METAL: A mission proposal to study **natural & anthropogenic metallic ions** in the ionosphere

M Yamauchi (IRF) and the METAL team

ESA "mini-Fast" class

- Aiming 5-year from selection to launch
- Exploratory (=virtual) call in 2025
- 11 out of 34 proposals passed "virtual" screening
- METAL is one of 11 proposals
- Real call later this year ???

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Why Metallic ions @ ionosphere?

A1: Very limited source

- Low charge-state = Only "**near mesopause**" (h=80-130 km) or **Moon**

A2: Different ionospheric chemistry from major volatiles (N^+, O^+, N_2^+, NO^+, and O_2^+)

- Fe^+ is fully ionized at >130 km: ⇒ Detected Fe^+ (& air-mass) = from < 130 km
- cf. N^+ and O^+ re-combine easily ⇒ Not easy to guess the source altitude
- With convection data (e.g., radars), source lat./long. can be traced back

➔ unique tracer of **transport from < 130 km** (including physical & chemical processes)

A3: Ionosphere can be contaminated by anthropogenic ions

- cf. **Mesosphere** is already contaminated by **ablated elements** during atmospheric re-entry of **space waste** (= used satellites/rockets + debris)

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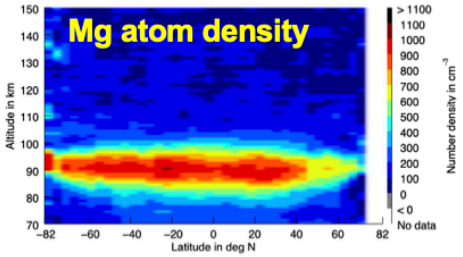
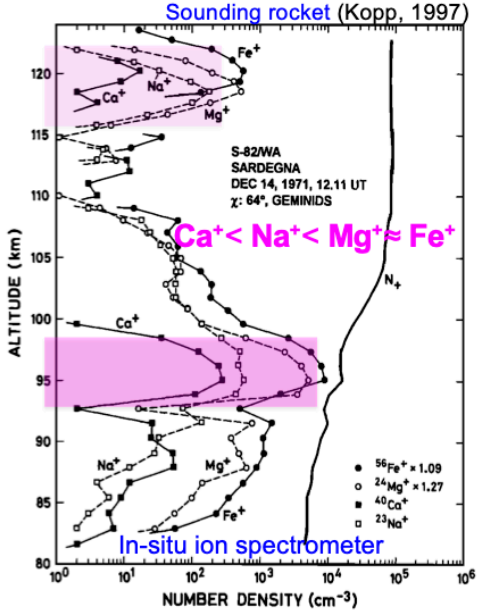
What we know is
source = "Metal layer"

Line-of-sight integration by Envisat/optical spectrometer (Langrowski+, 2015)



Metal layers: a thin (< 10 km) layer of metallic atoms/ions at around **80-130 km** altitude.

Sounding rocket (Kopp, 1997)



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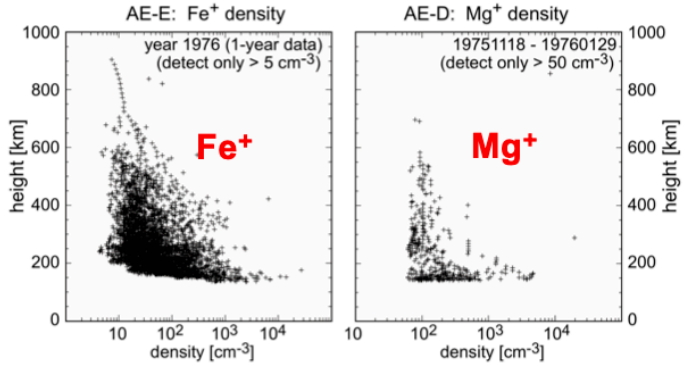
Old in-situ observations indicates upflow



But no in-situ observation @ > 130 km for nearly 50 year

⇒ Nearly no knowledge yet on **(Q1) How & How much of What species** are lifted up **from the metal layer to the exobase**

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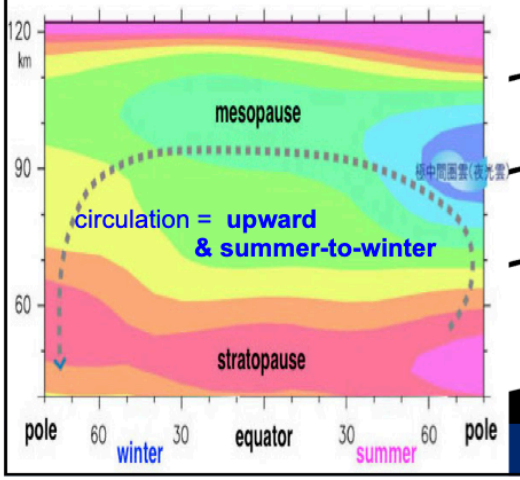
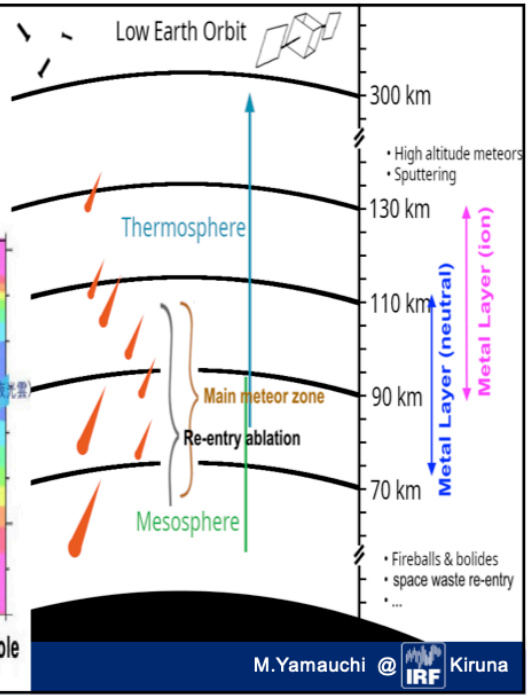
Gathering @mesopause

= Applies to space waste too !

⇒ Can be lifted up further after ionized:

= polluting even ionosphere?





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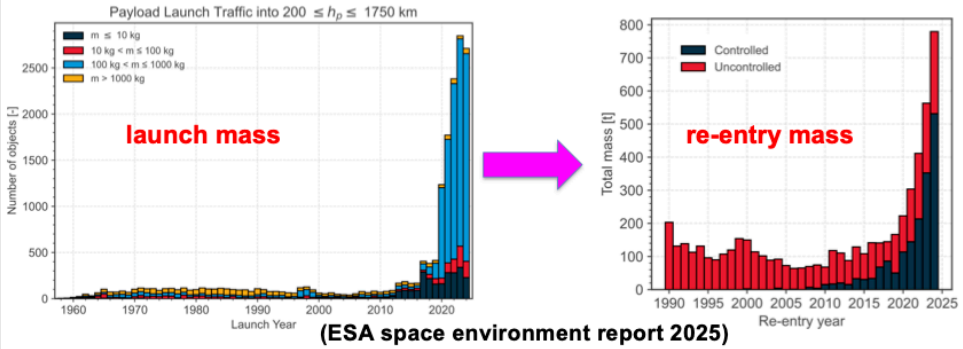
Emerging question: ablation of re-entering space waste



(ESA space environment report 2025)

- **Half the re-entry mass is ablated** (mainly in the mesosphere)
- **Space waste contains more "rare metals" than meteoroids**

⇒ For some elements, **space waste origin may exceed natural origin** in the mesosphere (& stratosphere/ionosphere)

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Is any element already "polluting"? **YES**

Estimated influx from space (Schulz+ 2026)				Available remote observation	
element		space waste (2024)	meteoroid	ground lidar	satellite limb scan
Li	m=7	2 t/y	0.02 t/y	< 105 km	
F	m=19	8 t/y	1 t/y		
Na	23	0.2 t/y	60 t/y	< 150 km	50-120 km
Mg	24	5 t/y	1400 t/y		100-150 km
Al	m=27	400 t/y	140 t/y		
Si	28	20 t/y	1800 t/y		
K	39	0.1 t/y	8 t/y	< 130 km	75-105 km
Ca	40	1 t/y	90 t/y	< 130 km	
Ti	m=48	40 t/y	8 t/y		
Fe	56	80 t/y	2500 t/y	< 150 km	(100-340 km)
Ni	m=58	30 t/y	100 t/y	< 105 km	
Cu	m=63	50 t/y	2 t/y		
Ge	m=74	1 t/y	0.5 t/y		
Nb	m=93	12 t/y	< 0.01 t/y		
heavier		> 10 t/y	< 1 t/y		

Monitoring them is difficult ⇒ But **they may reach satellite altitude**!

⇒ **(Q2) How much** is ionosphere **polluted by anthropogenic ions** of space waste origin?

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In-situ measurement requirement

Q1: Uplifting mechanism ⇒ We target Fe^+ and Mg^+ @ **h > 300 km**

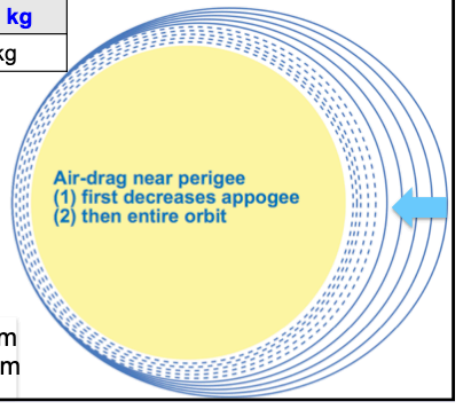
Q2: Anthropogenic pollution? ⇒ we target Cu^+ and Li^+ @ **h < 300-350 km**

⇒ Can answer them with ion mass spectrometer (INMS) on board METAL

Instrument	m/Δm	m	E/ΔE	Weight
INMS+ (Juice*)	**>700**	**1–63+**	**no**	**10 kg**
IMA (MEX/optional)	≥4**	4–40+	8%	4 kg

* Upgrading from Juice from (TRL to be 7 in 2027)
** After combining energy distribution

⇒ INMS can even measure volatile ions (important reference to metallic ions)



Schematic (exaggerated) illustration of METAL orbit

300 km x 1000 km ⇒ <300 km x ~300 km
⇒ ~200 km x ~200 km

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Related observations

(a) metallic ions/atoms: Lidar, Sounding Rocket, Satellite optics (limb can)

(b) convection: Radars (e.g.,EISCAT, SuperDARN), **Fabry-Perot, Geomag**

⇨ The mission team includes them

Summary of METAL

By **in-situ measurement** of metallic ions, **METAL** addresses the following overlooked basic questions for the first time:

Q1: How and how much are metallic ions, the best tracer in the ionosphere, **lifted up in various conditions?** This includes locations of both physical and chemical processes.

Q2: How much is the ionosphere polluted by ablated anthropogenic metallic ions originating from space waste?

The **ground-based observations** (particularly by radars) **enhances** the science output for both Q1 and Q2.

Technical summary of METAL

skip

Piggy-back of any LEO satellites, as long as meeting:
- Initial perigee: ideally <300 km (< 350 km is acceptable)
- Initial apogee: ideally ~ 1000 km (500-600 km is acceptable)
- Cover polar regions, 10-13 LT (ideally drifting 30°/ months)

One (or two) ion instrument: INMS+ (and IMA, if possible)
- INMS+: 10 kg, 40 W, <60 MB per orbit (can be reduced)
- IMA: 4 kg, 8 W, <20 MB per orbit (can be reduced)

Any satellite platform with
- Can survive 300 km perigee 1 year (e.g., against AtOx, airdrag)
- Minimum propulsion: attitude (3°): (??? collision avoidance & de-orbiting).
- High positioning accuracy (e.g. with GNSS) is desirable (not required).

Ground-based observations: Important segment of mission
- Metal Lidar
- Radars (e.g., EISCAT, SuperDARN)

METAL team @ 2025

We **seek & welcome more members** (particularly ground-based team, but also any other contribution)

➔ contact M.Yamauchi@irf.se

related session: Friday 16:15 (**AS3.37: keyword = "re-entry"**)

Institution	Payload	Ground-based	Model
U. Bern	Primary (PI)		
IRF, Kiruna	Optional (PI)	EISCAT	
??? (TBD)	DPU		
IRAP, Toulouse	Primary (Co-I)		dynamic & chemistry
MSSL, UC London	Optional (Co-I)		
SwRI, USA	Backup (provider)		
NCAS, U. Leed			dynamic & chemistry
TU-Braunschweig			ablation
U. Rostock		Lidar (Andøya)	
Stockholm U.		Lidar (Esrange)	
U. Electro-Communications, Japan		Lidar (Tokyo)	
Nagoya U., Japan		Lidar (Tromsø)	