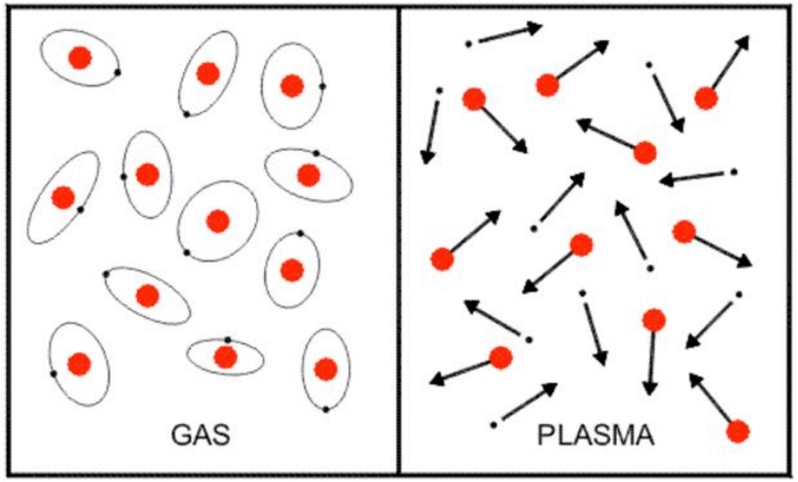
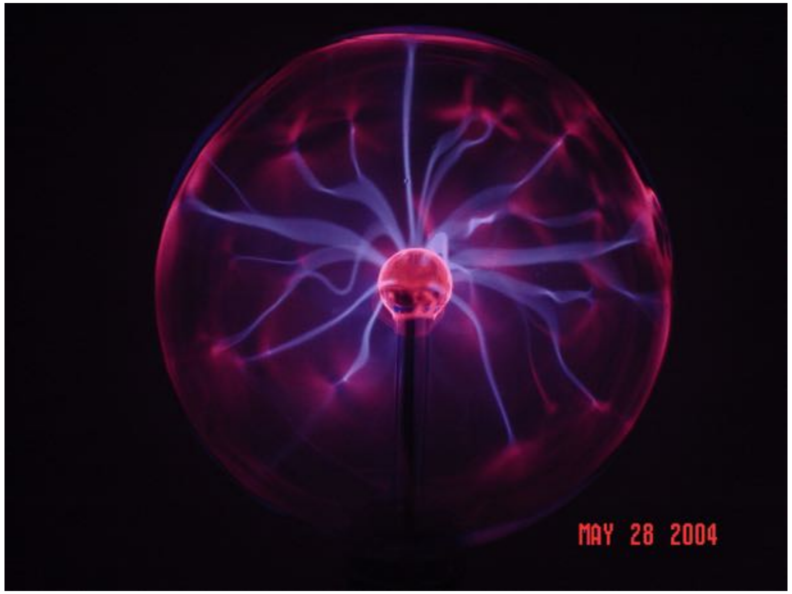
Floating potential and Convective Electric Field

Kobe-Oslo Numerical Workshop

W. Miloch

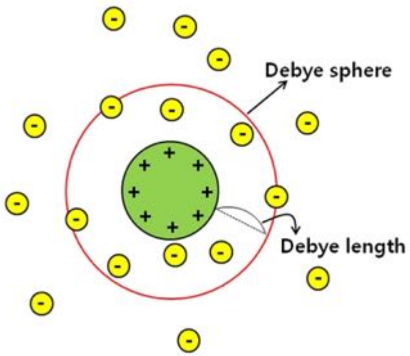
Spacecraft (object) in plasma



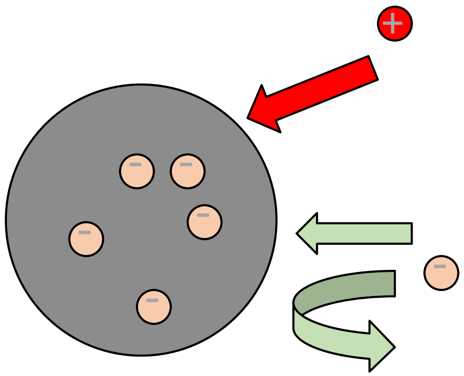


- Ionized gas
- Electrically conductive
- Large scales: quasineutral
- Small scales: plasma shielding
- Dynamics are electro-magnetic

$$\lambda_{De} = \sqrt{\frac{\epsilon_0 k T_e}{n_{e0} q_e^2}}$$



Spacecraft (object) in plasma

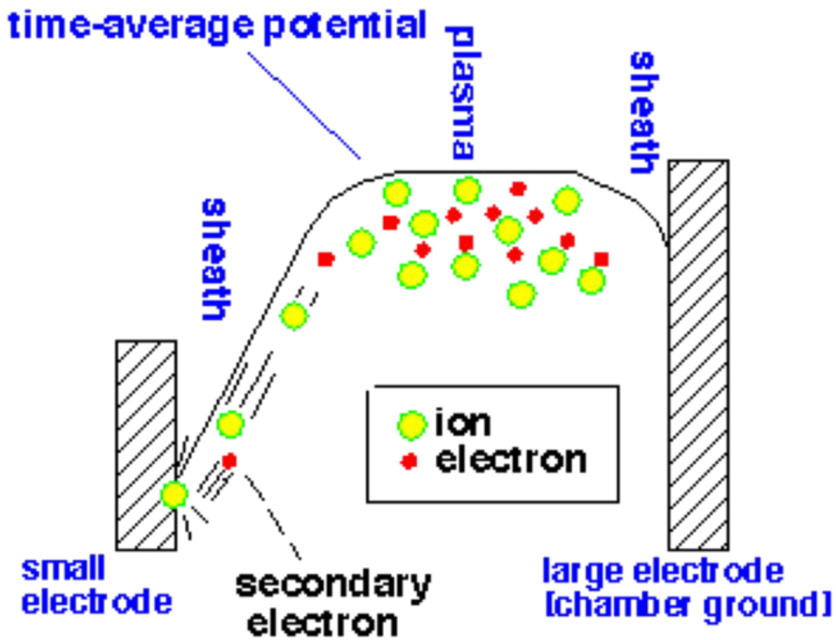


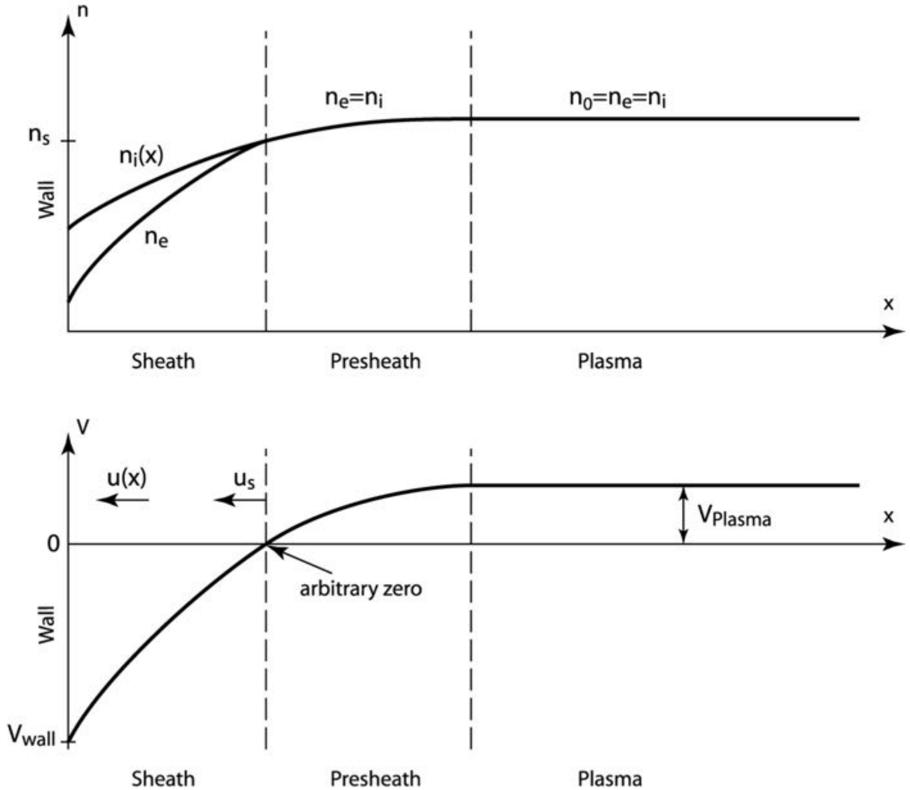
$$v_{th,e} \gg v_{th,i}$$

$$v_{th,\alpha} \approx \sqrt{kT_\alpha / m_\alpha}$$

- Electrons are more mobile than ions
- Object acquires negative potential
- Electrons are repelled
- Ions are attracted
- Object is shielded by plasma
- Surface charge distribution depends on material conditions.

Plasma sheath





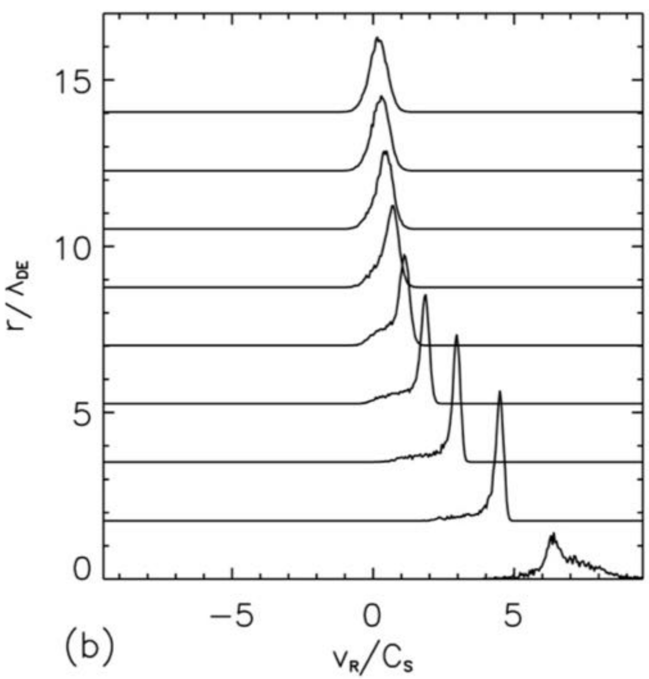
Sheath formation:
- quasineutrality broken

Sheath edge – Bohm criteron

- Collisionless plasma
- 1D Problem
- Cold ions moving towards the surface
- It can be shown that the ion speed must be greater than the Bohm velocity for the sheath to exist.

$$v_B = \sqrt{\frac{kT_e}{m_i}}$$

- The ion flow is supersonic!
- In reality: ion velocity distribution - can get distorted.



Phys. Plasmas **18**, 083502 (2011)

Sheath formation:
- quasineutrality broken
- change of velocity distributions

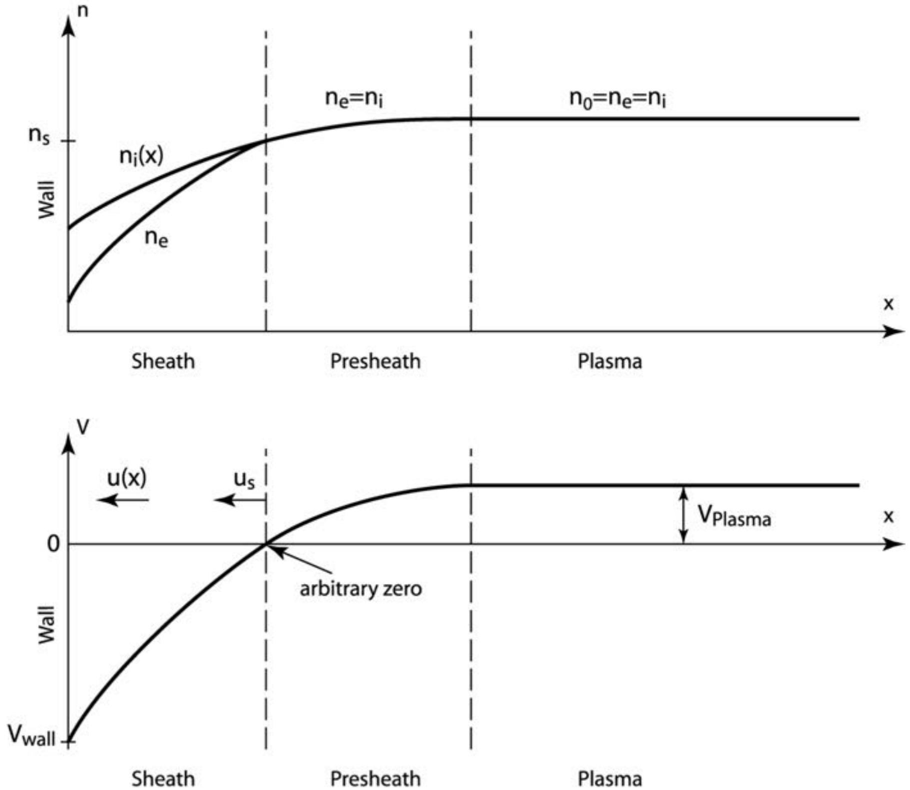
Presheath?

- To obtain Bohm velocity – need to accelerate to $v_B = \sqrt{kT_e/m_i}$

- Presheath potential:
$$\Phi \approx 0.5kT_e/e$$

- Can extend over a very large distance

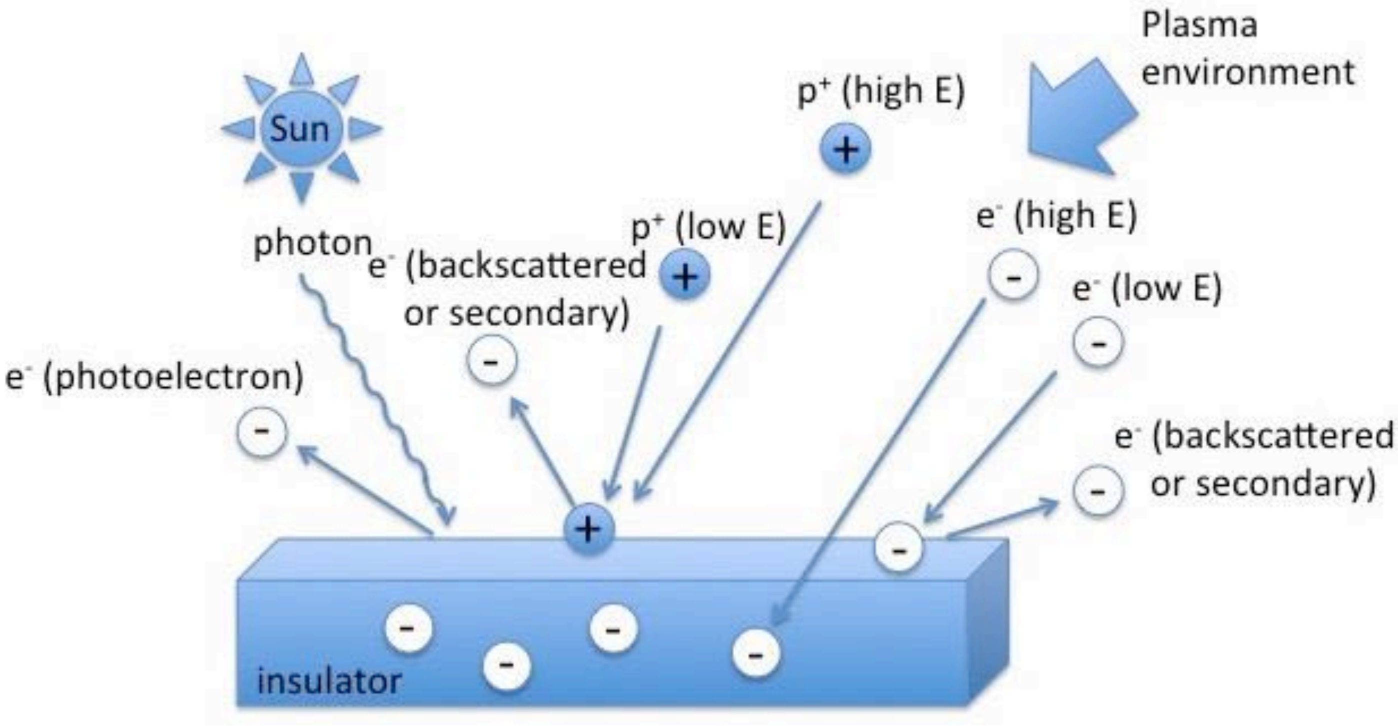
- Bohm velocity derived for cold ions…



Floating potential - concept

- In reality: many different charging currents.
- The net charge is all about the balance of currents to the surface
- At equilibrium – floating potential

$$\frac{dQ}{dt} = \frac{d\sigma}{dt} A = C \frac{dV}{dt} = \sum_k I_k \approx 0$$



Floating potential – model PP

Let us find the potential of a large spacecraft

- Let us assume it is large with respect to the sheath size.
- Sheath is planar… effectively it is 1D case…
- Electron current: $I_e = j_e A$
- Ion current: $I_i = j_i A$

$$f(v)\ \mathrm{d}v = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{mv^2}{2kT}}\ \mathrm{d}v$$

Maxwellian distribution

- Current density (general): $j_\alpha = \boxed{\frac{1}{4}} q_\alpha n_\alpha \langle v_\alpha \rangle$
- For electrons: $I_e = -\frac{1}{4} A e n_e \langle v_e \rangle e^{-e\Phi/kT_e} = -\frac{1}{4} A e n_e \sqrt{\frac{8kTe}{\pi m_e}} e^{-e\Phi/kT_e}$
- For ions:

$$I_i = \frac{1}{4} q_i n_i \langle v_i \rangle A = \frac{1}{4} q_i n_i \sqrt{\frac{8kT_i}{\pi m_i}} A$$

$$\int_0^\infty x^n e^{-ax^2} dx = \frac{k!}{2a^{k+1}} \quad \text{for odd} \quad n = 2k+1 \quad .$$

Floating potential – model PP

- When the currents to the surface balance each other

$$I_e = I_i$$

- We can find floating potential…

$$\boxed{\Psi_{fl} = -\frac{kT_e}{e}\ln\frac{\langle v_e\rangle}{\langle v_i\rangle} + \Phi_0 = -\frac{kT_e}{2e}\ln\left(\frac{T_e m_i}{T_i m_e}\right) + \Phi_0 .}$$

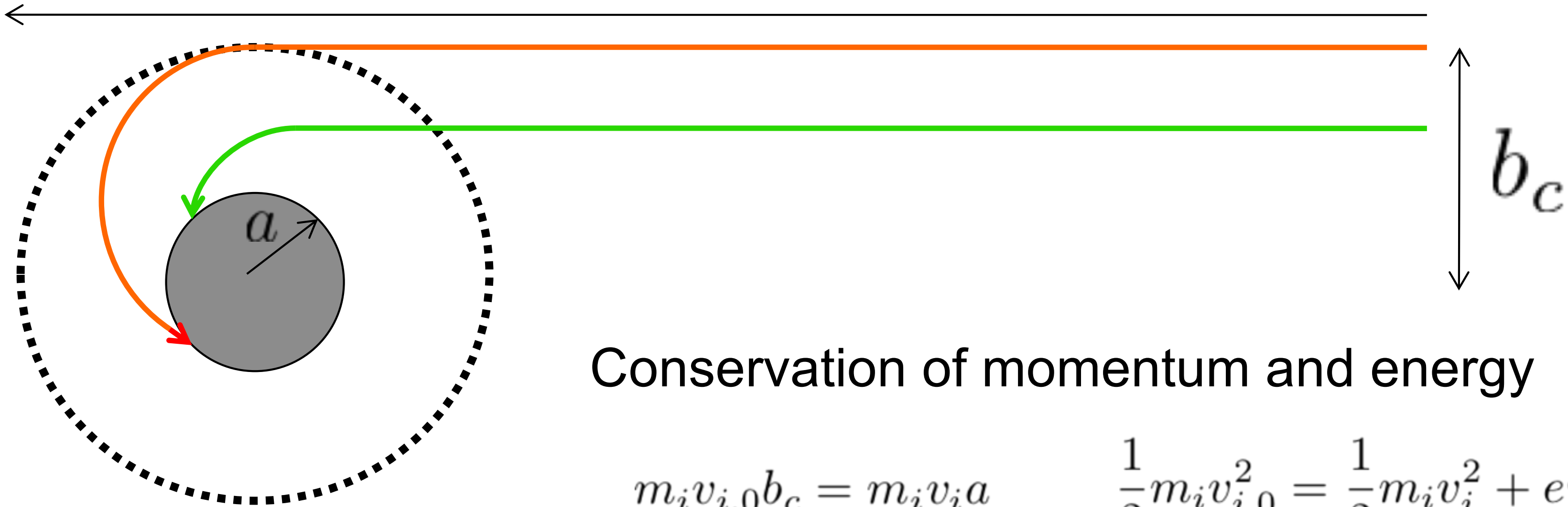
- And if ions are cold… $\Psi_{fl} = -\frac{kT_e}{2e}\left[\ln\left(\frac{m_i}{2\pi m_e}\right) + 1\right] + \Phi_0$

Valid for a large object with respect to the sheath size (ie., Debye length!!!)

THIN SHEATH…

Floating potential – model OML

Stationary plasma – OML (orbit motion limited) theory – **thick sheath**

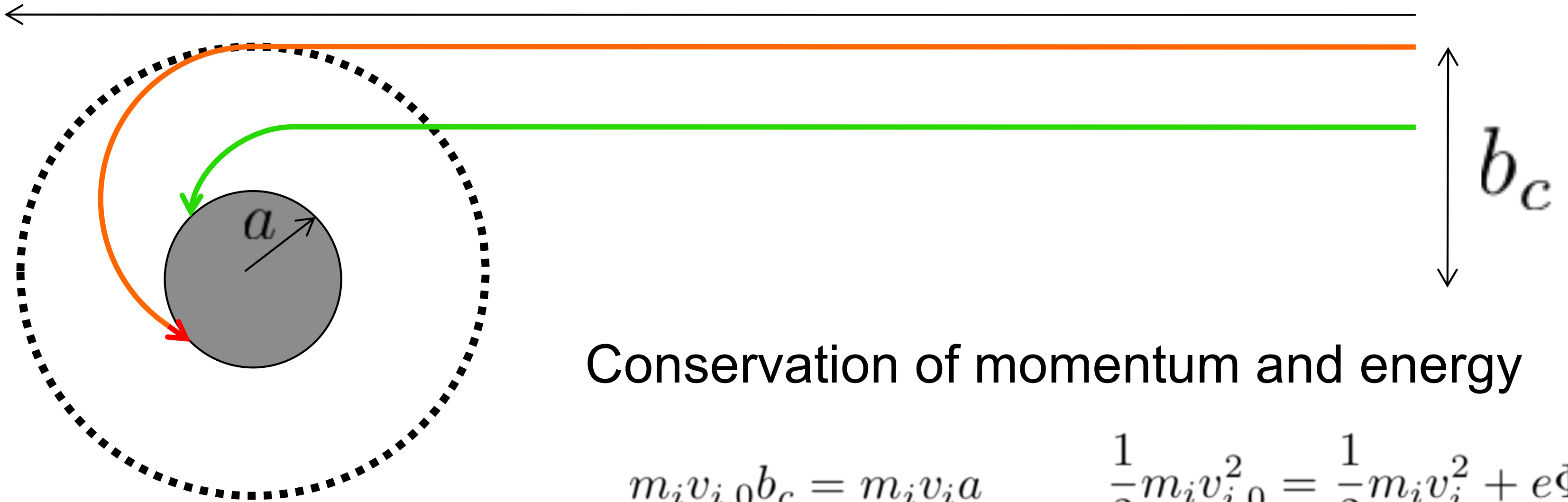


Conservation of momentum and energy

$$m_i v_{i,0} b_c = m_i v_i a \qquad \frac{1}{2} m_i v_{i,0}^2 = \frac{1}{2} m_i v_i^2 + e\Phi_d$$

Floating potential – model OML

Stationary plasma – OML (orbit motion limited) theory



Conservation of momentum and energy

$$m_i v_{i,0} b_c = m_i v_i a \qquad \frac{1}{2} m_i v_{i,0}^2 = \frac{1}{2} m_i v_i^2 + e\Phi_d$$

$$\sigma_c = \pi b_c^2 = \pi a^2 \left(1 - \frac{2e\Phi_d}{m_i v_{i,0}^2}\right)$$

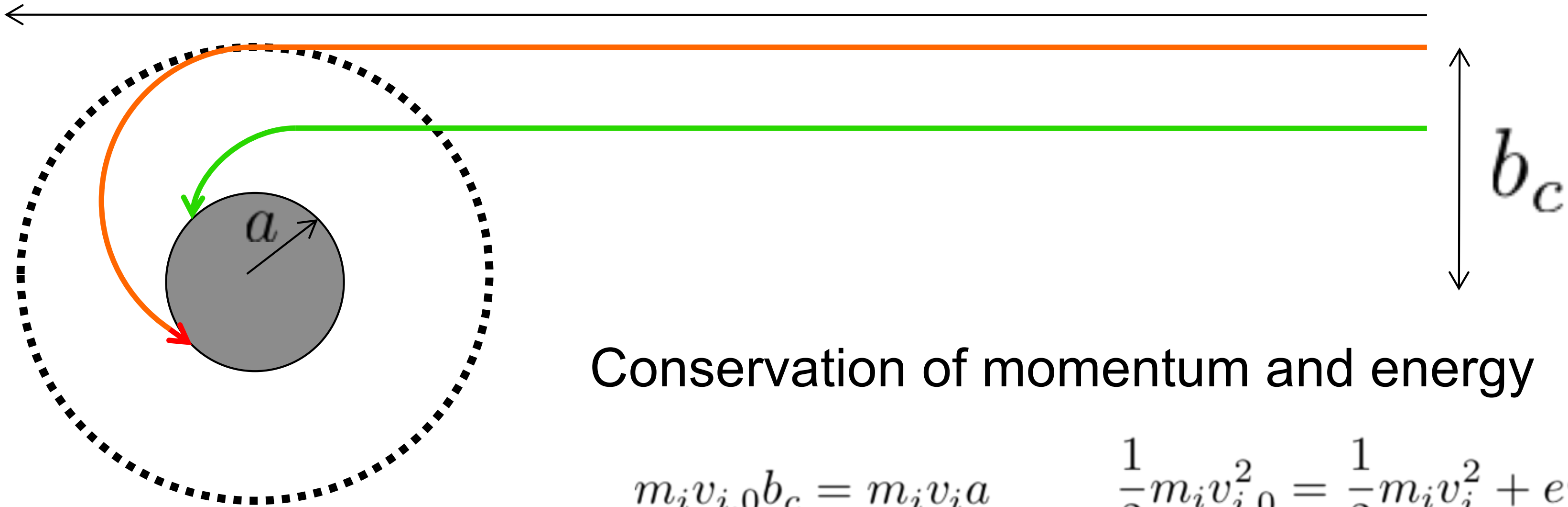
collection cross section

$$\mathrm{d}I_i = \sigma_c(v_i) n_i e v_i f(v_i) \mathrm{d}v_i$$

ion current

Floating potential – model OML

Stationary plasma – OML (orbit motion limited) theory



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collection cross section

$$\mathrm{d}I_i = \sigma_c(v_i) n_i e v_i f(v_i) \mathrm{d}v_i$$

ion current

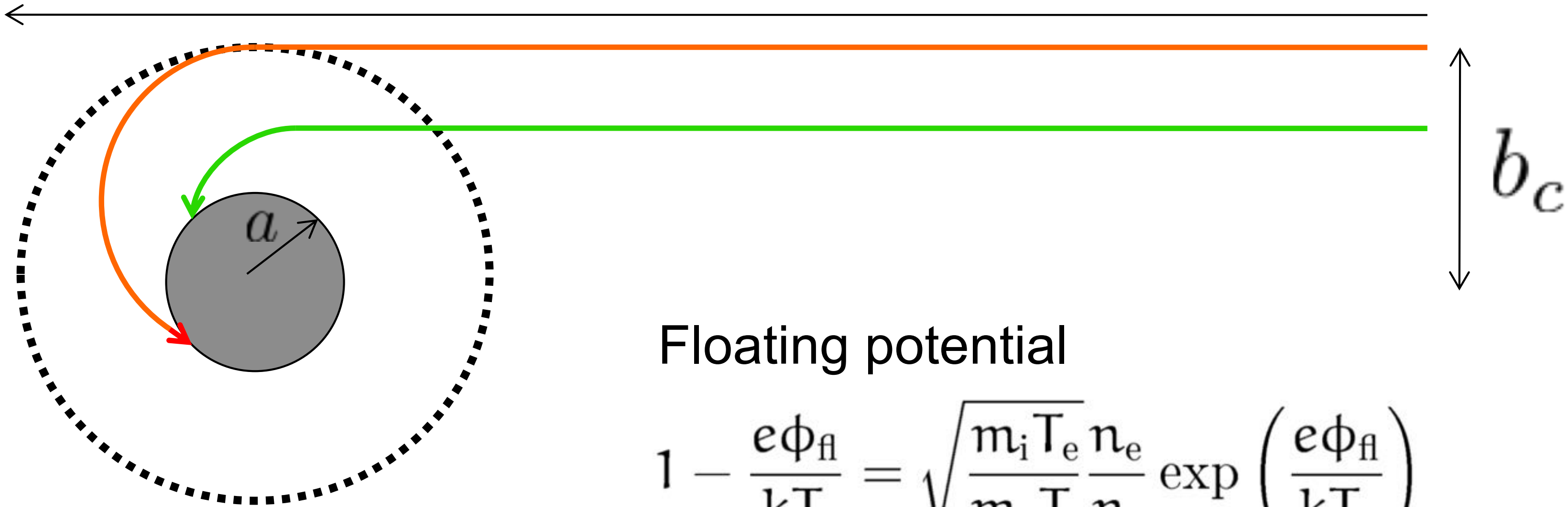
$$I_i = \pi a^2 n_i e \sqrt{\frac{8kT_i}{\pi m_i}} \left(1 - \frac{e\Phi_d}{kT_i}\right)$$

$$I_e = -\pi a^2 n_e e \sqrt{\frac{8kT_e}{\pi m_e}} \exp\left(\frac{e\Phi_d}{kT_e}\right)$$

for Maxwellian velocity distributions

Floating potential – model OML

Stationary plasma – OML (orbit motion limited) theory



Floating potential

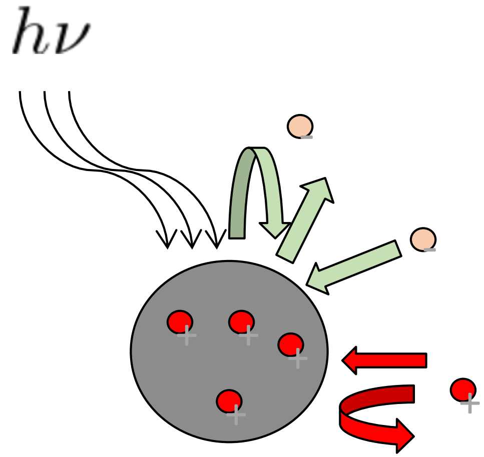
$$1 - \frac{e\phi_{fl}}{kT_i} = \sqrt{\frac{m_i T_e}{m_e T_i}\frac{n_e}{n_i}} \exp\left(\frac{e\phi_{fl}}{kT_e}\right)$$

Spitzer value

T_e/T_i	1	2	5	10	20	50	100
H	-2.504	-2.360	-2.114	-1.909	-1.700	-1.430	-1.236
He	-3.052	-2.885	-2.612	-2.388	-2.160	-1.862	-1.645
Ar	-3.994	-3.798	-3.491	-3.244	-2.992	-2.660	-2.414

Table 2.1: *Normalized floating potentials* $e\phi_{fl}/kT_e$ *in quasineutral plasmas* $n_e = n_i$ *in Hydrogen, Helium and Argon for different electron-to-ion temperature ratios.*

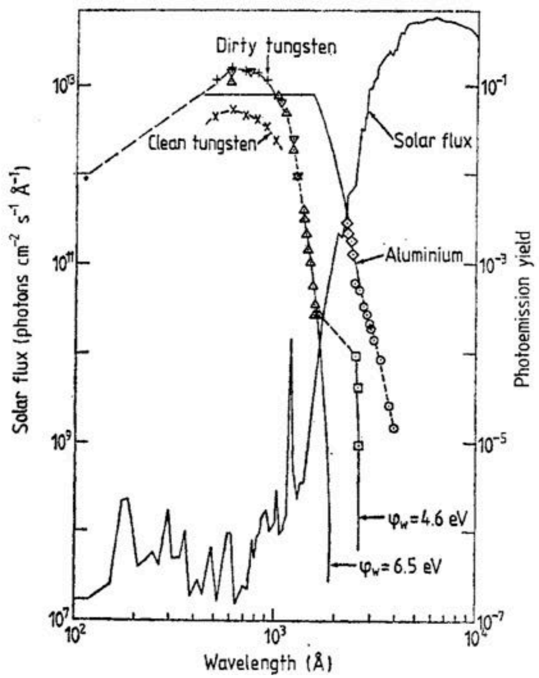
Photoemission



Due to UV light: $E_{ph} = h\nu - W$

- Depends on the photon flux and work function of the material

$$I_{\mathrm{ph}} = \begin{cases} -I_{0\mathrm{ph}}, & V_{\mathrm{p}} < 0 \\ -I_{0\mathrm{ph}} \left(1 - \frac{eV_{\mathrm{p}}}{kT_{\mathrm{ph}}}\right) e^{-\frac{eV_{\mathrm{p}}}{kT_{\mathrm{ph}}}}, & V_{\mathrm{p}} > 0, \end{cases}$$



- Leads to photoelectron cloud

- Important on the moon, in deep space, when teh plasma density is low

Charging at different orbits

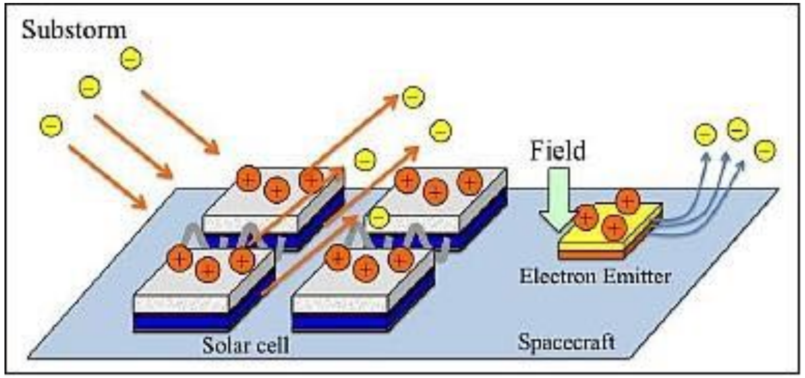
LEO

- Spacecraft negatively charged
- Plasma is dense but low energy
- Orbital velocity is higher than ion thermal velocity
- Lower than electron thermal velocity
- Electrons impact all surfaces
- Ions impact ram surfaces only

GEO

Spacecraft charge during magnetospheric substorms between longitudes corresponding to midnight and dawn

Charging effects



Effects of charging on spacecraft:

- Instrument reading bias
- Arcing-induced EMI, electronics upsets
- Increased current collection
- Re-attraction of contaminants
- Ion sputtering, accelerated erosion of materials

Spacecraft must be designed to keep differential charging below the breakdown voltages or must tolerate the effects of discharges.

Plasma effects

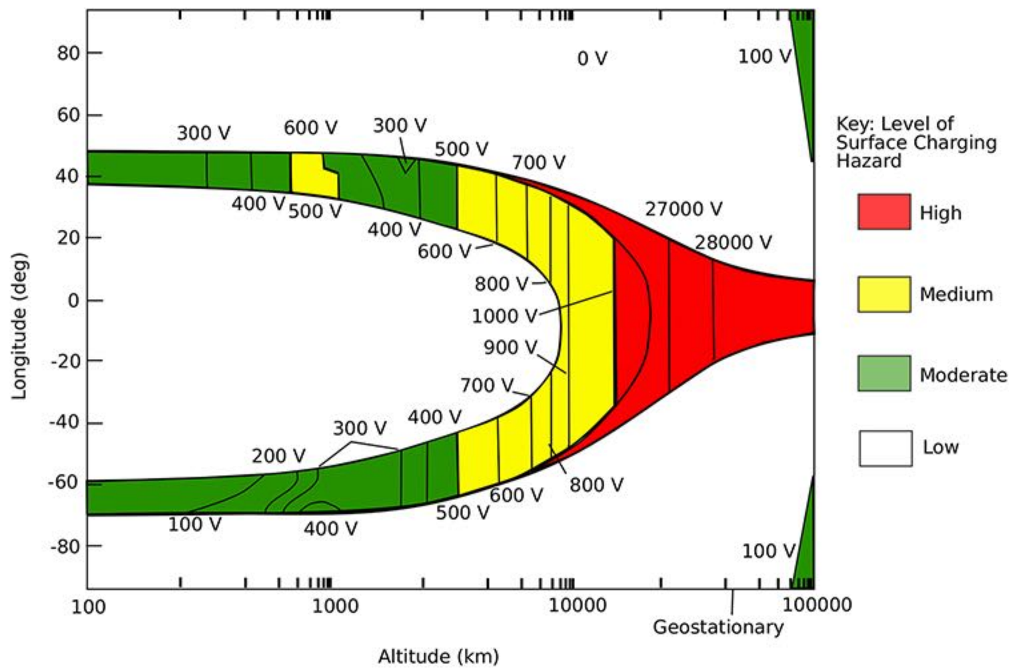
Spacecraft charging & arcing

- differential potential
- spacecraft (frame) potential
- arcing when potential difference is too strong and causes the dielectric breakdown in the material. Eenrgy available to arc $E=0.5\ CV^2$

But also :

Elecromagnetic Interference

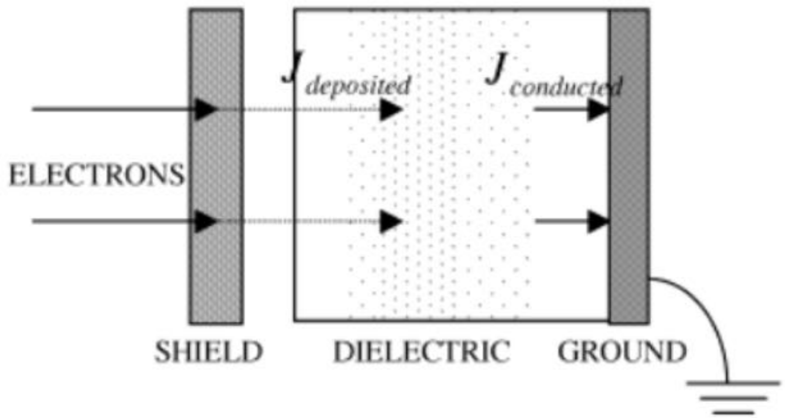
Material effects – e.g., ageing.



Internal charging and radiation

- High energy electrons get deep into dielectrics and charge them internally...
- Radiation: High energy particles travel through spacecraft material and deposit kinetic energy
  - Displaces atoms.
  - Leaves a stream of charged atoms in their wake.

- Reduces power output of solar arrays
- Causes sensitive electronics to fail
- Increases sensor background noise
- Radiation exposure to crews



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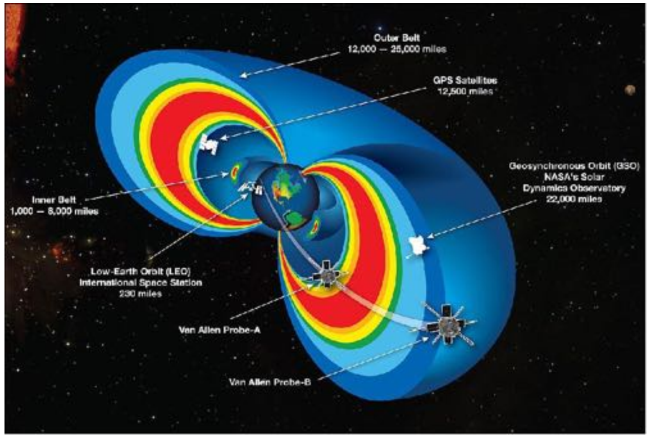
Internal charging

Definition of high energies

For electrons E > 100 keV
For protons and heavy ions E > 1 MeV



- Sources
  - Van Allen Belt (electrons and protons) (trapped radiation)
  - Galactic cosmic rays interplanetary protons
  - Ionized heavy nuclei
  - Protons associated with solar proton events

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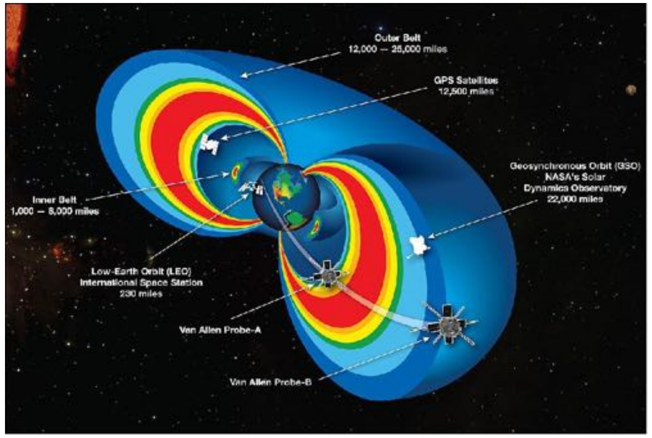
Van Allen belts and their stability



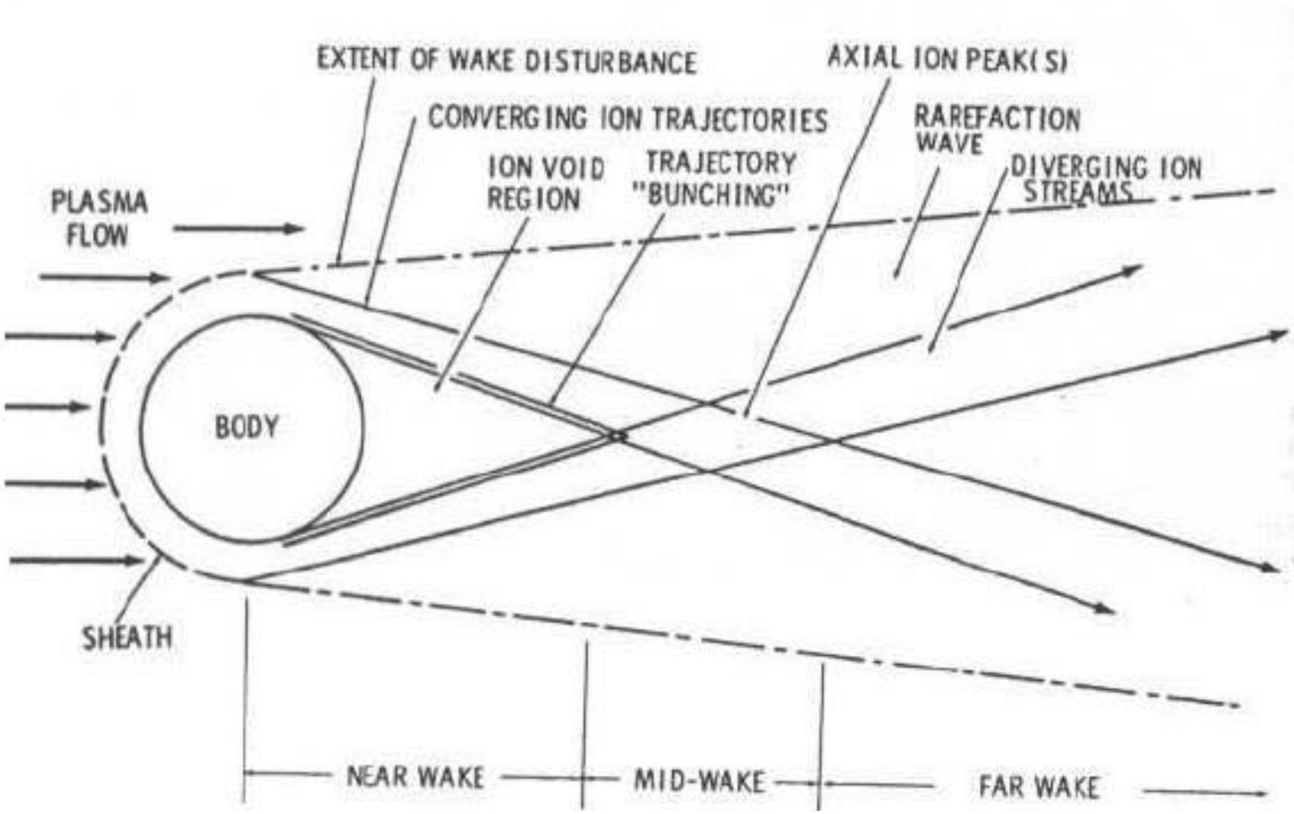
Inner belt ~ 1000 Km 6000 km altitude
Protons E > 10's of MeV
ElectronsE~1-10MeV

Outer belt 10,000 - 60,000 km
Electrons E ~ 0.04 - 4.5 MeV

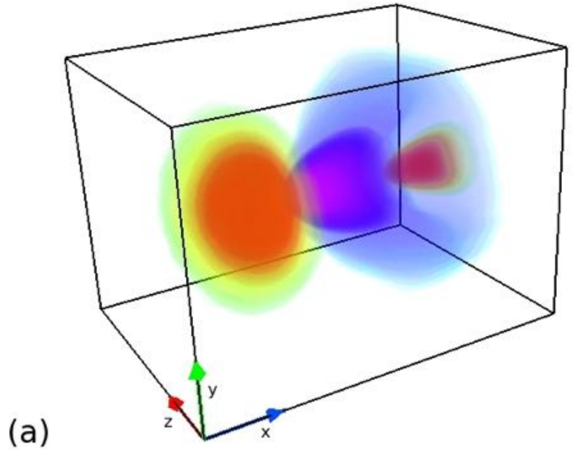
Inner belt
– Fairly stable with changes in solar cycle
– May change by a factor of three as a result of geomagnetic storms loading in high energy electrons.

Outer belt
– Electron concentrations may change by a factor of 1000 during geomagnetic storms.

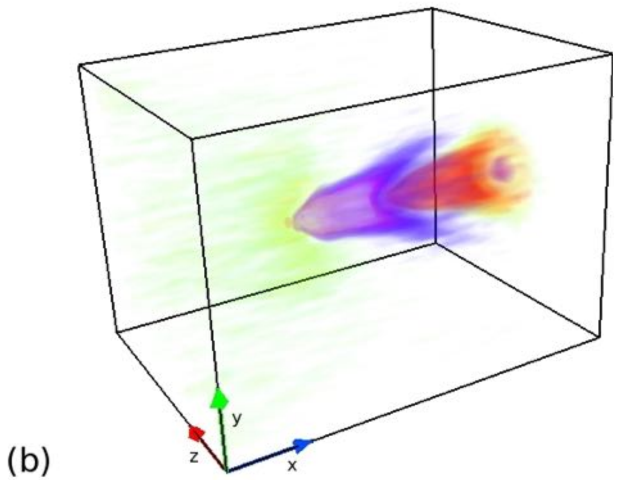
Wake effects



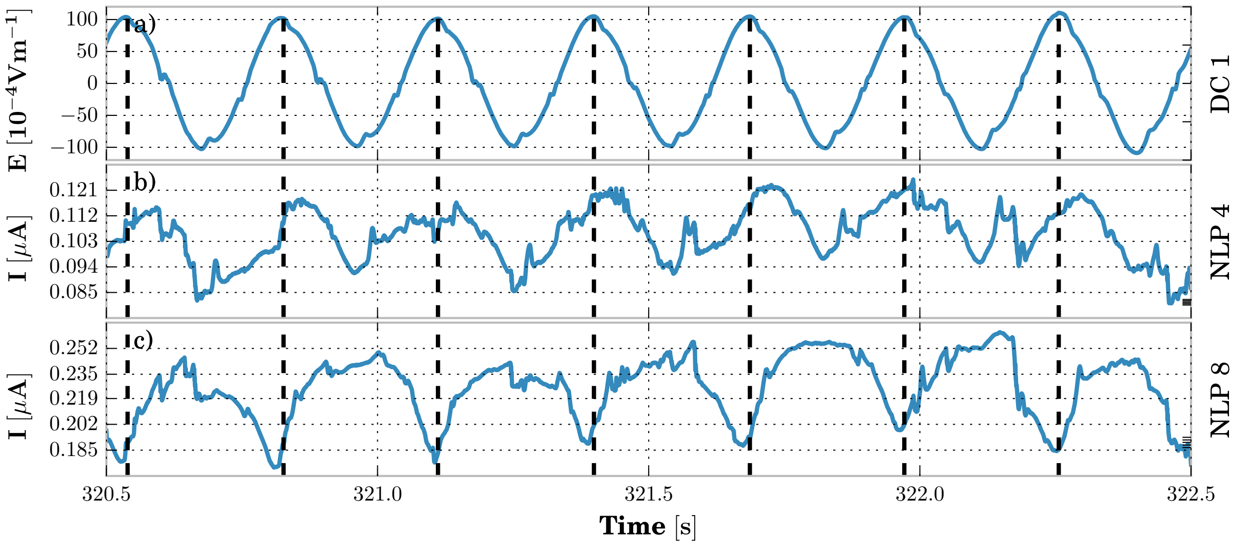
Wake effects 2



Electrostatic potential



Ion density



Data from ICI-3 rocket

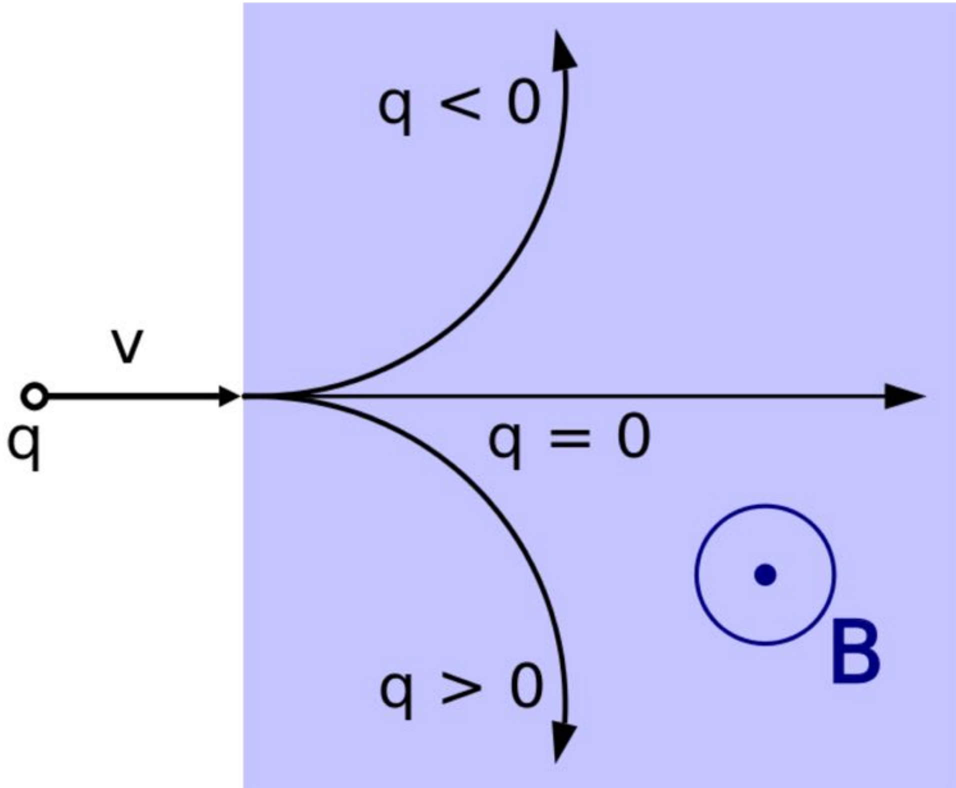
Charging effects

Spacecraft	Year(s)	Orbit	Impact*	Spacecraft	Year(s)	Orbit	Impact*
DSCS II	1973	GEO	LOM	Intelsat K	1994		Anom
Voyager 1	1979	Jupiter	Anom	DMSP F13	1995	LEO	Anom
SCATHA	1982	GEO	Anom	Telstar 401	1994, 1997	GEO	Anom/LOM
GOES 4	1982	GEO	LOM	TSS-1R	1996	LEO	Failure
AUSSAT-A1, -A2, -A3	1986-1990	GEO	Anom	TDRS F-1	1986-1988	GEO	Anom
FLTSATCOM 6071	1987	GEO	Anom	TDRS F-3,F-4	1998-1989	GEO	Anom
GOES 7	1987-1989	GEO	Anom/SF	INSAT 2	1997	GEO	Anom/LOM
Feng Yun 1A	1988	LEO	Anom/LOM	Tempo-2	1997	GEO	LOM
MOP-1, -2	1989-1994	GEO	Anom	PAS-6	1997	GEO	LOM
GMS-4	1991	GEO	Anom	Feng Yun 1C	1999	LEO	Anom
BS-3A	1990	GEO	Anom	Landsat 7	1999-2003	LEO	Anom
MARECS A	1991	GEO	LOM	ADEOS-II	2003	LEO	LOM
Anik E1	1991	GEO	Anom/LOM	TC-1,2	2004	~2GTO, GTO	Anom
Anik E2	1991	GEO	Anom	Galaxy 15	2010	GEO	Anom
Intelsat 511	1995	GEO	Anom	Echostar 129	2011	GEO	Anom
SAMPEX	1992-2001	LEO	Anom	Suomi NPP	2011-2014	LEO	Anom

Anomally, Loss of Mission, System Failure

Electric field

Lorentz Force



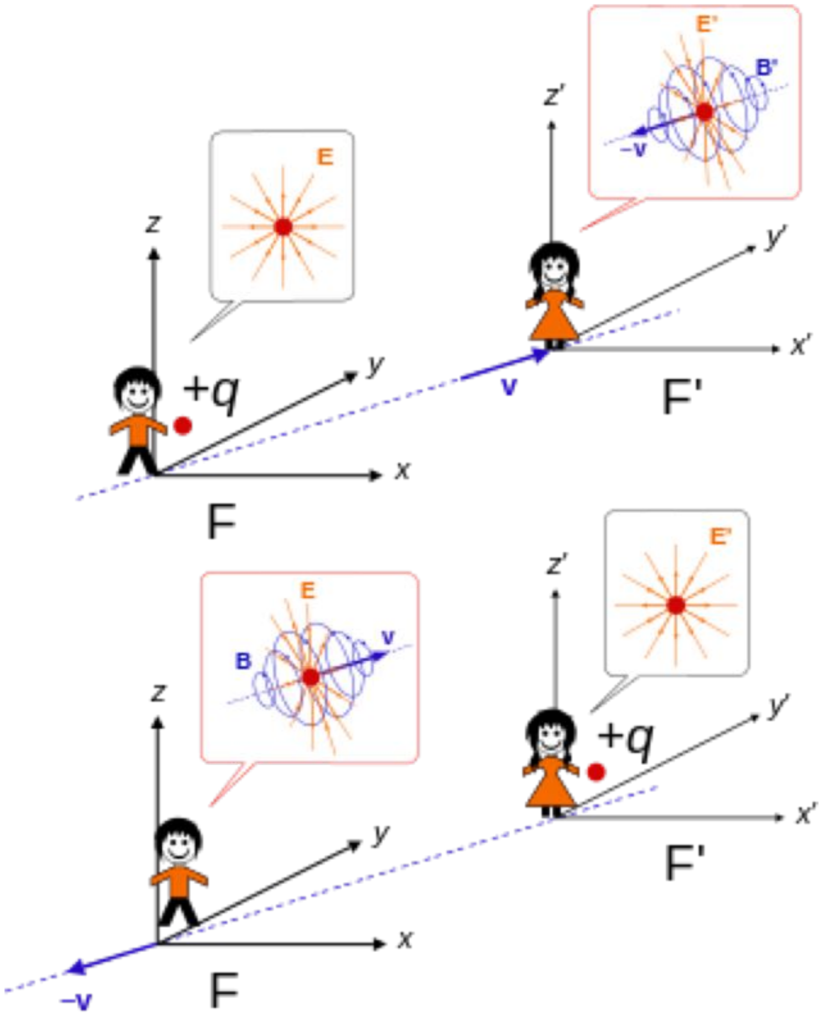
$$\vec{F} = \underbrace{q\vec{E}}_{Electric\ force} + \underbrace{q\vec{v} \times \vec{B}}_{Magnetic\ force}$$

Electric & Magnetic field aspects of the same force EM force.

Loretnz Transformation

If we move across the magnetic field, the electric field will appear.

$$\beta \equiv \frac{1}{\sqrt{1-(U/c)^2}}$$



$$\mathbf{E} = \frac{Q}{4\pi\varepsilon_0} \frac{1-(U/c)^2}{(1-(U/c)^2\sin^2\Theta)^{3/2}} \frac{\mathbf{R}}{R^3}$$

$$\begin{aligned} \mathbf{B} &= \frac{\beta}{c^2}\mathbf{U}\times\mathbf{E}' = \frac{1}{c^2}\mathbf{U}\times\mathbf{E} \\ &= \frac{Q\mu_0}{4\pi} \frac{1-(U/c)^2}{(1-(U/c)^2\sin^2\Theta)^{3/2}} \frac{\mathbf{U}\times\mathbf{R}}{R^3}, \end{aligned}$$

Loretnz Transformation

Classical limit of Lorentz Transformation

$$\mathbf{B}' = \mathbf{B}$$

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}$$

Paradox????!!!!

If we have no E field in one frame of reference, why should we get it in another moving frame of reference?

Convective electric field

Plasma drift due to electric field.

$$\mathbf{v}_{\mathrm{ExB}} = \frac{\mathbf{E} \times \mathbf{B}}{B^2},$$

The plasma drift velocity in the spacecraft frame...

$$\mathbf{v}'_D = \mathbf{V} - \mathbf{v}_D,$$

Motion of a spacecraft in a plasma will induce electric field.

$$\bar{\mathbf{v}}'_D = \frac{\mathbf{E}' \times \mathbf{B}}{B^2},$$

Convective electric field

We try to measure $$E = E' - v \times B$$

So we need to account for the electric field that is due to motion of the spacecraft!