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Space Science in an Anthropogenic Environment

Jesse Woodroffe

Group Leader, ISR-1: Space Science and Applications

Michigan Plasma Science and Engineering Seminar

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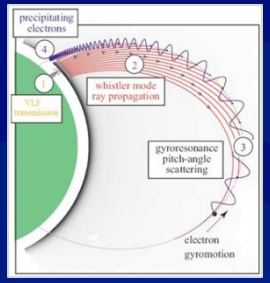
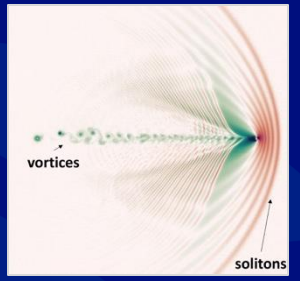
LA-UR-25-29683





Sources (clockwise from top):
https://www.discovermagazine.com/the-50th-anniversary-of-starfish-prime-the-nuke-that-shook-the-world-238
https://vlfstanford.ku.edu.tr/research_topic_inlin/transmitter-induced-precipitation-radiation-belt-electrons/
https://www.nrl.navy.mil/Media/News/Article/3601018/ghosts-in-the-plasma-tracking-the-footprints-of-orbital-debris
https://www.scientificamerican.com/article/low-earth-orbit-faces-a-spiraling-debris-threat

Overview

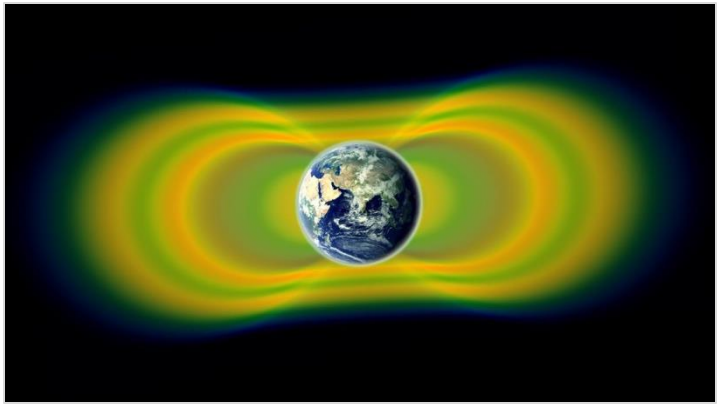
1. Introduction: Humans as Plasma Experimenters
2. Case Study: Starfish Prime
3. A Broader Theme: Anthropogenic Space Weather
4. Space Debris and Dusty Plasmas
5. Anthropogenic Electromagnetic Waves
6. Spacecraft Influences on the Environment
7. Synthesis and Outlook
8. Closing Thoughts

Section 1

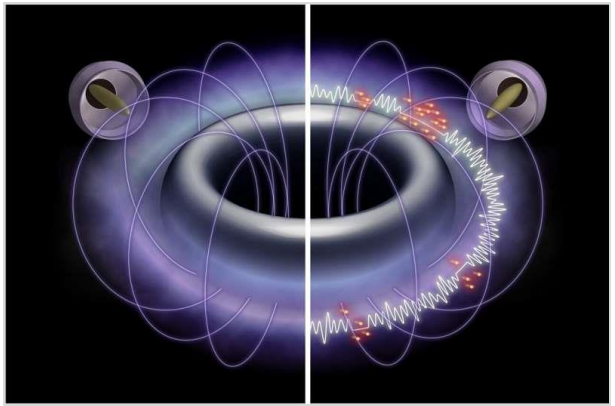
Introduction

The Evolving Use of Space as a Plasma Laboratory

- There is a long history of viewing space as a laboratory for basic plasma physics.
- Our growing human footprint in space affects the surrounding environment in numerous and potentially lasting ways.
- Increasingly, space is as much experiment as it is laboratory – potentially both complicating *and* enriching scientific opportunities.



Source: https://svs.gsfc.nasa.gov/11239/



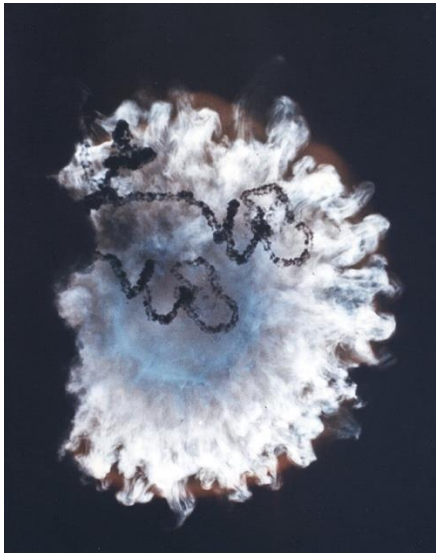
Source: https://www.eurekalert.org/news-releases/1034207

Section 2

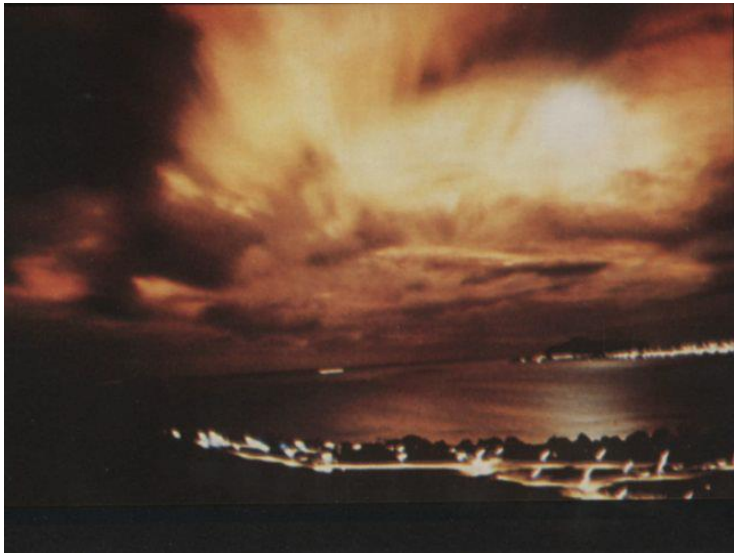
High Altitude Nuclear Explosions

High Altitude Nuclear Explosions (HANE)

On July 9, 1962, the US detonated a 1.4 Mt nuclear device at an altitude of 250 mi above Johnston Island in the Pacific [source: DOE/NV—209-REV 16]



*Initial Cloud**



View from Hawaii

Artificial Aurora
(See also LASL report LA-6405)

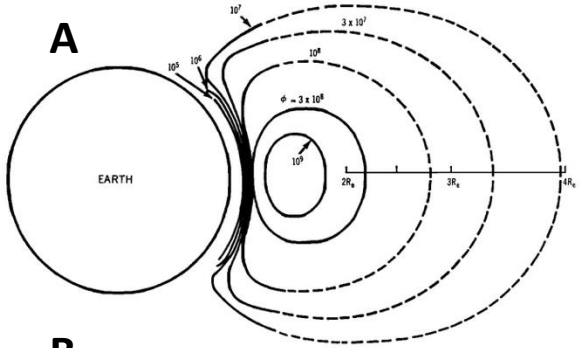
Source: https://en.wikipedia.org/wiki/Starfish_Prime (original attributions therein)

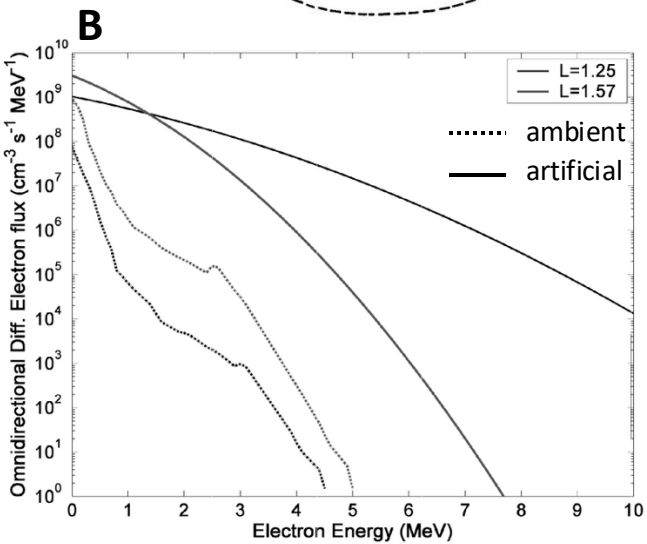
Artificial Radiation Belts

- One of the most striking results of Starfish Prime was the creation of an intense, long-lived artificial radiation belt.
- The full spatial extent of the Starfish belt is not known, but it's thought that it extended beyond L=3, and Ariel showed enhancements out to 5-6 R_E

	Ariel	Traac and Transit 4B	Telstar	Tiros 5	Oso 1
Perigee, km	390	960	952	590	552
Apogee, km	1210	1106	5660	971	594
Inclination	54°	32°	45°	58°	33°
Altitude, km					
30°S latitude	1067	1000	5138	963	594
30°W longitude			1758		
Calculated R/day					
outside vehicle	110,000	180,000	800,000	46,000	27,000
Length of machine run					
in satellite days	4	4	4	4	4
Elec/cm²/day	2.8×10^{13}	4.5×10^{12}	2.0×10^{13}	1.15×10^{12}	6.8×10^{11}

Hess (1963)





Sources

(A) Hess (1963), https://doi.org/10.1029%2FJZ068i003p00667

(B) Rodger et al. (2006), http://www.ann-geophys.net/24/2025/2006/

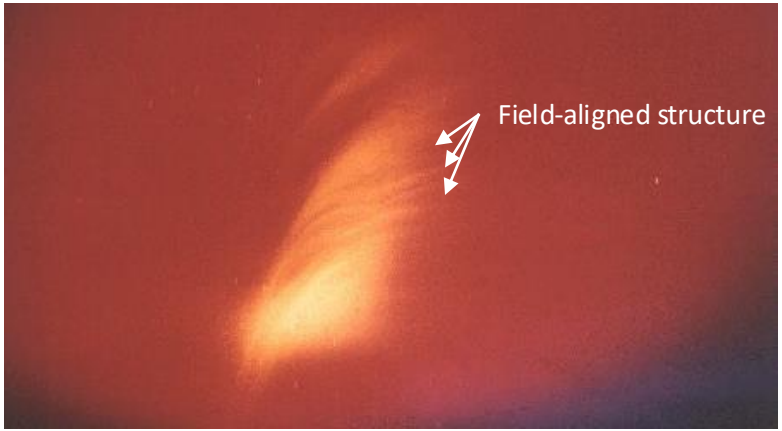
Satellite Impacts

- Space was not as crowded in 1962 as it is today, but there were more than enough in orbit to know that Starfish Prime had a big effect.
- These observations contributed to the establishment of radiation hardening requirements for spacecraft, adopted for both civil and military domains.
- Due to cost, many commercial spacecraft do not use hardening.

SATELLITE	TIME IN ORBIT	DAMAGE
TRAAC	15 Nov 61- 12 Aug 62	• 1120 km x 950 km/32.4° • Solar cell damage due to STARFISH PRIME • Satellite stopped transmitting 36 days after the STARFISH PRIME event due to STARFISH PRIME radiation
Telstar-1	10 July 62 - 21 Feb 63	• 5656 km x 955 km/45° • 7 Aug 62 - Intermittent operation of one of two command decoders • 21 Aug 62 - complete failure of the one command decoder • Intermittent recovery made via corrective procedures – power adjustments to affected transistors – continuous commanding – modified commands • 21 Feb 63 - complete failure of command system – end of mission • Lab tests confirm ionization damage to critical transistors
Explorer 14	2 Oct 62-8 Oct 63	• 98,850km x 278 km/33° • problems encountered 10-24 Jan 63 • Encoder malfunction-11 Aug 63-ended transmissions • After 8-9 orbits, solar cell damage: – Unshielded p-on-n:70% – Unshielded n-on-p: 40% – 3-mil shielded cells (both types): 10%
Explorer 15	27 Oct 62-9 Feb 63	• 17,300 km x 310 km/18° • minor short period encoder malfunctions • Undervoltage turnoff 27 Jan 63 • Second undervoltage turnoff 30 Jan 63 – encoder permanent failure
Transit - 4B	15 Nov 61 - 2 Aug 62	• 1110 km x 950 km/32.4° •Solar panels showed 22% decrease in output 25 days after the STARFISH PRIME event – Lead to demise of satellite
Alouette - 1	29 Sept 62 - ?	• 1040 km x 993 km/80° •Satellite place on standby status Sept 72 due to battery degradation • Satellite overdesign prevented failure, however degradation still occurred due to STARFISH PRIME.
OSO-1	7 March 62 - 6 Aug 63	• 591 km x 550 km/32.8° • Solar Array degradation due to STARFISH PRIME event • Provided real-time data until May 64 when its power cells failed
Ariel-1	26 April 62 - Nov 62	•1210 km x 390 km/53.° •Undervoltage condition occurred 104 hours after STARFISH PRIME event –Solar Cell efficiency reduced by 25% •Intermittent loss of modulation both on real-time telemetry and tape recorders –Speculation that this modulation problem was a result of a STARFISH PRIME - induced electrostatic discharge on the satellite
Anna-1B	31 Oct 62- ?	•1250km X 1151Km/50° •Solar Cell deterioration due to STARFISH PRIME

Source: DTRA-IR-10-22, https://apps.dtic.mil/sti/pdfs/ADA531197.pdf

A First Foray Into Anthropogenic Space Science

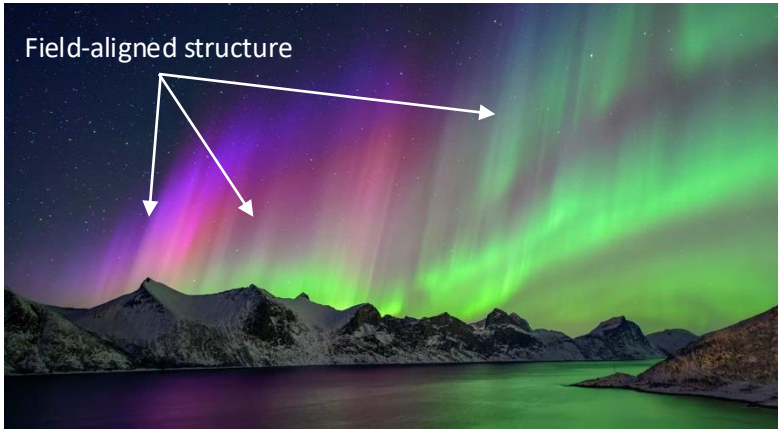


Post-burst Emissions from Starfish HANE

Anthropogenic

Characteristics: High energy, spatially localized within regions having magnetic conjugacy to burst.

Driver: Nuclear explosion and follow-on processes including particle precipitation.



Aurora Borealis

Natural

Characteristics: Low(er) energy, may be spatially distributed across regions with magnetic conjugacy to magnetotail.

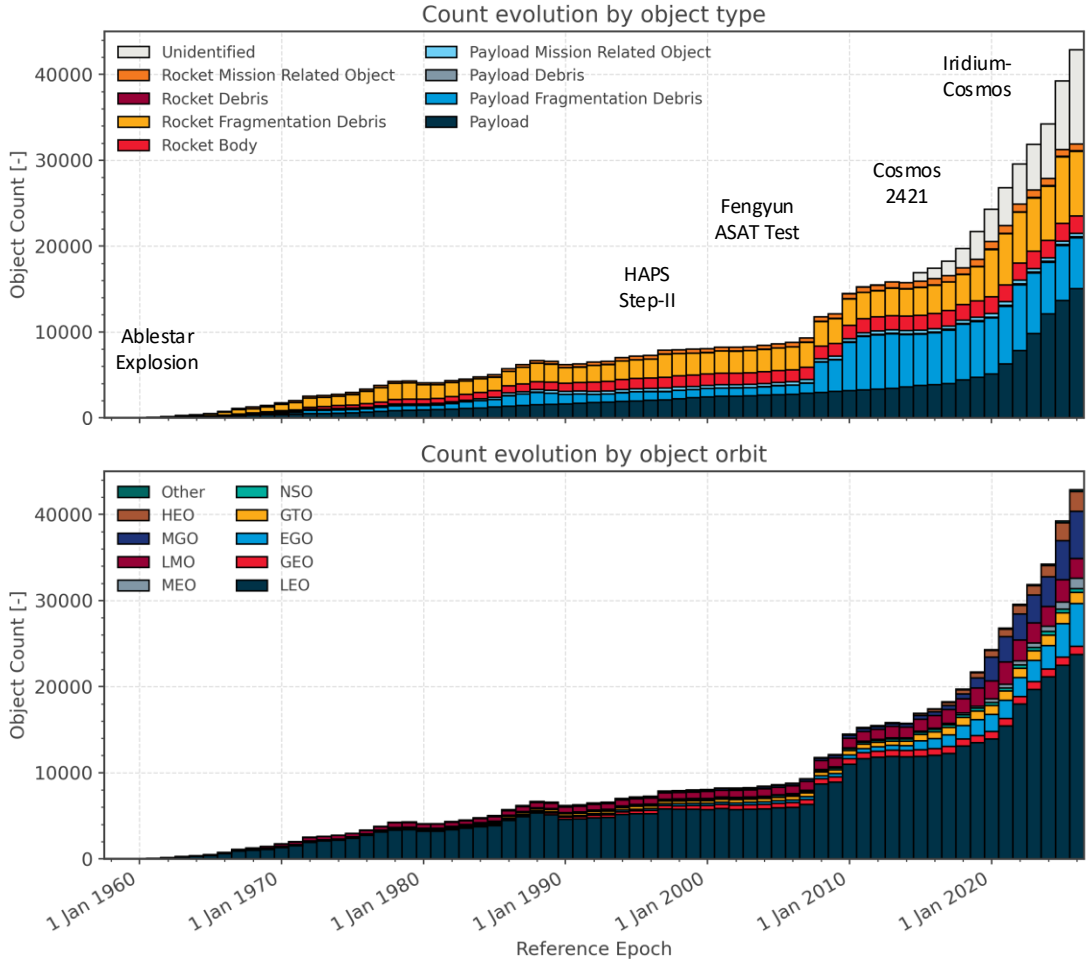
Driver: Magnetic reconnection (primarily) and follow-on processes including particle precipitation.

Section 3

Dust and Debris

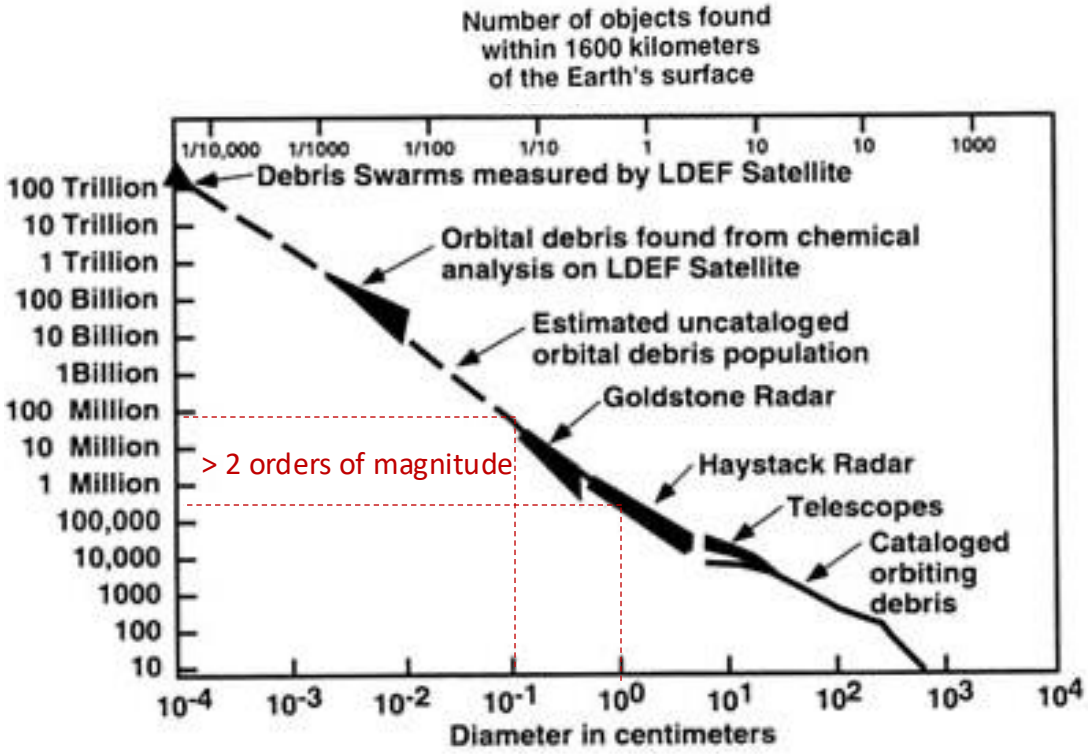
Space Debris

- Encounters with debris is a known threat for space assets and mitigation of debris is a driver of de-orbit requirements for all new missions.
- Unplanned or unusual human activity (explosions, ASAT tests) can (and do) cause rapid increases in the debris population.



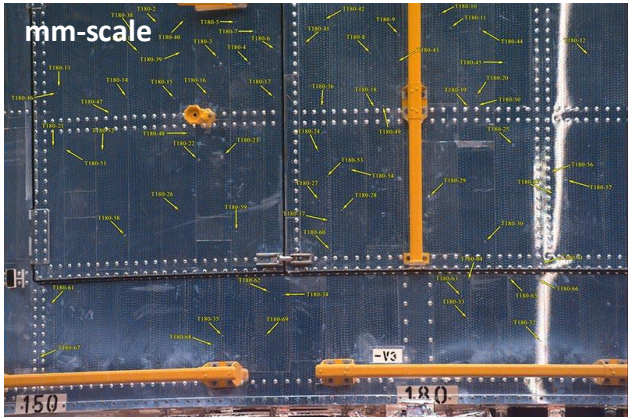
Source: European Space Agency, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

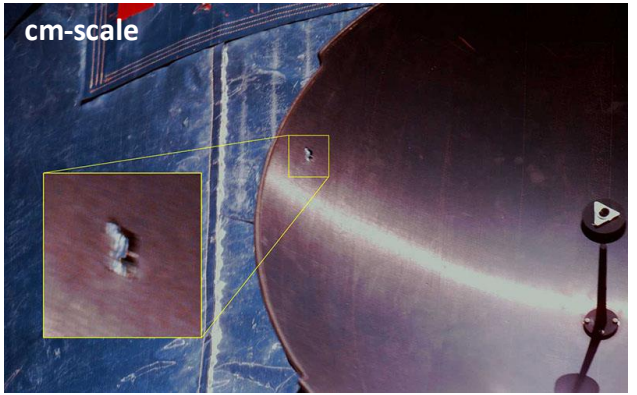
The Debris Distribution



Source: National Academies
https://nap.nationalacademies.org/read/4765/chapter/6

Debris damage to Hubble

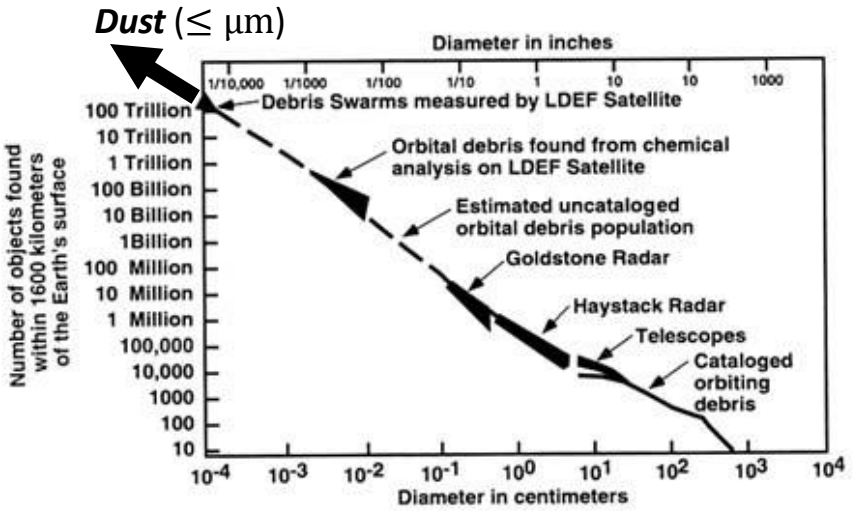




Source: NASA ODPO
https://www.orbitaldebris.jsc.nasa.gov/photo-gallery/

Space Dust – The Tail of the Distribution

- A robust power-law distribution suggests scale-free processes.
- In this case, debris-debris collisions can be inferred to be causing interactions create an ever-growing but ever-smaller cascade of collision products.
- Observations are consistent with scaling to micron and likely down to nanometer – dust – scales.
- Potential for long-term evolution of plasma environment. *If… or when?*



Havnes Parameter

$$P = 4\pi\,\lambda_D^3 n_d \left(\frac{r_d}{\lambda_D}\right)$$

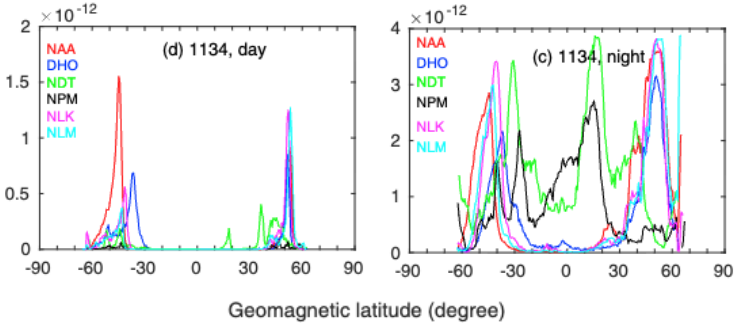
- $P \ll 1$ → Dust *in plasma*
- $P \gg 1$ → *Dusty* plasma

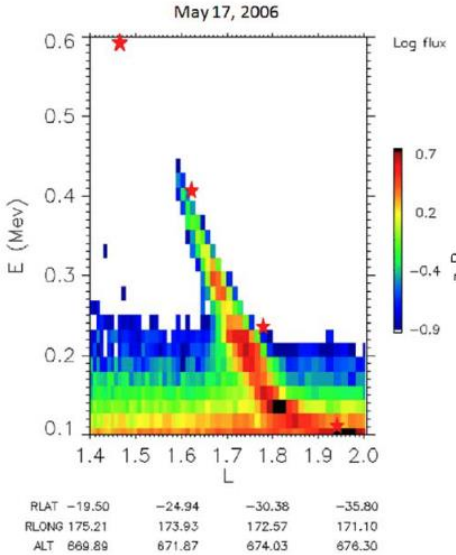
Section 4

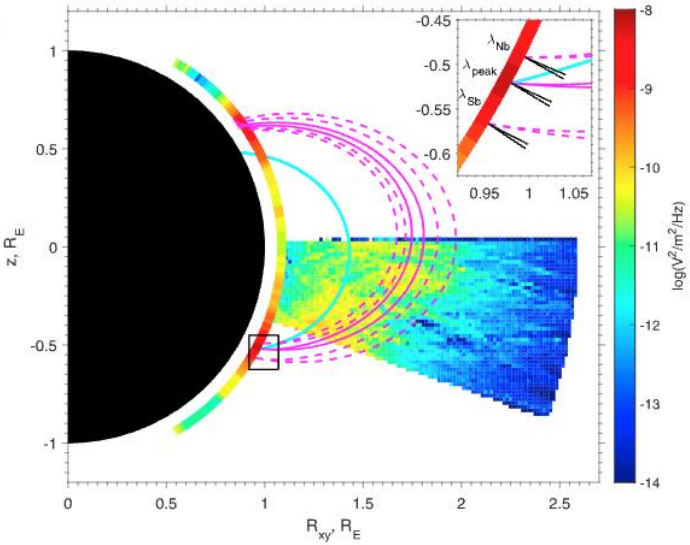
Electromagnetic Noise

VLF Transmitters

- The DEMETER satellite observed very-low frequency (VLF) energy enhancements that were directly traceable to back to ground-based VLF emitters.
- VLF transmissions are used for long-range naval comms.
- Signatures of precipitating particles are consistent with VLF-induced scattering.







Sources

Savaud et al. (2008), https://doi.org/10.1029%2F2008GL033194

Zhang et al. (2018), https://doi.org/10.1029%2F2018JA025637

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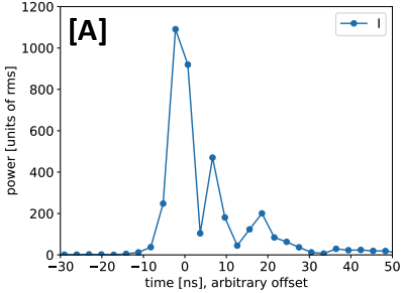
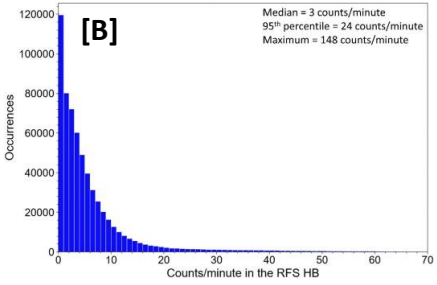
Electrostatic Discharge

- The interaction between satellites and the environment is also a source of both routine and exceptional noise.
- Primary cause is interaction of satellite and natural plasmas.





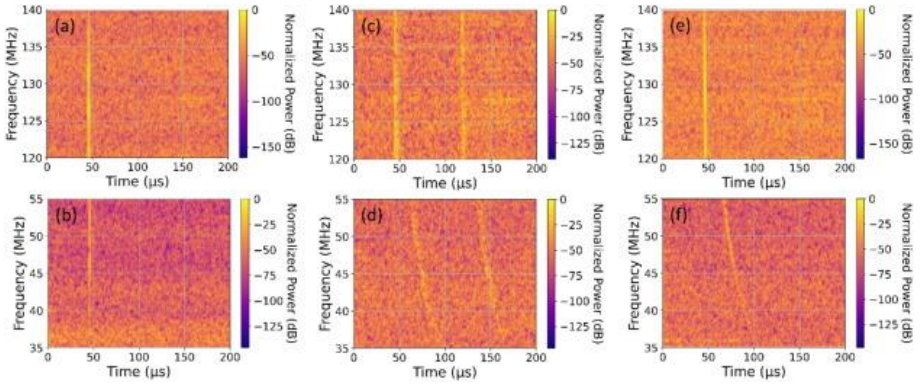
THE SCIENCES

[C]

A Dead NASA Satellite Has Sent a Strange Radio Signal to Earth — Here's How

Learn how a deactivated satellite sends signals from beyond, not by reviving its systems, but by inadvertently setting off sparks.

Radio frequency transients correlated with electron flux measured on-board the SPT-Sat6 (Nag et al., 2025) [D]



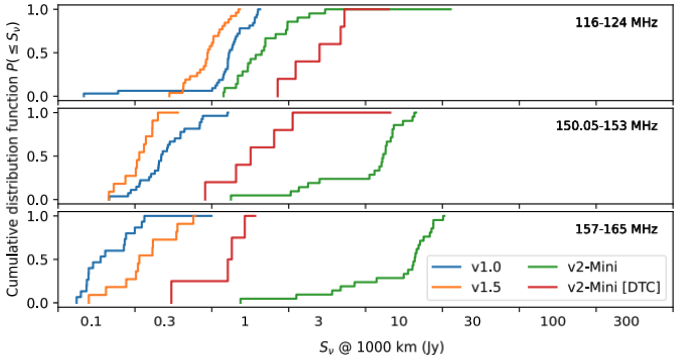
Sources

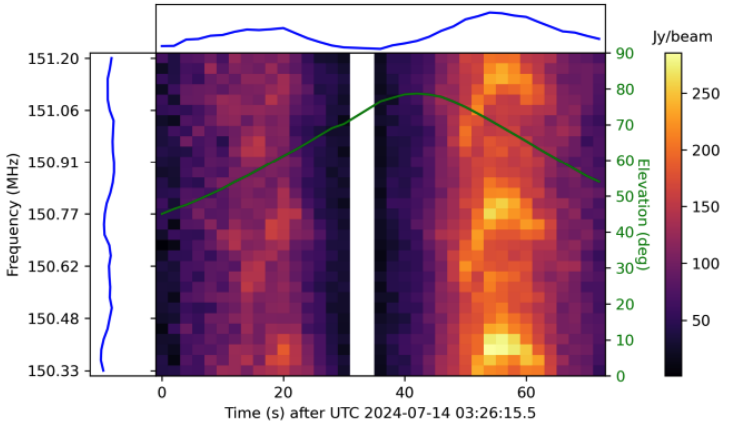
[A], [C]: James et al. (2025), https://arxiv.org/pdf/2506.11462

[B], [D]: Nag et al. (2025), https://doi.org/10.1016/j.asr.2025.07.026

Constellation Effects

- The presence of Unintended Electromagnetic Radiation (UEMR) from large constellations of spacecraft is increasingly prominent in the 30-300 MHz (VHF) frequency range
- May impact lightning science and radio astronomy (early observations from the Square Kilometre Array radio telescope)
- There is already a well-known impact at optical frequencies.





Sources

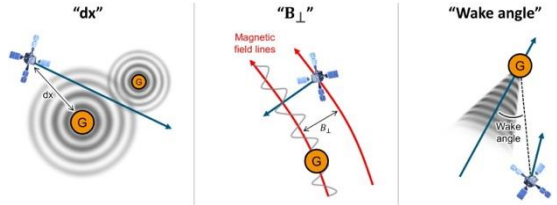
Bassa et al. (2024), https://doi.org/10.1051/0004-6361/202451856

Grigg et al. (2025), https://doi.org/10.1051/0004-6361/202554787

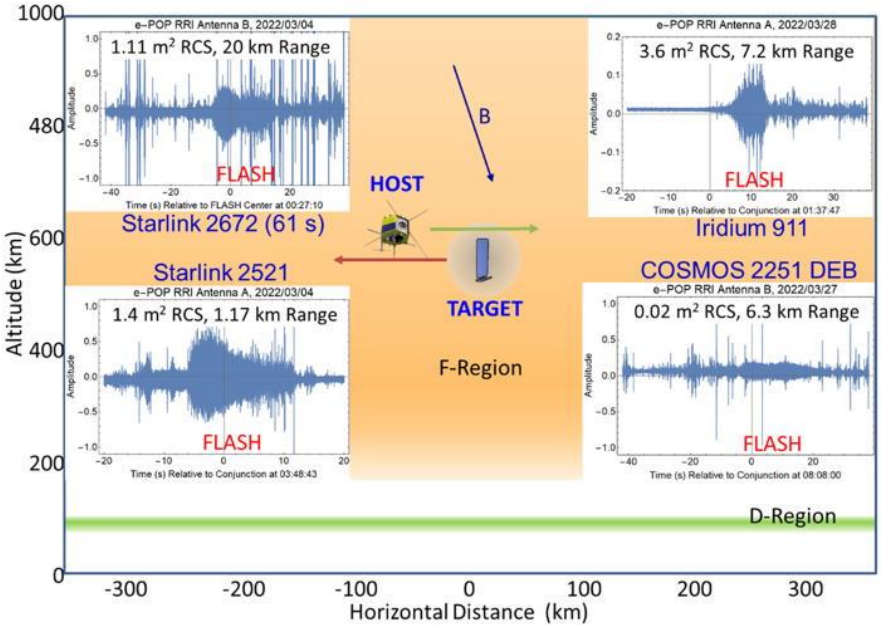
Section 5

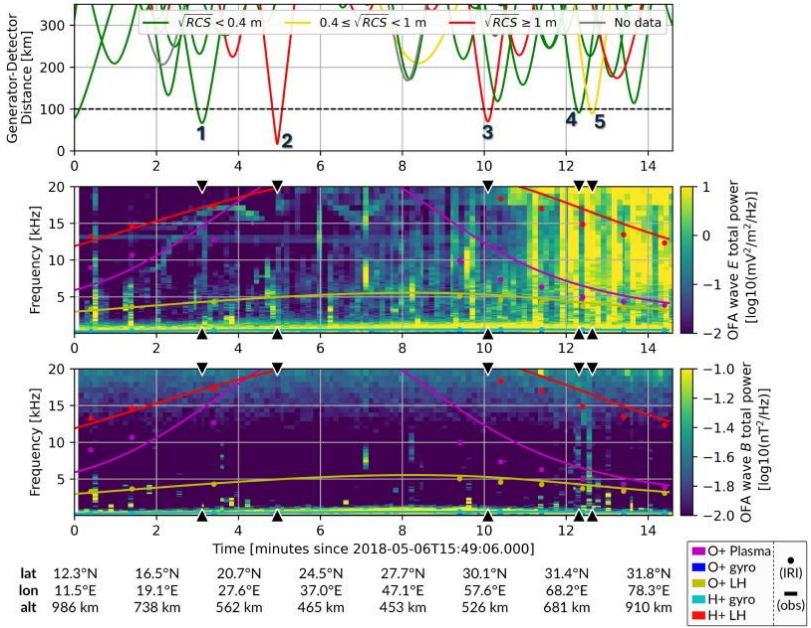
Satellite Signatures

Signatures of Moving Spacecraft



Current hypotheses suggest that space objects produce detectable plasma signatures (this is the basis of the IARPA SINTRA program, https://www.iarpa.gov/research-programs/sintra).





Source: Bernhardt et al. (2023), https://doi.org/10.1063/5.0155454

Source: Hughes et al. (2025), https://doi.org/10.1016/j.asr.2025.07.013

Section 6

Outlook

Challenge and Opportunity

- This is an incredibly interesting and challenging time for space science. Not only do we have a proliferation of measurements and interest from diverse stakeholders, but we may also have a complexification due to ***interaction and feedback between humans and the space environment***.
- Space, particularly near Earth, can no longer be considered a pristine natural laboratory.
- Unless priorities and geopolitics change abruptly, we as a scientific community are going to have to come to terms with this new complexity. Historical results may – some day, maybe soon – no longer represent current realities and we will have to revisit core facts *and* assumptions about our space environment.

Thank You!