Secondary Ion Observations of Small Bodies for Remote SIMS Analyses

The ejection of the surface material is an unique and common feature for airless small bodies in space. In particular, the tenuous and transient atmosphere, called surface-based exosphere, around the Moon, Mercury and asteroids have been great of interest since the discovery of the alkali species by ground-based observations. Although the exosphere of the Moon is dominantly maintained by the photon-stimulated desorption (PSD) which preferably emits the alkali, there exist substantial amounts of the surface materials ejected due to the bombardments of the solar wind ions (sputtering).

In the planetary science, meteorites and returned samples were analyzed with Secondary Ion Mass Spectrometry (SIMS) for inspecting their compositions, evolutions, and ages. The laboratory SIMS utilizes primary ion beams to eject secondary ions which reflect the abundance of the target materials. In the interplanetary space, airless small bodies are exposed to the solar wind. In analogy with the laboratory SIMS, the solar wind ions can play a role of the primary ion beam that causes the secondary ion emission from the surface of small bodies. Since the secondary ions are picked up by the surrounding solar wind electric and magnetic fields, some of them reach the altitude of orbiters. Therefore, it was proposed that 'Natural' SIMS analyses of small bodies were performed by ion mass spectrometers on orbiters. Moreover, when the altitude is small compared to the sizes of the bodies, the composition mapping is possible by tracing the secondary ion trajectories back to their sputtering points.

Although the secondary ion emission yields by the sputtering depend on the chemical and physical parameters of the surface materials and primary beam even in the laboratory SIMS, it is believed that the SIMS analyses by orbiters have the potential to investigate the surface materials of small bodies. Based on the estimation of the secondary ion yields from the results of laboratory meteoroid analyses and numerical models, it is proposed that orbiter measurements of the refractory species relative to Si+ can determine the meteorite groups according primitive-type and geologically evolved parent bodies.

We utilized the data from the ion mass spectrometer on KAGUYA which completed 1.5-year observation of the secondary ions around the Moon. The observation results of the refractory species relative to Si+ showed that the lunar surface materials were not primitive but evolved, indicating that 'natural' SIMS analyses of small bodies by orbiters are possible.

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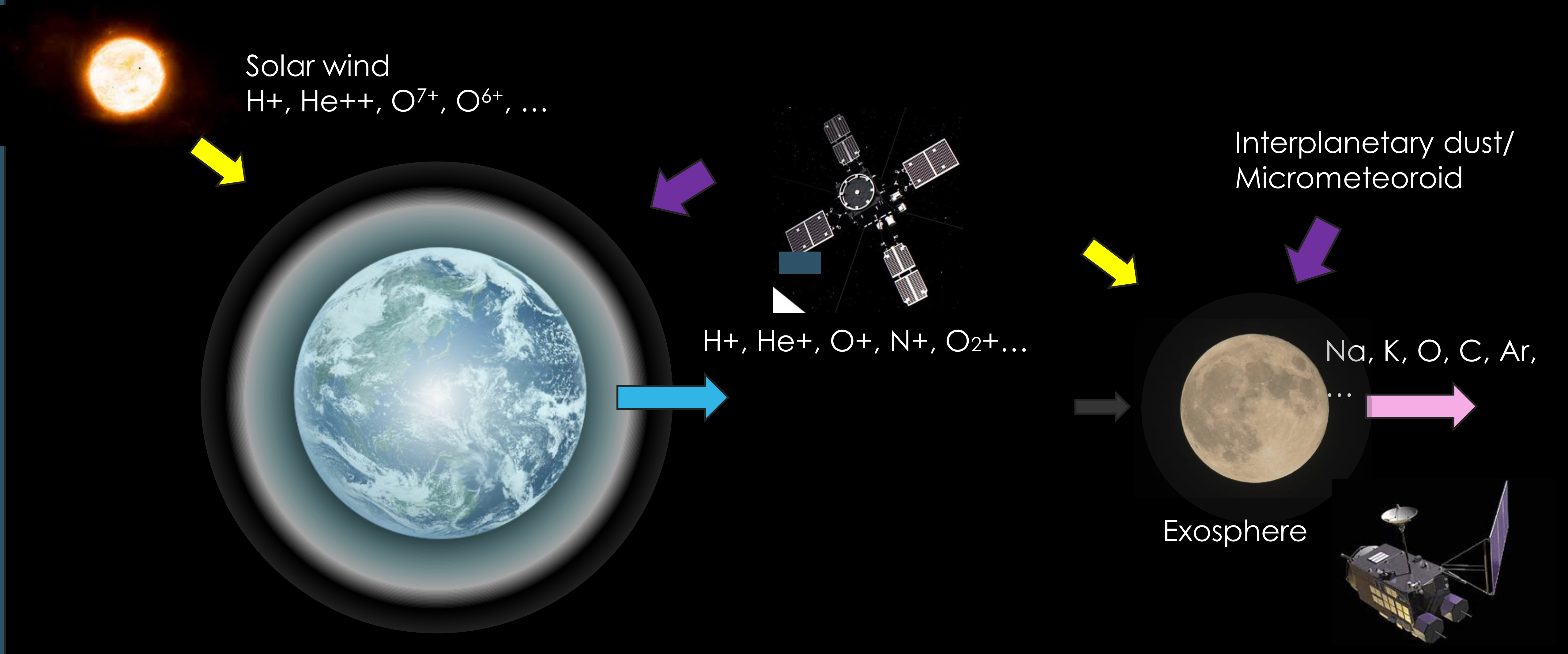
Ion observation in the interplanetary space



Small bodies

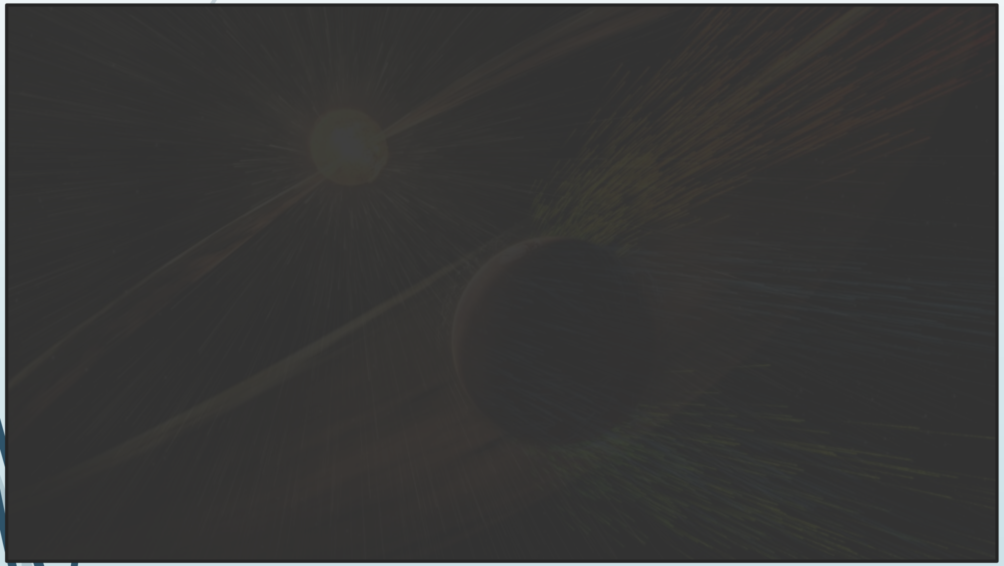
Can we obtain the chemical composition of the surface **remotely**?

Solar wind

- <u>Sputtering</u>, exosphere, wake, void, magnetic anomalies, charged surface, dust, …

(Natural) SIMS analyses of small bodies

Can The solar wind (1-10/cm^3, 400km → 10^8 H+/cm^2) play a role of the primary beam for SIMS analyses?



Primary beam: O_2^+, O^-, Ga^+, Cs^+, ~3 keV

1nA/10-um diameter → >10^{20} ions/cm^2

Small bodies

Lunar exosphere

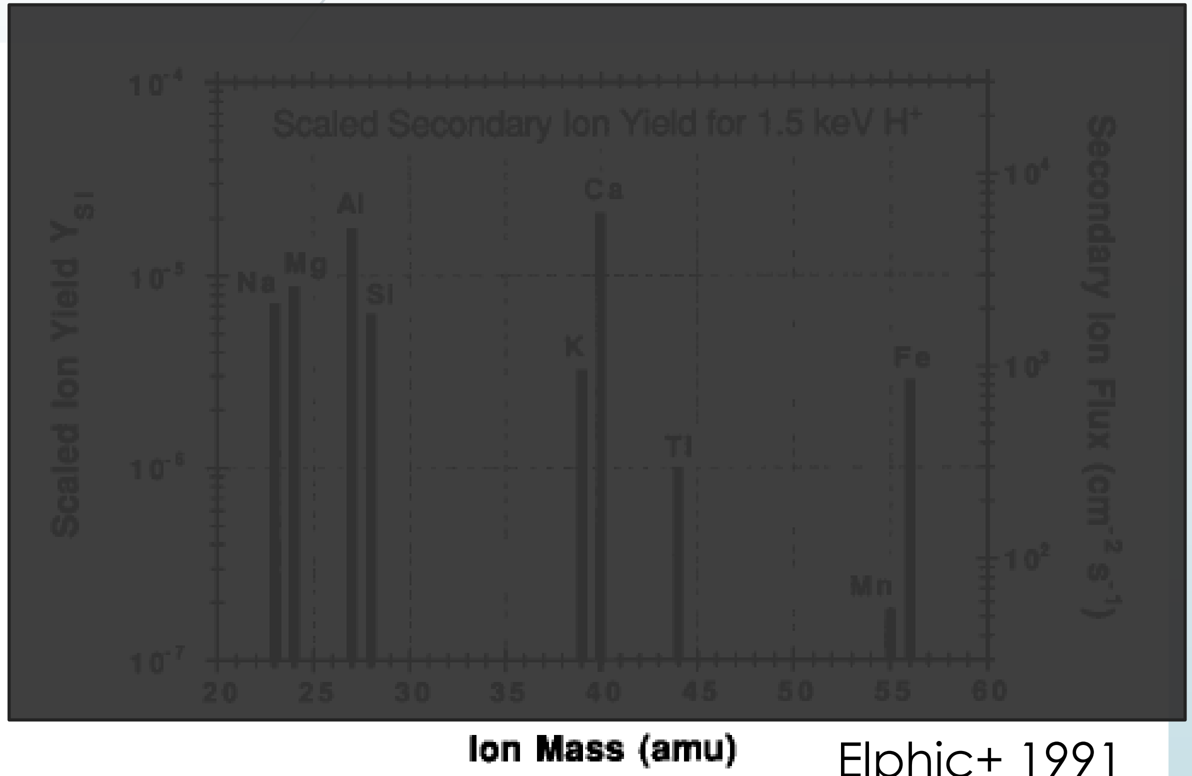
Species	Surface Density or tangent column density:	Sensed by:	Reported by:
^{40}Ar	$8 \times 10^4/cm^3$	LADEE NMS	Benna et al., 2015
He	$3 \times 10^4/cm^3$	LADEE NMS	Benna et al., 2015
Ne	$3 \times 10^4/cm^3$	LADEE NMS	Benna et al., 2015
Energetic H	~20% of incident SW flux	IBEX, Chandrayaan-1 SARA	McComas et al., 2009; Futaana et al., 2012
H_2	10-50% of incident SW flux	LRO/LAMP	Stern et al., 2013; Hurley et al., 2017
CH_4	$450/cm^3$	LADEE NMS	Hodges, 2016
Na	$5 \times 10^9/cm^2$ column	LADEE UVS	Colaprete et al., 2016b
K	$4 \times 10^8/cm^2$ column	LADEE UVS	Colaprete et al., 2016b
Ti	TBD*	LADEE UVS	Colaprete et al 2016a
Fe	TBD*	LADEE UVS/meteor streams	Colaprete et al 2015
Al	TBD	LADEE UVS	Colaprete et al 2015
Ca	TBD*	LADEE UVS/meteor streams	Colaprete et al 2015
Mg	TBD	LADEE UVS	Colaprete et al 2016a
O	TBD*	LADEE UVS/meteor streams	Colaprete et al 2015
OH	TBD*	LADEE UVS/meteor streams	Colaprete et al 2015
H_2O	$> 100/cm^3$	LADEE NMS/meteor streams	Benna et al 2015b

Noble gasses and volatile elements are selectively desorbed.

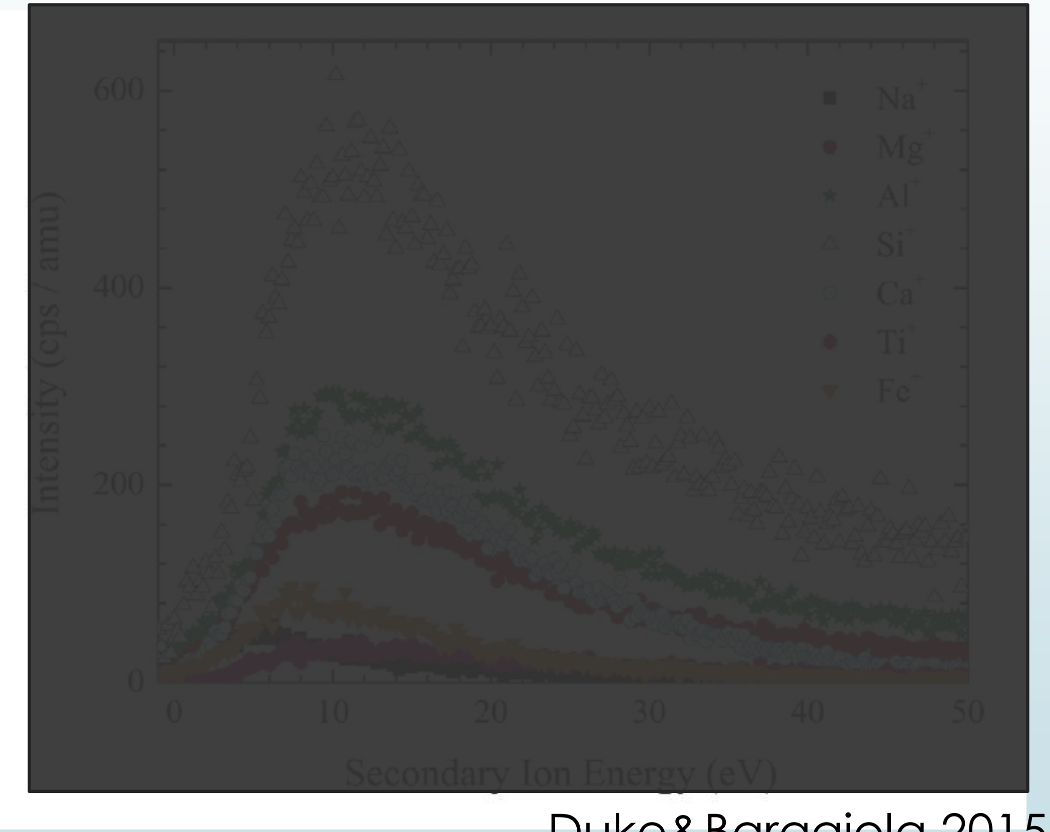
Small bodies

Lunar mare soil 10084 & 4-keV He+

Lunar soil simulants & solar wind-like ion beams



Elphic+ 1991

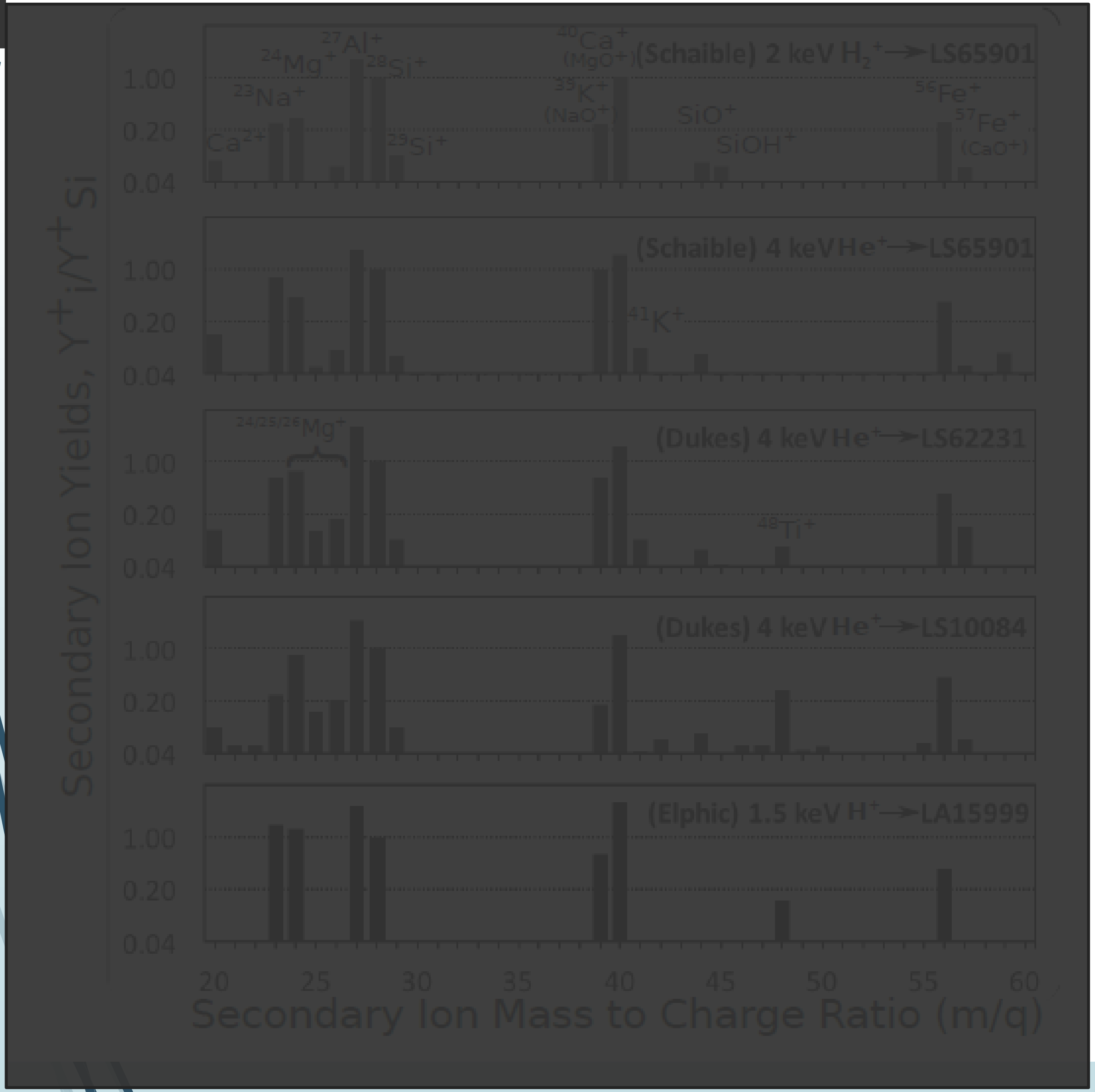


Duke&Baragiola 2015

Solar wind ions possibly make secondary ion emissions.

Small bodies

How are secondary ions emitted?



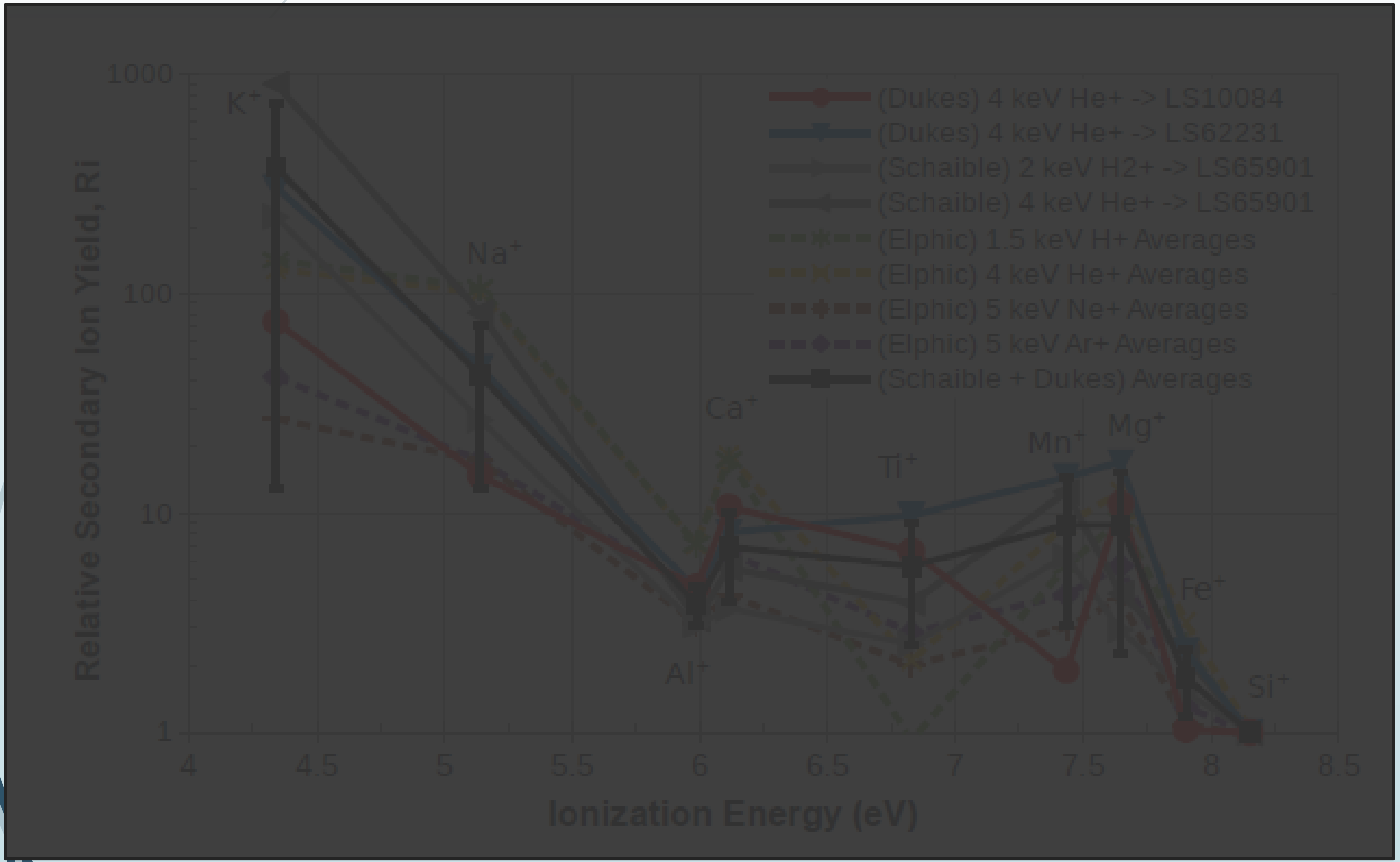
Secondary ion emissions are different in different experiments.

Ratios to Si+ are relatively stable.

Elphic et al., 1991
Dukes&aragiola 2015
Schaible 2014

Small bodies

How are secondary ions emitted?



Elphic et al., 1991
Dukes&aragiola 2015
Schaible 2014

Ion yields strongly depend on their ionization energies.

How are secondary ions emitted?

TRIM/SRIM

poorly simulate it for primary beam less than10keV, (Ziegler et al., 2008)

include no time variations of the surface composition and structure

←Weak beams (SW) preferentially emit oxygen, causing O depletion (Dukes&Baragiola, 2015)

SDTrimSP

well simulate it for primary beam less than10keV (Hofsäss et al., 2014)

include time variations of the surface&material depletion (Mutzke et al., 2011)

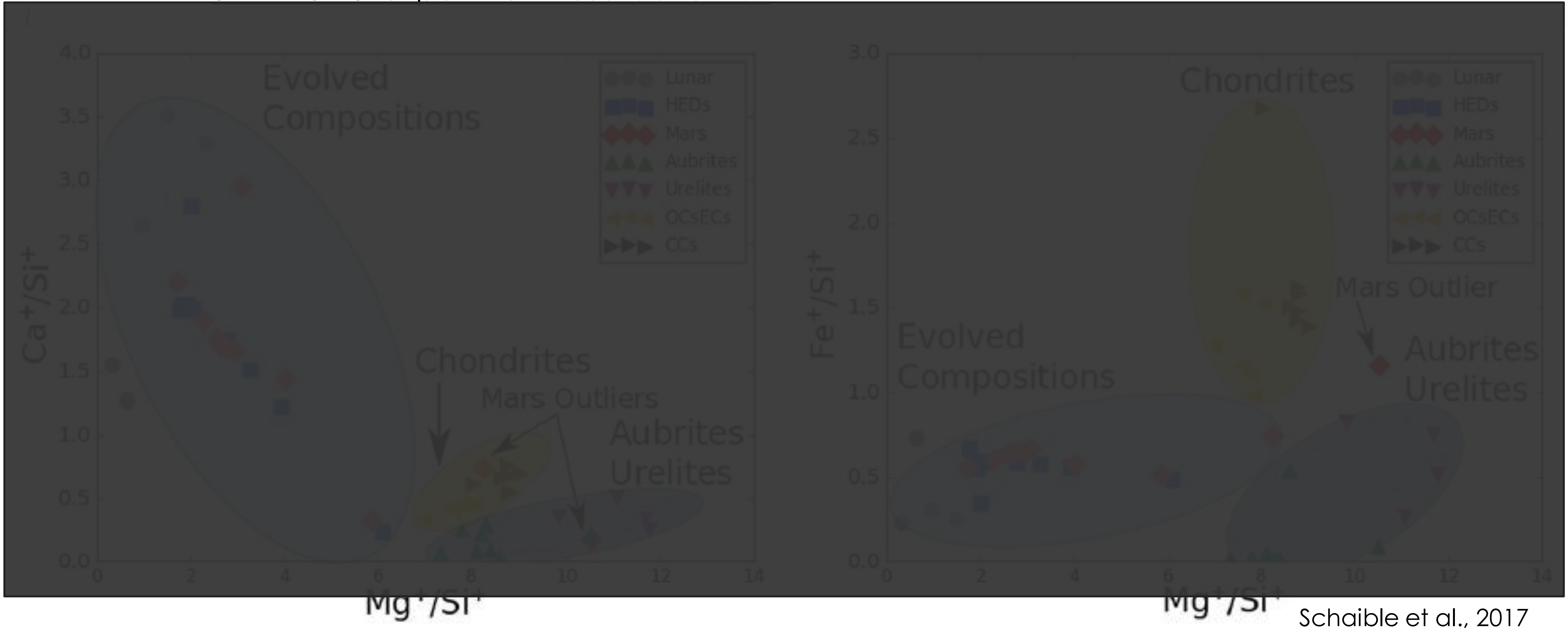
#Neither crystallization, chemical effects, nor surface topography are considered in both models.

SDTrimSP well simulate the secondary ion yields due to the solar wind sputtering.

Schaible et al., 2017

(Natural) SIMS analyses of small bodies

SDTrimSP & experiment results show …



Schaible et al., 2017

Secondary ion yields indicate whether a body is primitive or has undergone geologic reprocessing.

Data


KAGUYA
Jan. 2008-Jun. 2009
MAP-LMAG → B
MAP-PACE-IEA → Vsw
IMA → Secondary ions

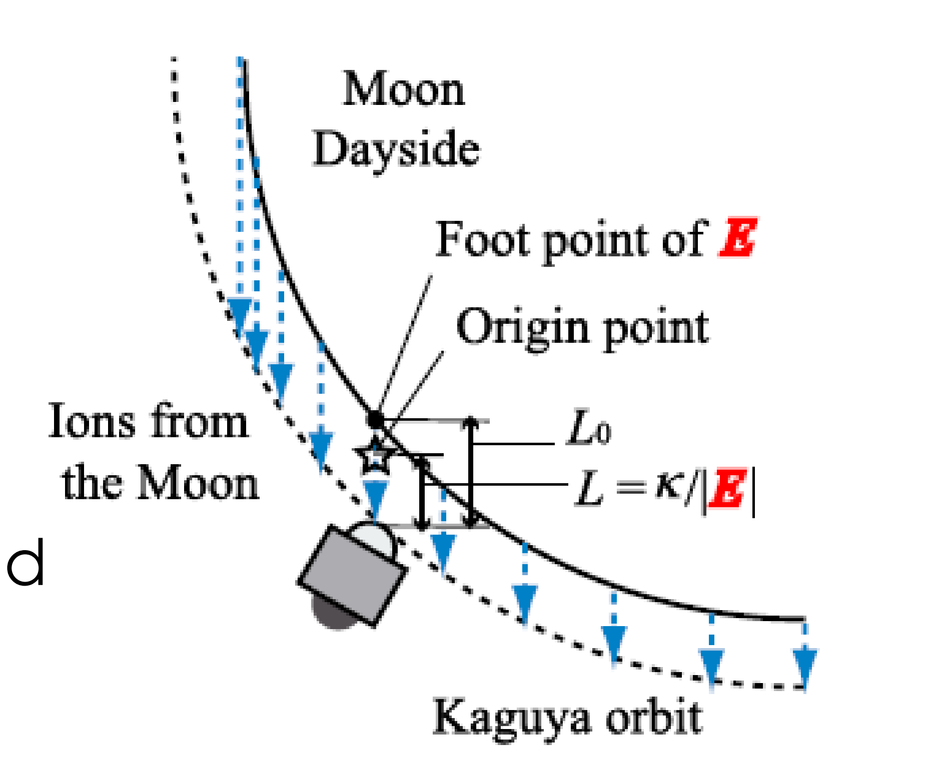
(Natural) SIMS analyses of small bodies

Solar wind (1-10/cm^3, 400km, 5nT)

Secondary ions are emitted from the surface.

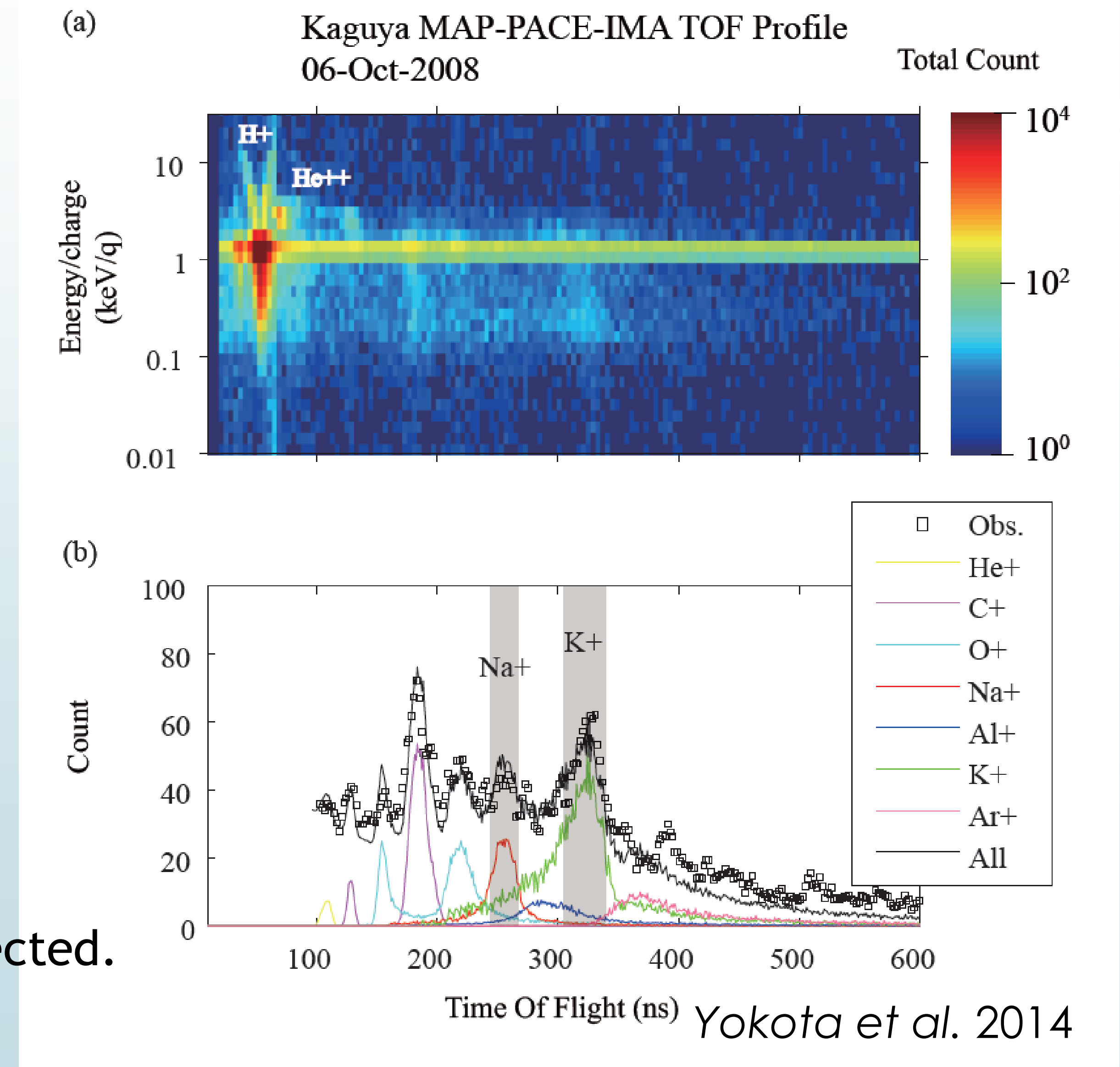
Secondary ions are picked up by the solar wind and reach the orbiter altitude.

Ordinary orbiters and ion analyzers can achieve it without landers and rovers.



Observation of secondary ions by Kaguya

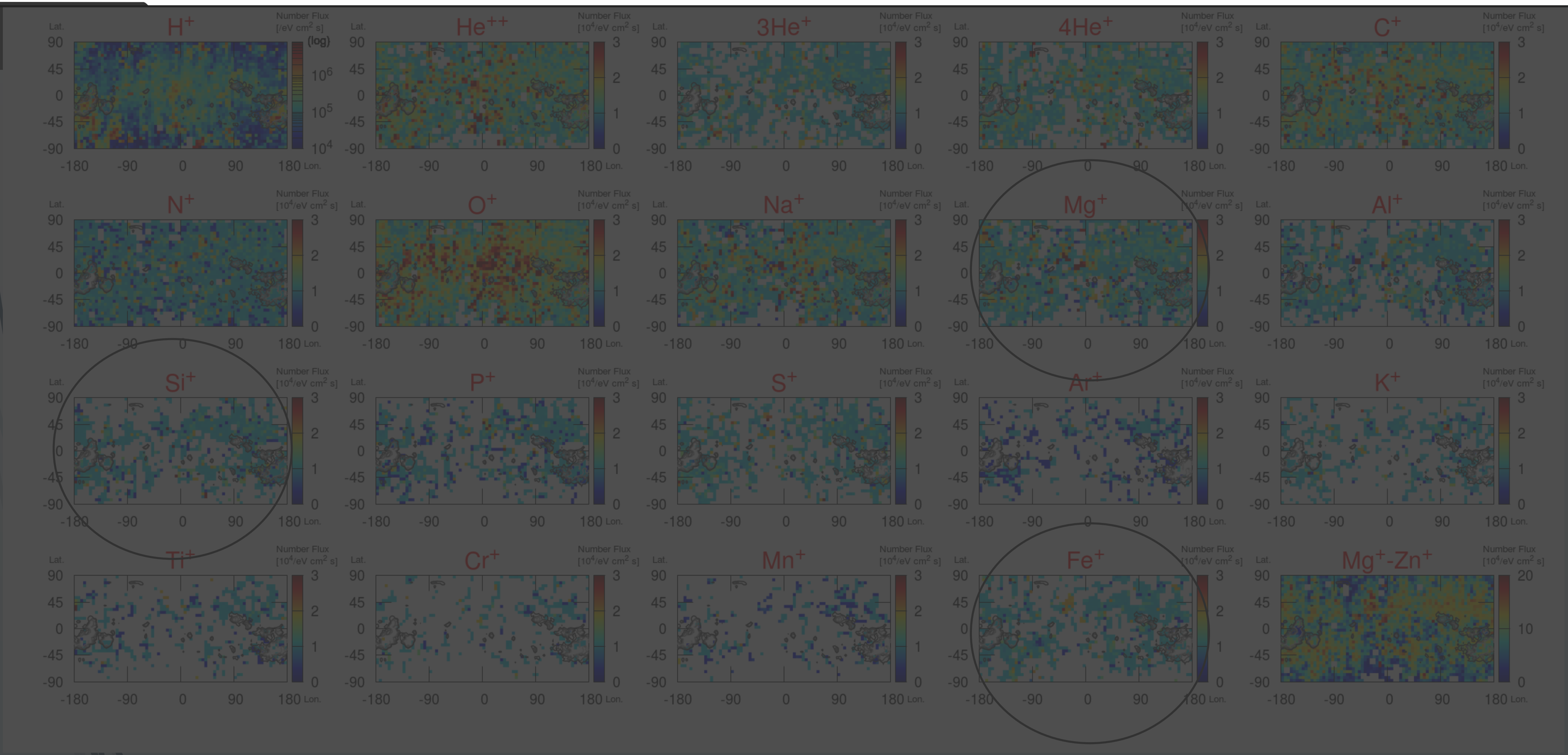
- SW : H+, He++
- Scattered SW ions : H+.
- Secondary ions :
  He+, C+, O+, Na+, K+ (Al+, Ar+)



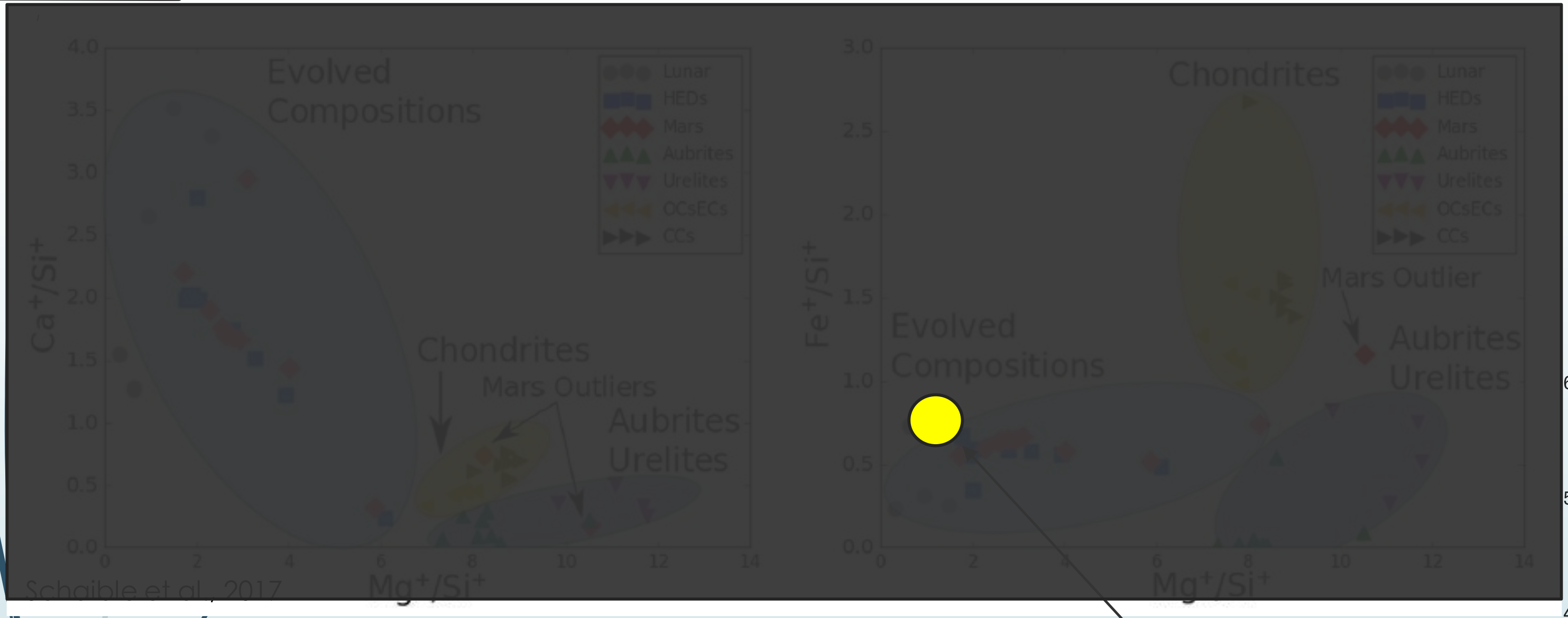
Yokota et al. 2014

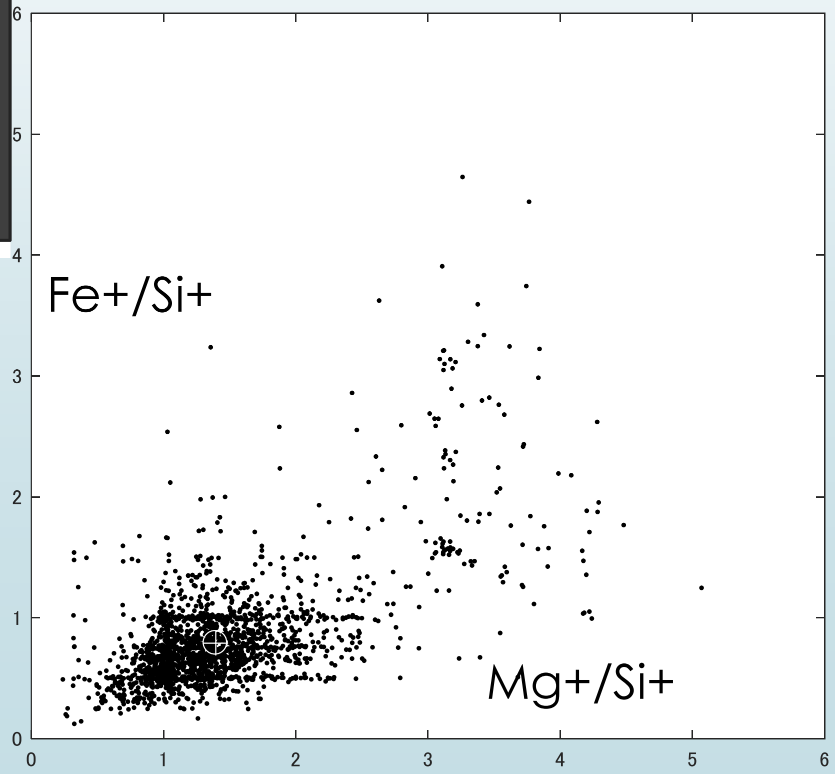
Fluxes of 10^3 ~10^4(ions/s cm^2) can be detected.

Observation of secondary ions by Kaguya



(Natural) SIMS analyses of small bodies





KAGUYA obs. shows that the lunar materials are evolved composition,

→supporting not capture but giant impact theory

summary

- Ordinary space-borne ion mass spectrometers for space plasma missions can be a tool to analyze the surface materials of small bodies remotely (at orbital altitude).

Model calculations & laboratory experiments (Schaible et al., 2017)

Observation of the Moon （Kaguya）

MMX(Martian Moons eXplanation)

・ガンマ線・中性子分光計：地下の物質分布、特に氷が存在の有無を調査

・広角分光カメラ：7つの画像センサを用いて、7色の画像を同時に取得

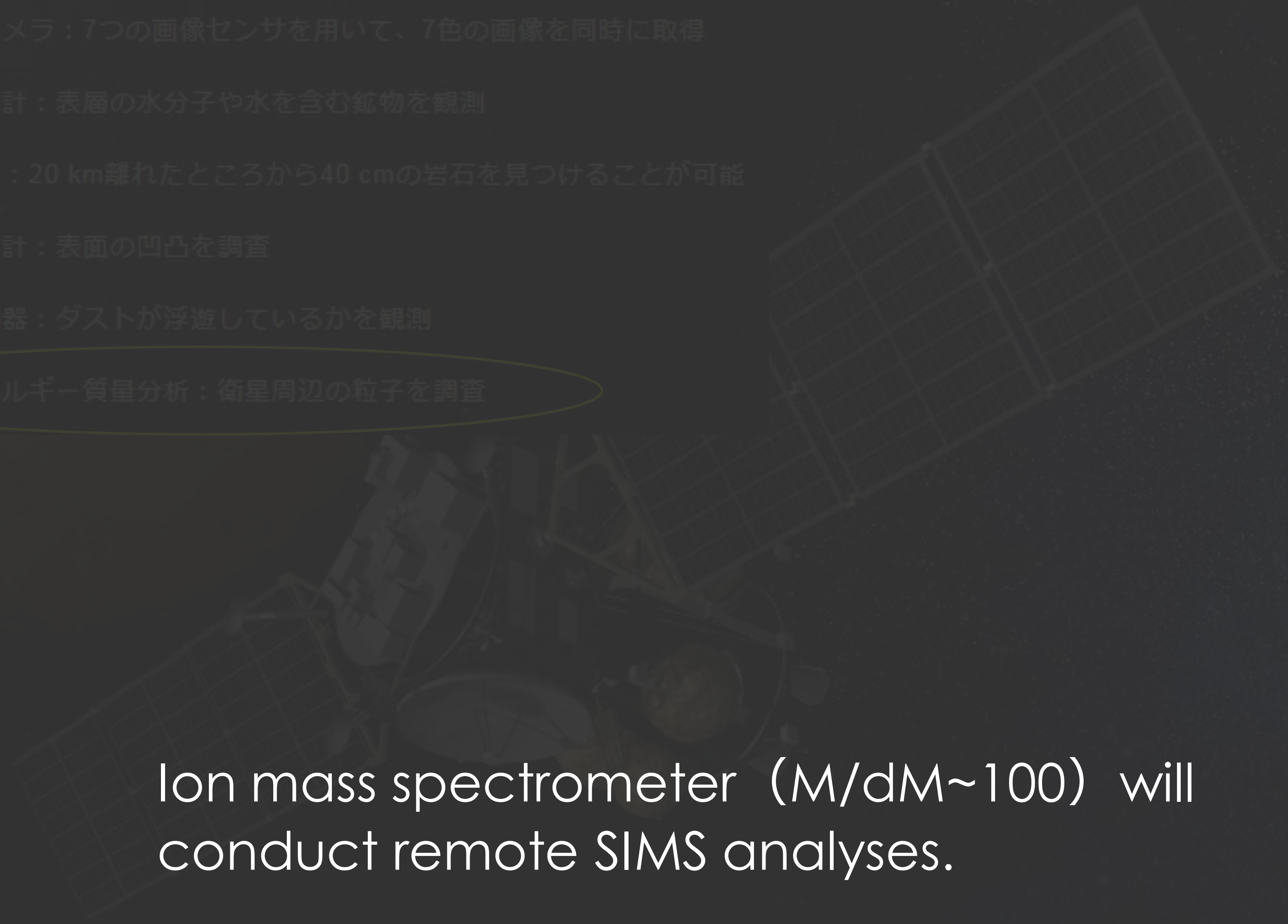
・近赤外分光計：表層の水分子や水を含む鉱物を観測

・望遠カメラ：20 km離れたところから40 cmの岩石を見つけることが可能

・レーザ高度計：表面の凹凸を調査

・ダスト計測器：ダストが浮遊しているかを観測

・イオンエネルギー質量分析：衛星周辺の粒子を調査



Ion mass spectrometer（M/dM~100）will conduct remote SIMS analyses.