Plasma sheaths around spacecraft: classical, space-charge-limited (SCL) and inverse sheaths

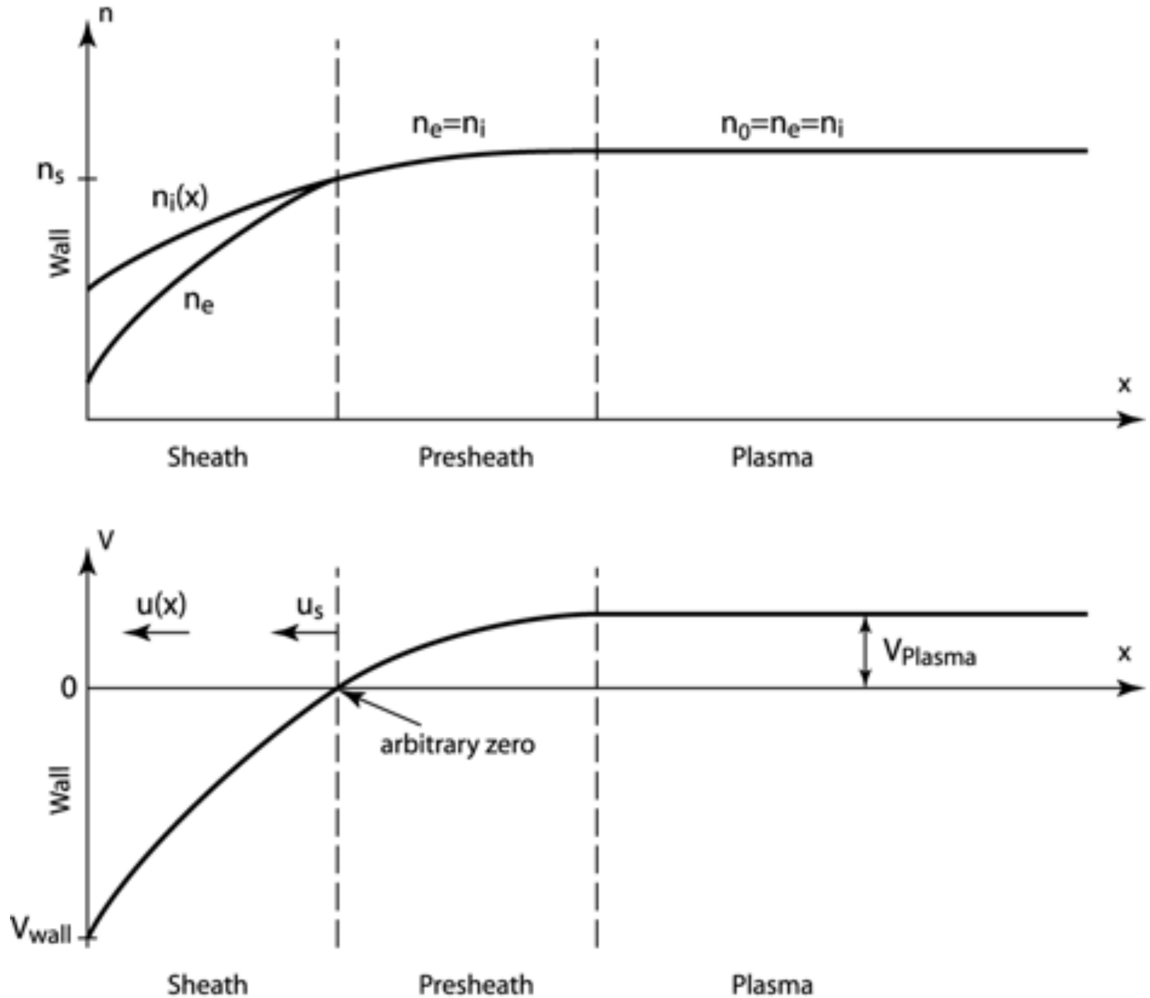
Xu Wang

Juliet Pilewskie, Hsiang-Wen Hsu, Mihály Horányi

SHIELDS Space Weather Workshop
April 4-8, 2016

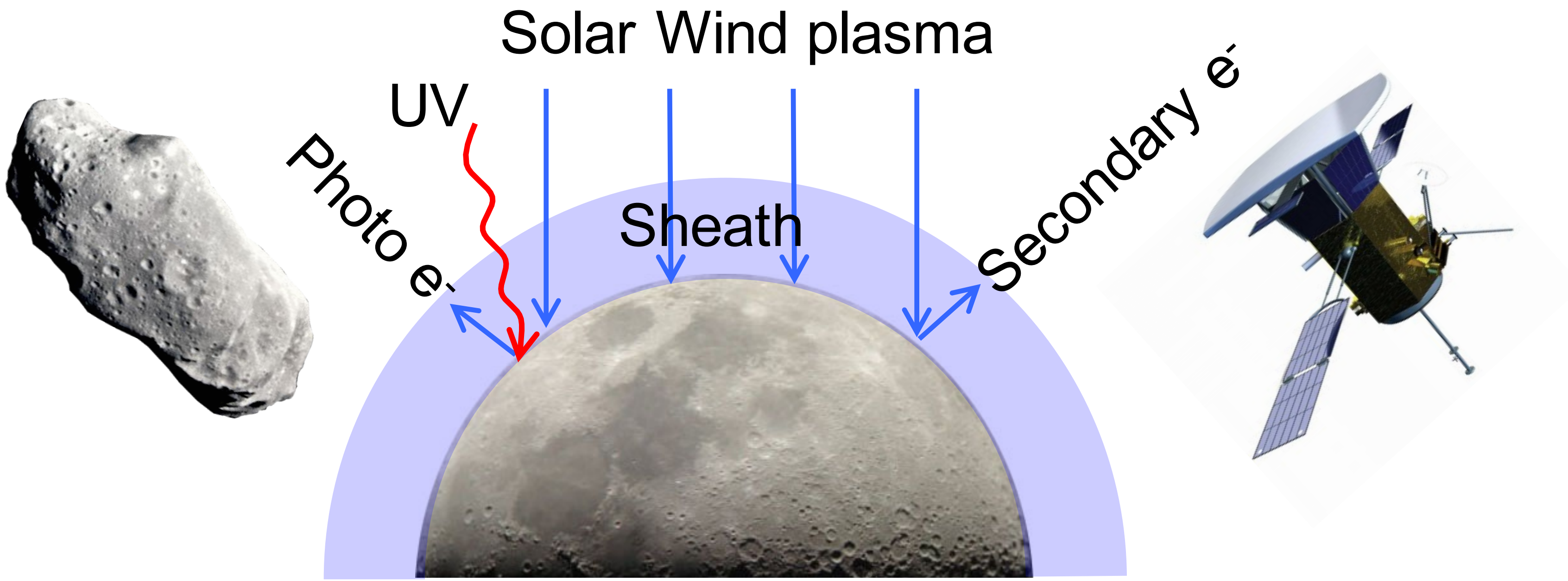
The formation of a plasma sheath

IMPACT



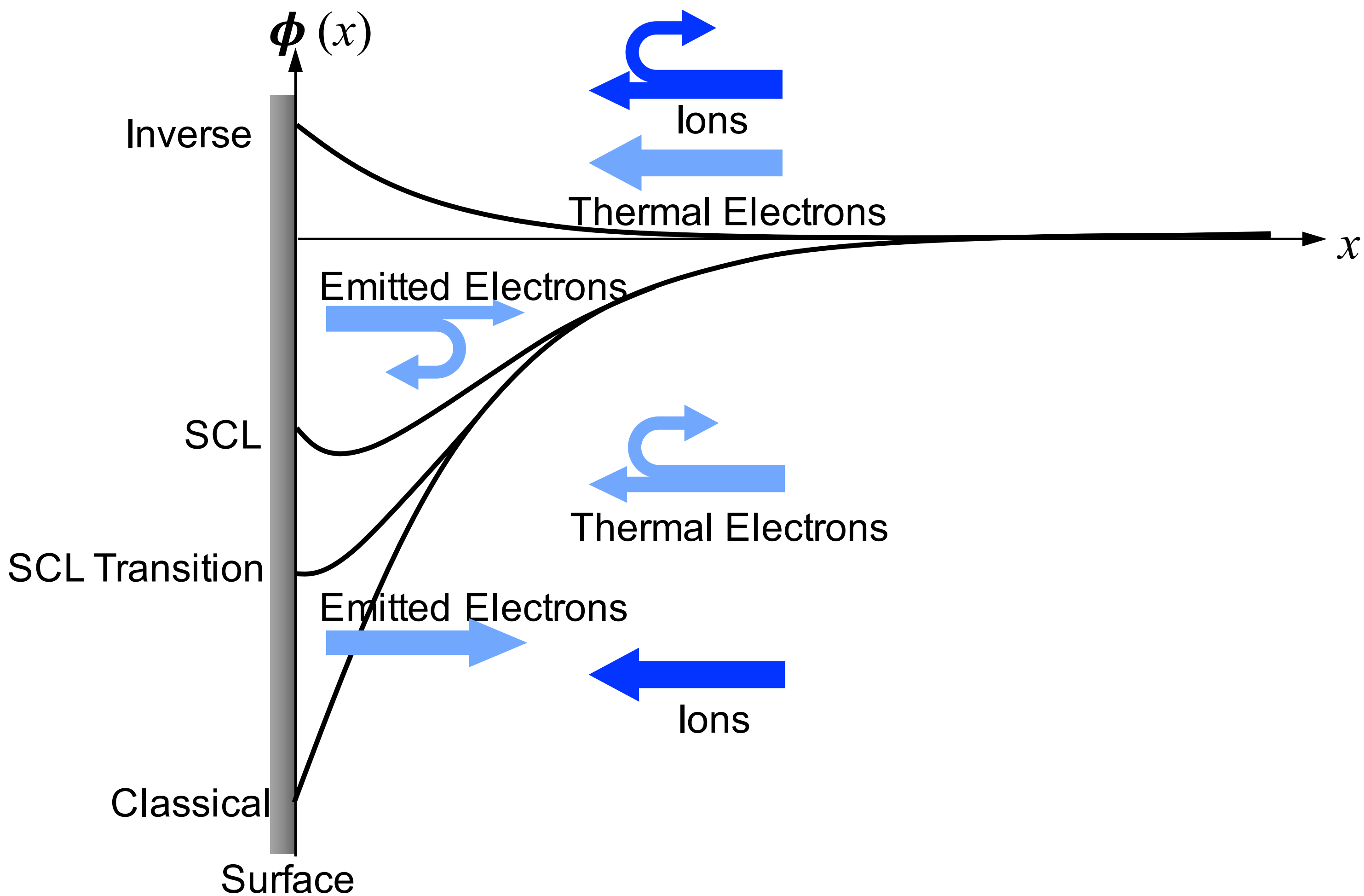
A sheath is a non-neutral region formed at a surface immersed in a plasma.

Sheaths around airless objects in space



- Surfaces in space emit electrons in addition to collecting electrons.
- Sheath structure can have large variations depending on the emission vs. collection fluxes

A variety of sheath formation

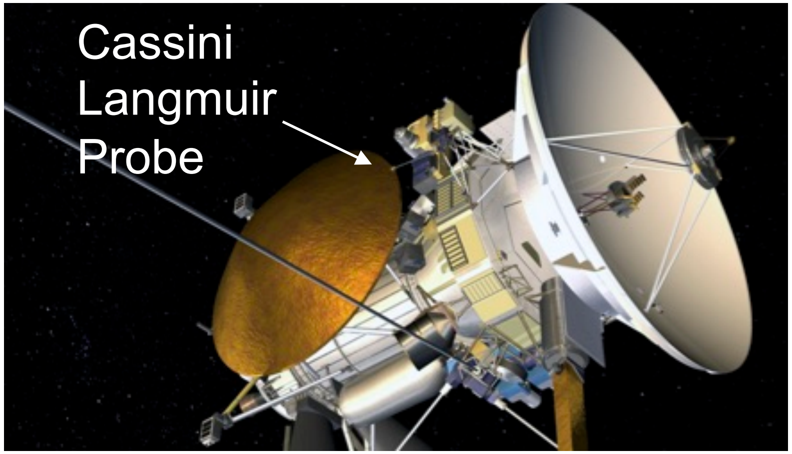


The importance of a spacecraft sheath problem

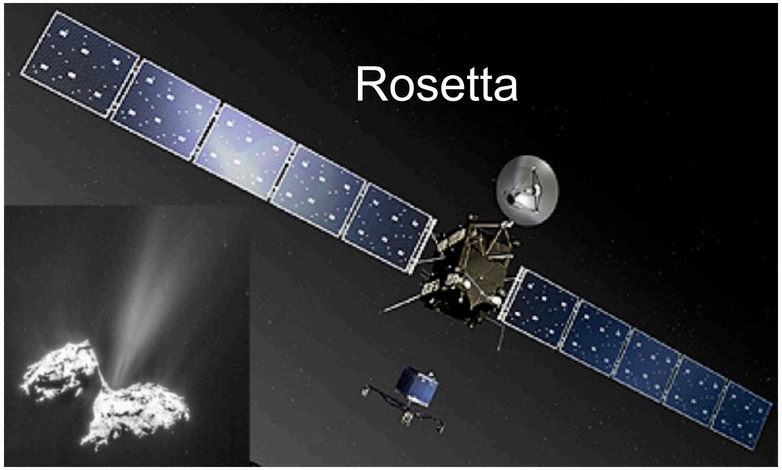
IMPACT

Sheaths around the spacecraft are an important problem for many in-situ instruments because:

- It can change the properties of charged particles collected by plasma instruments, such as energy, density, temperature. The sheath effect is prominent for low-energy particles.

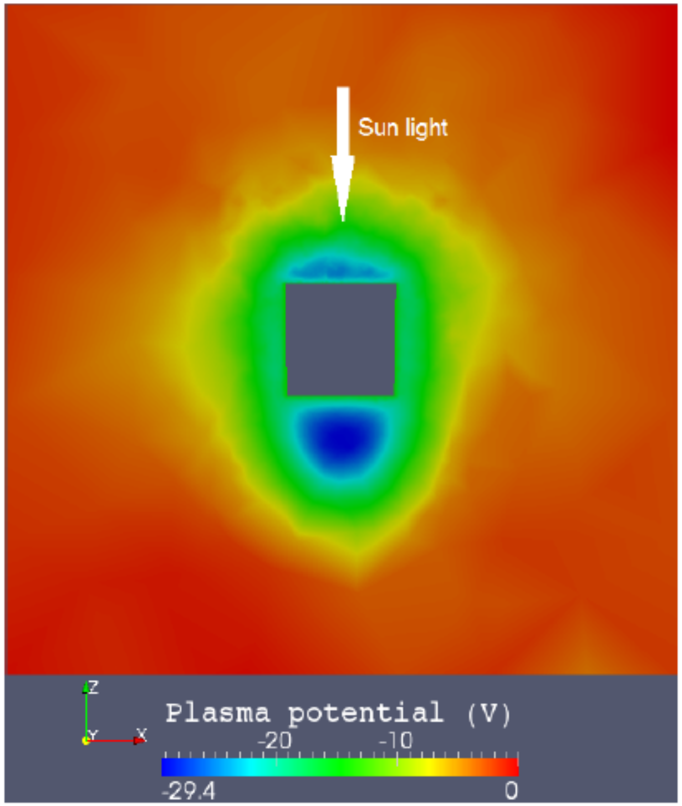


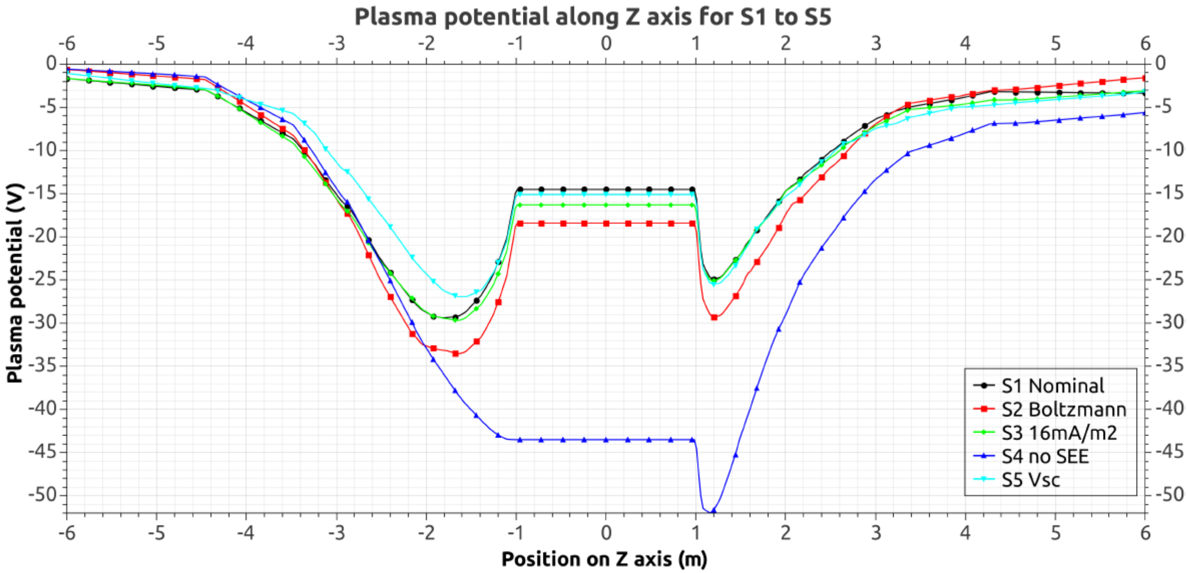
- It can also largely influence the properties of slow-moving charged dust particles collected by in-situ dust detectors, for example dust released from asteroid and/or cometary surfaces due to electrostatic forces and/or outgassing.



Sheaths around spacecraft

IMPACT





Simulation of potentials around Solar Probe Plus spacecraft in a near-Sun environment (Guillemant et al., 2012)

A simple theory

One-dimensional fluid model (Hobbs and Wesson, 1968)

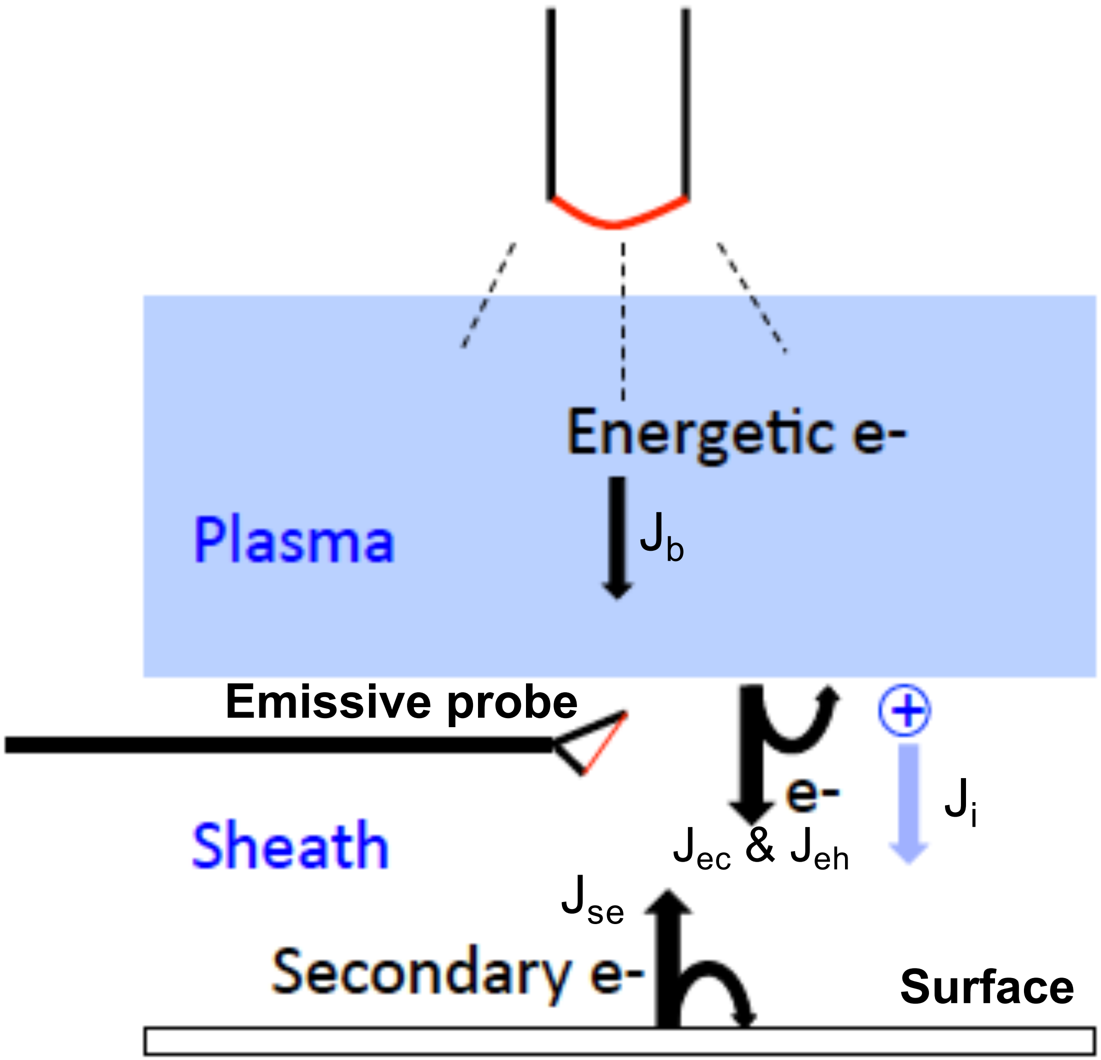
Assumptions: cold ions; Maxwellian electrons with a temperature T_e; and electrons emitted at the surface with zero energy.

At a critical emission the sheath transitions from classical to SCL with the electric field E at the surface equal to zero, so

$$e\phi_c' = 1.02\,T_e \text{ and } \Gamma_c = 1 - 8.3(m_e/m_i)^{1/2}$$

where ϕ_c' is the potential between the surface and plasma; Γ_c is the ratio of emitted to collected electron fluxes, and depends on the electron to ion mass ratio. Γ_c approaches and remains smaller than 1.

Experimental measurements



- **Fluxes to and from a surface:**
  - Primary beam electron flux: J_b
  - Thermal electron fluxes: J_{ec} (cold) and J_{eh} (hot)
  - Ion flux: J_i
  - Secondary electron flux: J_{se} created from J_b and J_{eh}.
- **An emissive probe is used to measure the potential profiles above the surface.**

The balance of the fluxes at the surface

$$J_b + J_{eh} + J_{ec} = J_i + J_{se}$$

where,

J_b is approximately constant ($2 - 2.3\times10^{-4}$ A m^{-2}).

$J_{ec,h} = en_{ec,h0}v_{thec,h}\exp[e(\phi - \phi_p)/T_{ec,h}]$, where $n_{ec,h0}$ is the densities of the cold and hot plasma electrons in the bulk and $v_{thec,h}$ is their thermal speeds; ϕ and ϕ_p are the potential in the sheath and the plasma potential in the bulk, respectively.

$J_i = en_0 (T_{ec}/m_i)^{1/2}$, where m_i is the ion mass and $n_0 = n_{ec0} + n_{eh0}$.

$J_{se} = J_{se0}$, for the monotonic classical sheath;

$= J_{se0}\exp[-e(\phi_{surf} - \phi_{min})/T_{se}]$, for the non-monotonic SCL sheath,

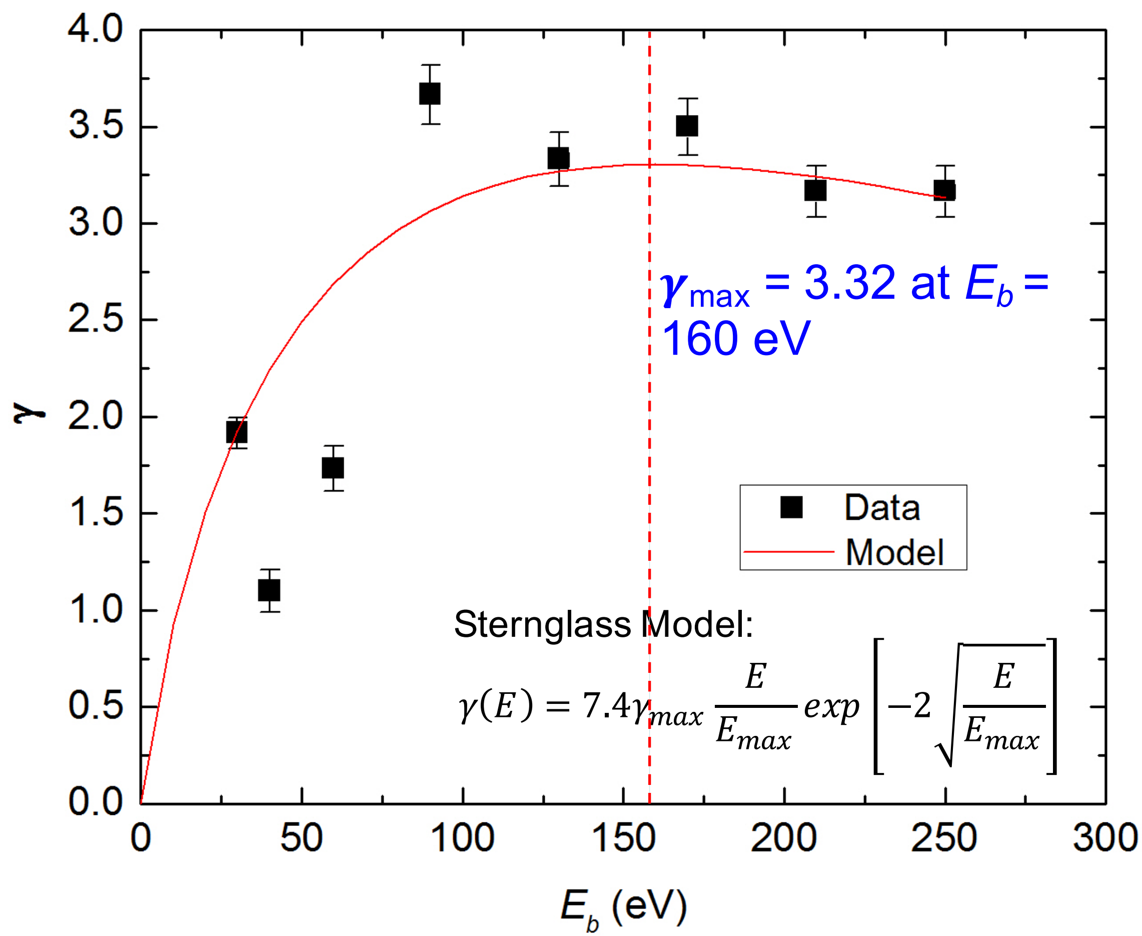
where J_{se0} is the total flux of the SEs emitted from the surface, ϕ_{surf} is the surface potential, ϕ_{min} is the potential minimum between ϕ_p and ϕ_{surf}. J_{se0} is created from J_b, J_{ec} and J_{eh} with a relationship in the following equation:

$$J_{se0} = \gamma(E_b - \phi')J_b + \sum_{T_e = T_{ec}, T_{eh}} en_{ec,h0}\int_{\phi''}^{E_b}\gamma(E - \phi')f(E, T_e)v(E)dE$$

where $f(E) = (1/E)^{1/2}[1/(4\pi T_e)]^{1/2}\exp(-E/T_e)$ and $v = (2eE/m_e)^{1/2}$. $\phi' = \phi_p - \phi_{surf}$ and $\phi'' = \phi_p - \phi_{min}$.

Secondary electron yields

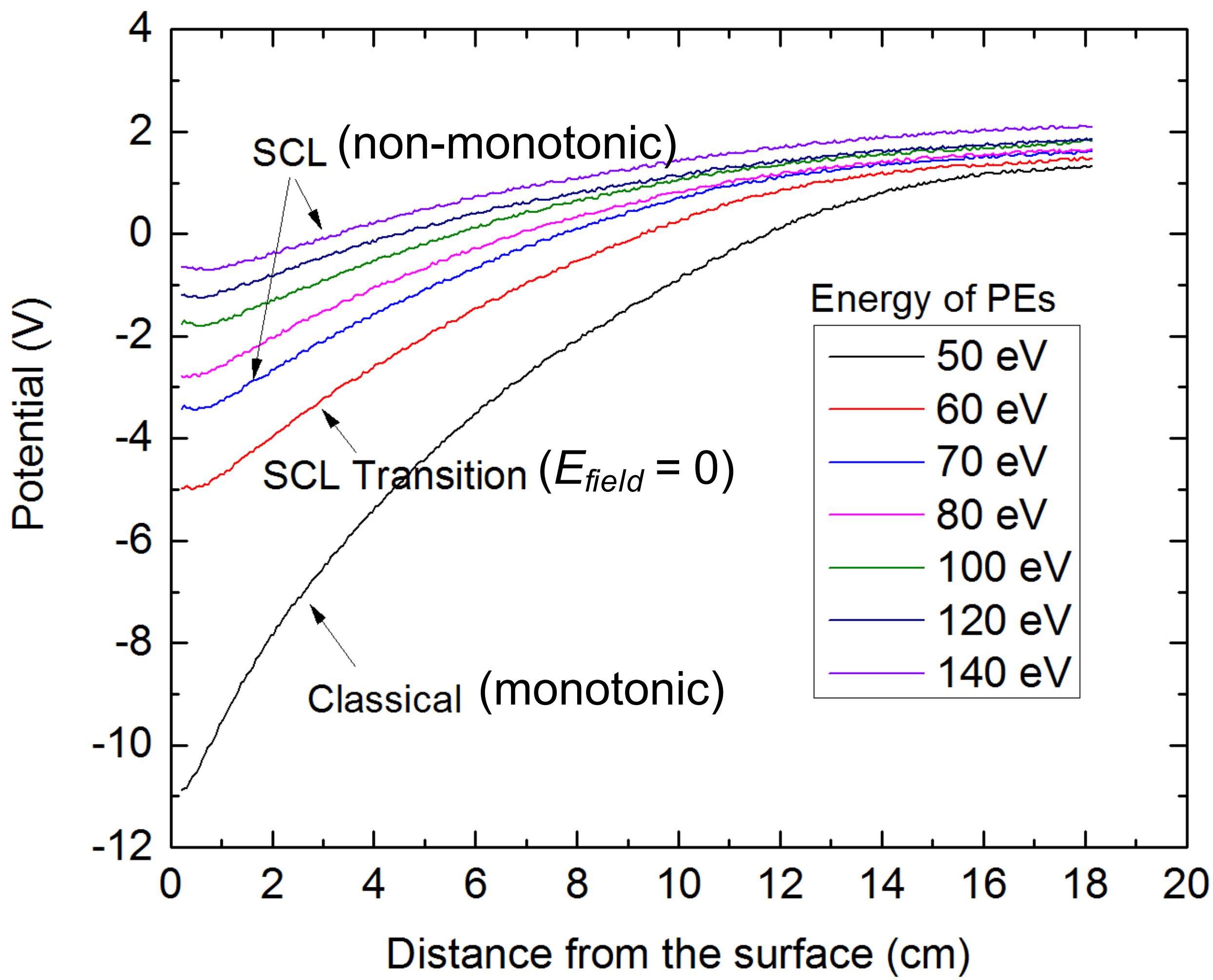
IMPACT



On a clean surface γ_{max} ~ 1 at 300 eV reported in the literature (Kanaya and Kawakatsu, 1972). The enhancement in our γ_{max} could be attributed to the surface oxidization and contamination (Baglin et al., 2000; Cimino et al., 2004).

Classical, SCL transition and SCL sheaths

IMPACT



By varying the energy of primary electrons (PEs), the sheath structure changes from classical Debye sheath to non-monotonic SCL sheath due to an increase in $\Gamma = J_{se0}/J_e$, where $J_e = J_b + J_{eh} + J_{ec}$ at the surface.

Classical to SCL sheaths

IMPACT

	E_b (eV)	n_{ec0} (10^5 cm^{-3})	T_{ec} (eV)	n_{eh0} (10^5 cm^{-3})	T_{eh} (eV)	λ_{De} (cm)	n_{se0} (10^5 cm^{-3})	λ_{Dse} (cm)	Γ
Debye sheath	50	1.8	2.3	0.5	11.2	2.3	0.36	6.8	0.968
SCL trans.	60	2.6	1.8	0.5	12.7	1.8	0.7	4.9	0.977
	70	1.8	2	0.4	15.6	2.2	0.83	4.5	1.019
	80	2.1	1.9	0.5	14.9	2	1	4.1	0.993
SCL sheaths	100	3	1.5	0.5	15.9	1.5	1.14	3.8	1.013
	120	3.2	1.4	0.5	16	1.4	1.25	3.6	1.001
	140	3.3	1.5	0.5	17.9	1.5	1.41	3.4	1.002

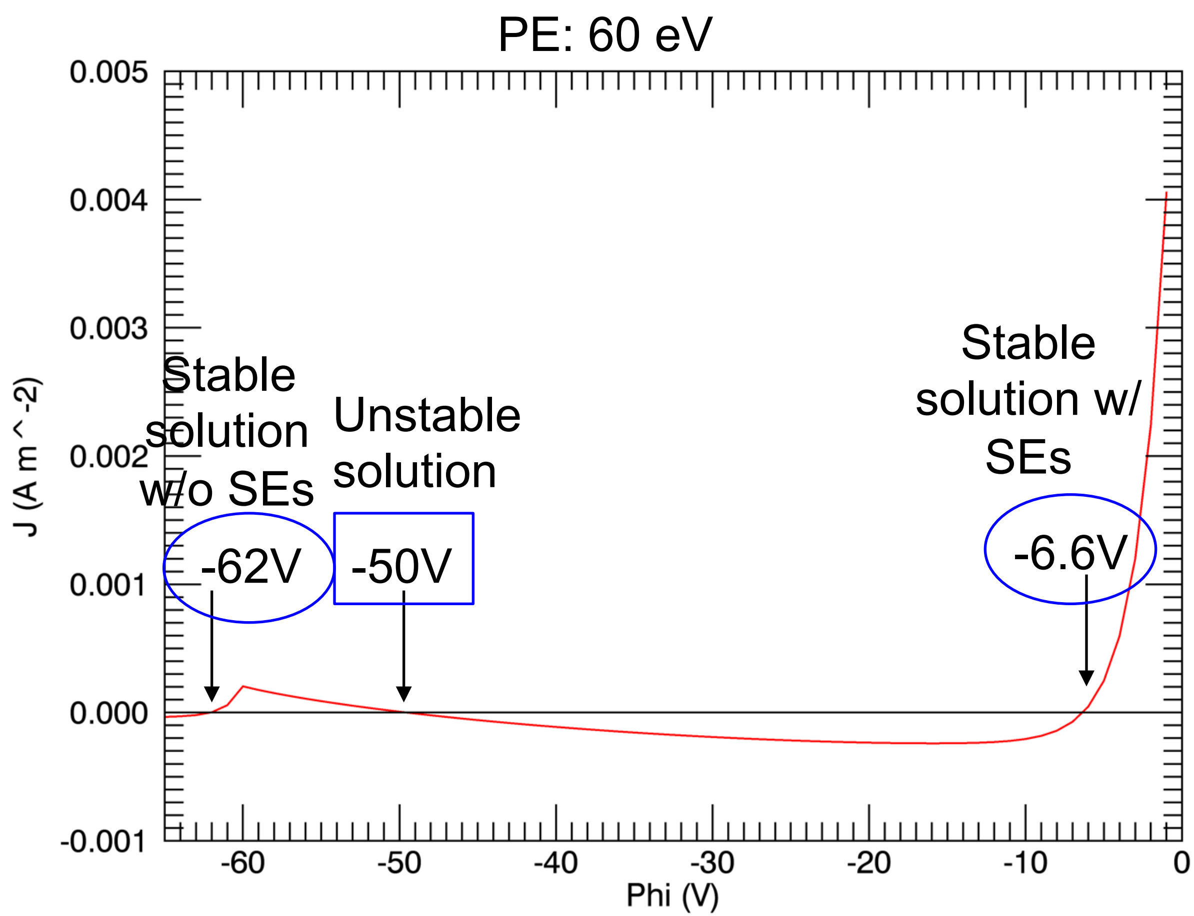
At the SCL transition (Γ approaches and remains smaller than 1),

Γ_c = 0.977 is in agreement with predicted 0.969 for Ar^+.

$e\phi_c'$ ~ 6.5 eV is between T_{ec} (1.8 eV) and T_{eh} (12.7 eV).

The surface potential at SCL transition

IMPACT

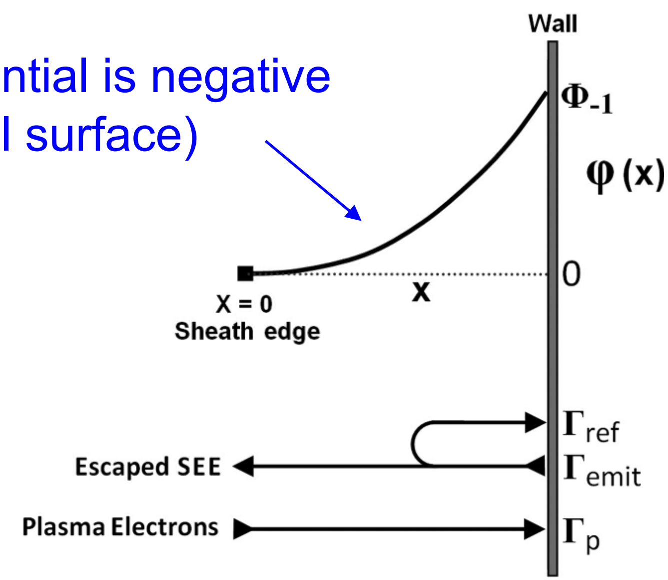


Three roots of $\phi' = \phi_{surf} - \phi_p$ from the flux balance equation.
The stable solution -6.6 V is in agreement with -6.5 V from the measurement.

Sheath structure in case Γ > 1

- Most works predict that non-monotonic SCL sheath forms when $\Gamma > 1$.
- Campanell (2013) also showed that an inverse sheath can also form, in which ions are trapped in the plasma and the fluxes of plasma electrons and escaped secondary electrons are balanced at the surface.

Inverse sheath
(The plasma potential is negative relative to the wall surface)

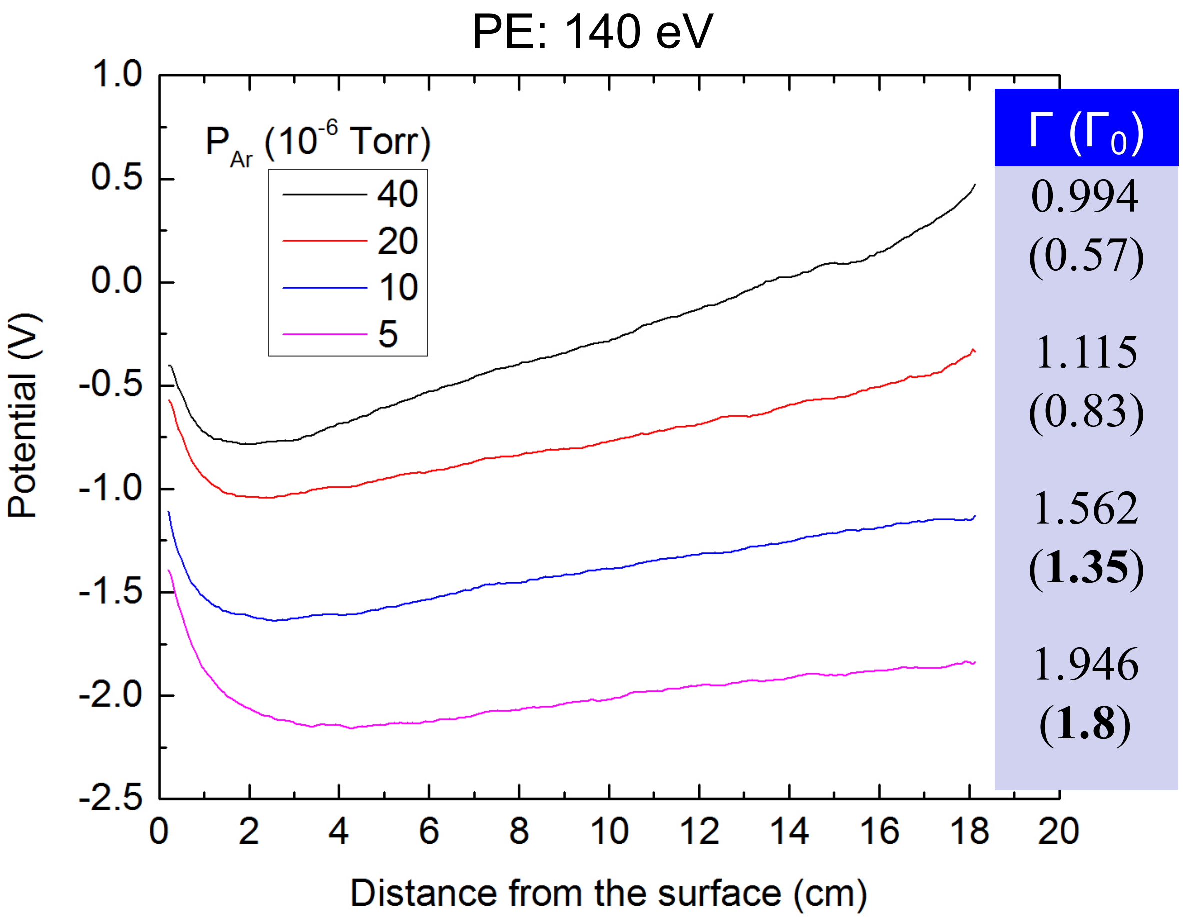


$$N_e = N_p + N_{emit} + N_{ref}$$

This can be a solution for $\Gamma_0 > 1$ with $\Gamma_0 = J_{se}/J_{e0}$, where J_{e0} is the plasma electron flux from the bulk plasma.

Sheaths in case $\Gamma > 1$

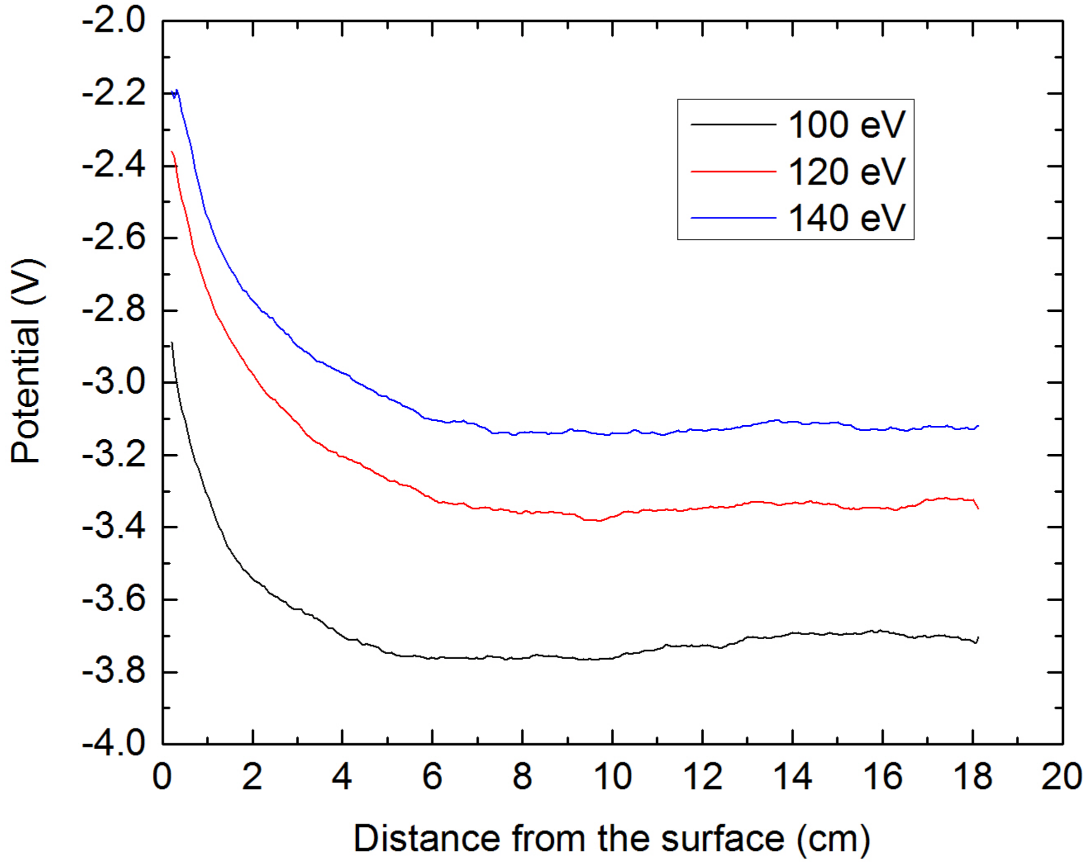
IMPACT



Non-monotonic structure persists for $\Gamma > 1$, indicating an SCL sheath solution is still a preferred solution over an inverse sheath solution that may also exist.

“Inverse sheaths”

IMPACT



Γ ~ 2 and the plasma electron density is very low with the Debye length larger than the measurement distance. The inverse sheath is more likely due to the domination of secondary electrons.

Conclusions

- We presented the first experimental measurements of all the three types of the sheath potentials: classical, SCL, and inverse.
- At the SCL transition in which $E_{field} = 0$ at the surface, the sheath potential $e\phi_c'$ was on the order of the electron temperature T_e, and Γ approached but remained smaller than 1, in agreement with the theoretical expectation.
- The nonmonotonic SCL sheath persists steadily for Γ>1.
- When the emitted electron density becomes larger than the plasma electron density, a monotonic inverse sheath forms with a positive surface potential relative to the ambient.

Backup slides

SCL to Inverse sheaths

IMPACT

P_{Ar} (10^{-6} Torr)	n_{e0} (10^5 cm^{-3})	T_e (eV)	λ_{De} (cm)	n_{se0} (10^5 cm^{-3})	λ_{Dse} (cm)	Γ
40	0.3	2.1	6.3	0.17	10	0.994
20	0.18	2.1	8	0.17	10	1.115
10	0.08	2.4	12.9	0.16	10.3	1.562
5	0.04	3	20.3	0.15	10.4	1.946
0.6	0.03	3.1	22.1	0.15	10.4	1.956