \]

- With high field aligned mobility, \( E = v_o \times B \) is constant below the \( j_{\parallel} \) front, and the front moves at \( v_{\parallel} \).
- Integrate cloud and front along \( Z \).

\[
j_{pu} = \int j_p dz = \int j_p v_{\parallel} dt = \int (v_{\parallel} \rho / B^2) dE = (\rho / B) v_{\parallel} v_o
\]

- The braking force on the cloud plasma is

\[
j_{pu} \times B = -\left( \frac{2}{h} \right) \rho v_{\parallel} v_o
\]

- Drell, Foley and Ruderman [1965] first performed this analysis for ECHO I-II with the conjecture that \( v_{\parallel} = V_A \)
- With the realization that a tether more readily generates Whistler waves than Alfvén waves interest waned, but the conjecture has never been validated.

- They botch a space-charge limiting test

Alfvén Wings
Simulation of a positive probe in a flowing magneto-plasma with ICEPIC

Under-dense strongly magnetized plasma

Four regions:
- Quasi-trapped electron region
- Electron depletion wing
- Ion-rich wing
- Wake region
- Ion cyclotron wake eddies
  - characteristic wavelength
  \[ \lambda = \frac{2\pi U_{\text{drift}}}{\omega_{ci}} \]
- No magnetic perturbation observed

\[ r_e < \lambda_D < r_i < r_P \]

Charge Density Cross-Sections: \( t = 6.05 \times 10^{-6} \text{ s with } V_p = 200 \text{ V} \)

Dynamics of positive probes in under-dense, strongly magnetized, \( E \times B \) drifting cc plasma: Particle-in-cell simulations, Jonathon R. Heinrich and David L. Cooke, Physics Of Plasmas 20, 093503 (2013)


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Electron Depletion Wing

- Two populations of electrons in electron depletion wing.
- Secondary fast population propagating away from probe found on trailing edge of depletion wing.
- Propagation velocity of electron depletion wing follows velocity of secondary fast electrons.
- Secondary electrons originate from the quasi-trapped region.

\[ V_{te} = 1.5 \times 10^6 \text{ m/s} \]

Simulation using ICEPIC
Under-dense strongly magnetized plasma

New facility at AFRL Kirtland AFB, Space Vehicles Directorate

- 2m x 1m chamber, 300 G,
  - Glass inner doors to support transverse $\mathbf{E}$

- Plasma sources
  - Hollow cathode light sabers (shown) – Helicon in development

- Planned experiments
  - $\mathbf{E}_x\mathbf{B}$ drifting plasma to explore wings (Thermal vs Alfven)
  - Spinning CIV limited plasma
**Objectives**
- Plasma wing experiments
- Positive probe in flowing magnetoplasma
- Twin rotating columns for ExB boundary condition (Mach = 1 due to CHX)
- Injected Ions, $v_D = E/B$, Mach >1

**Plasma sources**
- Hollow Cathodes
- Helicon
- Bad Magnetron (sandbox effort)

**Diagnostics**
- Motion system (2x 2D, translation + rotation)
- 16 channel, HV, Low I, analog multiplex switch
- Keithley 237
- Cyl Langmuir Probes
- MACH probes
- Emissive probes
- Rogowski coils
- Doppler spectroscopy (later, $$)
MCX was designed to test supersonic plasma rotation for plasma confinement. The experiment suffered from a limit on the rotation velocity consistent with CIV at the insulators. (1)

- Magnetized plasma is observed to rotate with equal angular velocity along shaped field lines.
- Plasma velocity in the low field region was limited to a rotation corresponding to the CIV limit at the insulators in the high field region.
- The effect was observed using hydrogen and helium with the expected reduction in velocities in helium. (2)

(1) Ellis et al, Physics of Plasmas 12 055704 (2005)
(2) C. Teodorescu et al, Physics of Plasmas, 17, 052503 (2010)
Summary

• The utility of computer simulation in support of active experiment is not controversial
  – Less common is a commitment to build on a government owned legacy capability, i.e., Nascap. Turning Science into Engineering for over 30 yrs
  – Not just about Nascap

• Reviewed grounding of (+/-) charged rocket bodies in LEO
  – Much not mentioned
  – Now have a good understand of the physics
  – Captured in numerical models for future engineering needs

• HV & Wakes

• No discussion of plumes, but Nascap does that
  – Hall Thrusters in GEO

• Touched on numerical techniques
  – Steady State is still very important, PIC if really needed,
  – Heuristic algorithms can best illustrate the physics and run on your phone.

• DSX, VLF transmitter or plasma heater?

• Outstanding problem of a positive body in flowing magnetoplasma
Questions, Answers?
A Problem with Drell

Drell, Foley, and Ruderman, *Drag and propulsion in the ionosphere: An Alfven propulsion engine in space*, JGR, 1965

**Calculated the Aflvén wing current to the Echo 1 balloon**

The current of 0.2 amp/4 × 10^3 cm^2 < 0.1 μamp/cm^2 is well below the space charge limit. To show this, we compute the thickness of the ion sheath surrounding the conducting surface of the Echo 1 in order to neutralize the electric field in the plasma. It is, by Gauss’ law,

\[ l = \frac{E}{2 \times 4\pi n_{\text{ions}}e} = \frac{v_e B}{8\pi e c n_{\text{ions}}} \approx 10^{-1} \text{ cm} \]

where we used \( n_{\text{ions}} \sim n_{\text{electrons}} \sim 5 \times 10^3/\text{cm}^3 \) at 1600 km altitude. Thus we have a potential drop of 3 volts occurring in a distance of 0.1 cm from the surface of Echo, and through this drop a current of hundreds of microamperes can flow before being limited by space charge according to Child’s law.

- At 5×10^3/cc, and \( T_e = 1.0 \text{ eV} \) (not specified in Drell),
  - \( J_\text{the} = 0.013 \mu A/\text{cm}^2 \)
  - The Alfven wings give 0.1 \( \mu A/\text{cm}^2 \)
- Two mistakes
  - Incorrect sheath & space-charge limit,
  - Not recognizing the thermal current is the constant that sets the sheath size.
- Sheath calculation
  - They get \( D_S = 0.1 \text{ cm} \) assuming constant ion density
  - Child sheath at 3 Volts, \( \lambda_D = 10 \text{ cm} \), \( D_S = 29 \text{ cm} \)
  - \( D_S = 1.26 \lambda_D \left( \frac{eV}{kT} \right)^{3/4} \) (using thermal current)
- Many citations (over 100) using \( v_\parallel = v_A \),
  - Goertz and Machida, *Asymptotic state of CIV*, JGR, 1985
A Thermal Wing model

- Current closure still through polarization current
- Charges in the background plasma are only motivated by their thermal current

\[ j_p = \left( \rho / B^2 \right) \left( dE_y / dt \right) \]

\[ hj_{pu} = \int j_p dz = \int j_p v_{ll} dt = \int \left( v_{ll} \rho / B^2 \right) dE = \left( \rho / B \right) v_{ll} v_0. \]

- The braking force \( F = j_{pu} \times B = -\left( 2/h \right) \rho v_{ll} v_0 \)
- Compare the Thermal force to the Alfven force

\[ \frac{F_{th}}{F_A} = \frac{v_{th}}{v_A} = \left( 1/B \right) \sqrt{\frac{\mu_0 \rho_i kT_e}{m_e}} = \sqrt{\beta \left( \frac{m_i}{m_e} \right)} \]

- For the Drell case (10^3/cc and T = 1.0 eV)
  - \( F_{th}/F_{vA} = 0.001 \)
  - Higher in the plasmasphere we get up to 0.1
  - But in troughs and pauses, \( \rho \rightarrow 0 \), and \( v_A \rightarrow \infty \)