Particle Precipitation in Planetary Atmospheres

Guillaume Gronoff[1,2]

1) NASA LaRC, Hampton Va, USA 2) SSAI, Hampton Va, USA
Guillaume.P.Gronoff@nasa.gov

Aurora

Aurora

Introduction: energetic particles and atmospheres

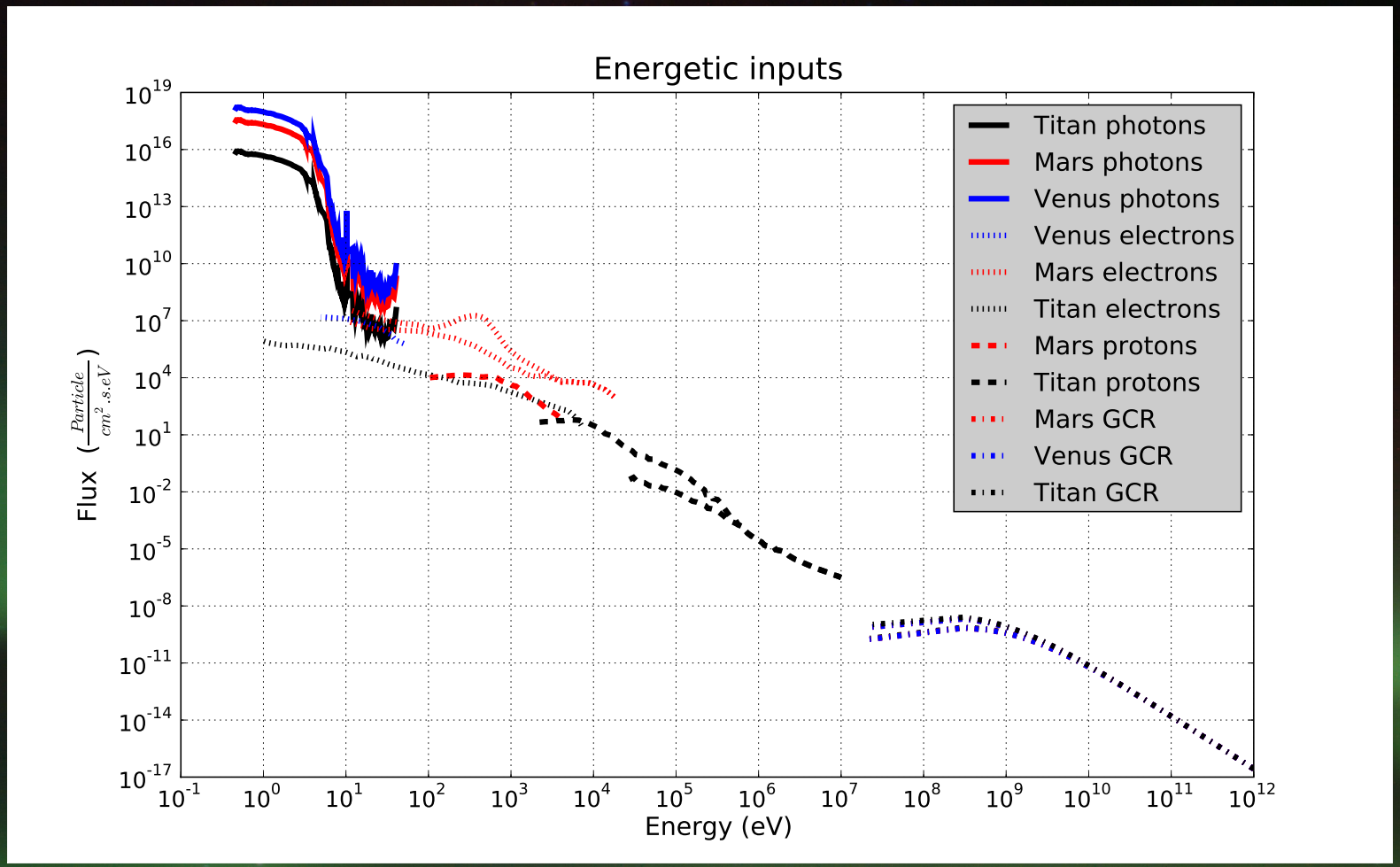
Particle effects on the planetary atmospheres

- Ionization
- Excitation
- Heating
- Airglow (aurora)

Interest of these studies

- Remote sensing of atmospheric variations
- Study of the history of the atmosphere
- Space weather

Introduction: Energetic inputs in atmospheres



The photoionization-photoexcitation model and its limitations

Equation solved

P_a^{phot} is the photoproduction of the specie a (ion or excited specie). Ionization (or excitation):

$$\begin{aligned} P_a^k(\lambda, z) &= n_k(z)\sigma_a^k(\lambda)I(\lambda, z) \\ P_a(z)^{phot} &= \sum_k \int_0^\infty P_a^k(\lambda, z)d\lambda \end{aligned}$$

Integration of the Beer-Lambert law for the 1D code, over the k neutral species:

$$\begin{aligned} I(\lambda, z) &= I_\infty(\lambda)e^{-\tau} \\ \tau &= \sum_k \sigma^k(\lambda) \int_z^\infty n_k(z')ch\chi(z')dz' \end{aligned}$$

The electron-impact model and its limitations

Equation solved

Boltzmann equation with particle creation and non-conservative force:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} + \frac{\partial \vec{F} f}{\partial \vec{p}} = \left.\frac{\delta f}{\delta t}\right|_{Coll} + Q(\vec{x}, \vec{p}, t)$$

Coulombian force (suprathermal electrons interaction with the thermalized electrons):

$$\vec{F} = -n_e L(E)\frac{\vec{v}}{v}$$

The coulombian force is non-conservative.

The electron-impact model and its limitations

Equation solved

Stationary electron flux (Φ) equation:

$$\mu \frac{\partial \Phi}{\partial z} - n \frac{\partial}{\partial E}\left(L(E)\Phi\right) = -\sum_k n_k(z)\sigma^k(E)\Phi + source$$

$$source = electron\ creation + redistribution$$

Production equation:

$$P_a^{elec}(z) = \sum_k n_k(z) 2\pi \int_{-1}^{1}\int_{E}^{\infty} \sigma_a^k(E')\Phi(z, E', \mu) dE' d\mu'$$

The electron-impact model and its limitations

The redistribution function

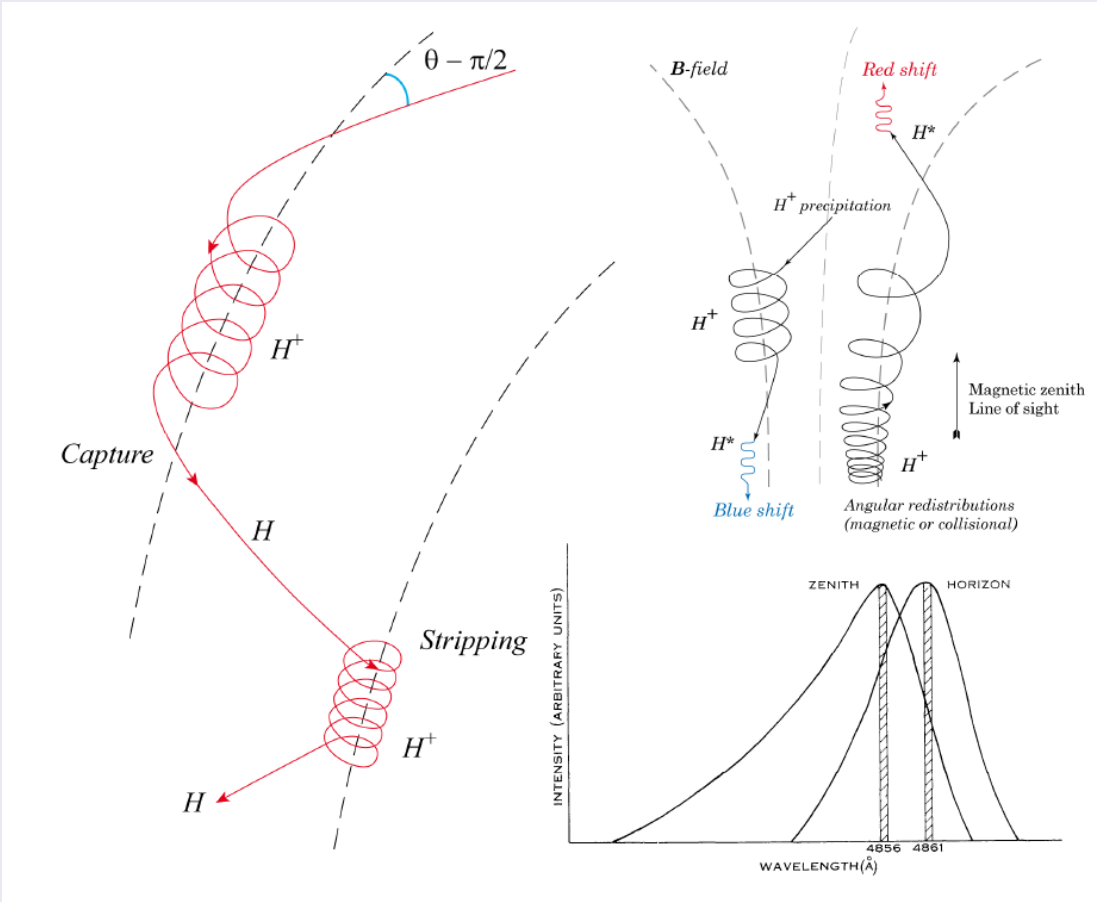
$$redistribution(z, E, \mu) = \int_E^{\infty} \int_{-1}^{1} \mathrm{Redi} \; d\mu' dE' \quad (1)$$

$$\mathrm{Redi} = R'((E', \mu') \rightarrow (E, \mu))\Phi(z, E', \mu') \quad (2)$$

- Angle redistribution
  - Porter parameter for elastic collisions
  - Isotropic for created electron
  - Forward approximation for inelastic (including ionization) collisions
- Energy redistribution
  - At Auger energy for Auger electrons
  - Opal parameter to compute doubly differential cross sections
  - Conservation of energy for the energy loss during inelastic impact
  - L(E) losses, energy conservation through heating

Proton Precipitations

The coupled H+/H transport principle (C. Simon thesis 2006)



Proton Precipitations

The coupled H+/H transport equation

Example for protons:

$$\mu \frac{\partial \Phi_P(s,E,\mu)}{\partial s} - \frac{1-\mu^2}{2B}\frac{dB}{ds}\frac{\partial \Phi_P(s,E,\mu)}{\partial \mu} - \sum_k n_k(s) \sum_\alpha \int d\mu' \frac{\partial}{\partial E}\left(L^\alpha_{k,P}(E,\mu' \to \mu)\Phi_P(s,E,\mu')\right) \quad (3)$$

$$- \sum_k n_k(s) \int d\mu' \frac{\partial}{\partial E}\left(L^{01}_{k}(E,\mu' \to \mu)\Phi_H(s,E,\mu')\right) = - \sum_k n_k(s)\sigma^T_{k,P}(E)\Phi_P(s,E,\mu) \quad (4)$$

$$+ \sum_k n_k(s) \sum_\alpha \int d\mu' \xi^\alpha_{k,P}(E,\mu \to \mu)\sigma^\alpha_{k,P}(E)\Phi_P(s,E,\mu') \quad (5)$$

$$+ \sum_k n_k(s) \int d\mu' \xi^{01}_{k}(E,\mu' \to \mu)\sigma^{01}_{k}(E)\Phi_H(s,E,\mu') \quad (6)$$

For hydrogen fluxes Φ_H, mirror equation save the magnetic term! Luckily, analytical solution of the form:

$$\Phi \propto e^{\mathcal{A}} \quad (7)$$

thanks to the nature of the matrix to solve: sparse matrix, exponential of a sparse matrix! (Galand et al. 1997,1998, Sidje, 1998).

Proton Precipitations

The coupled H+/H transport equation

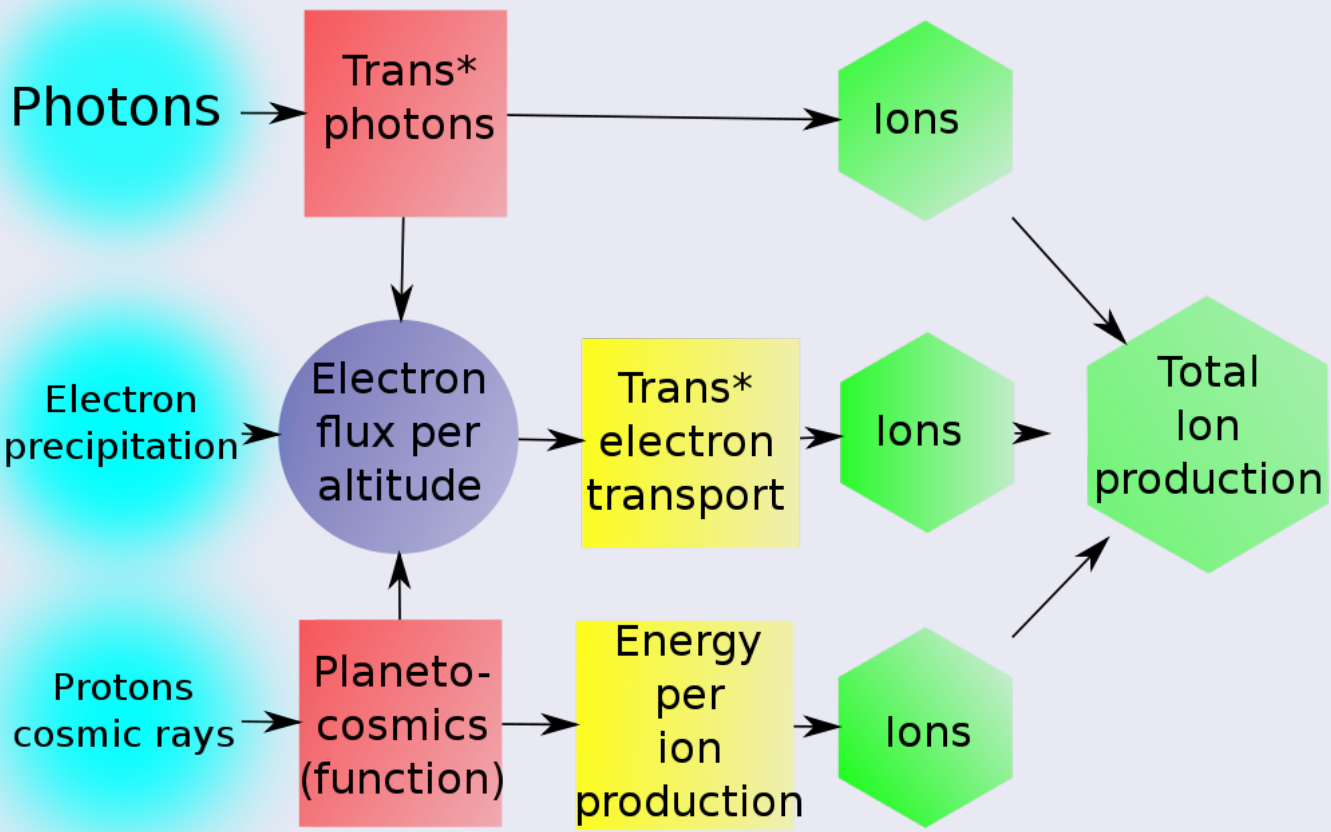
- The proton and hydrogen equations are symmetrical
- Losses include ionizations
- Electrons, from ionizations, are called proto-electrons
- The proto-electrons can have enough energy to ionize/excite

$$P_k(z) = 2\pi n_k(s) \sum_{j=H^+,H} \int d\mu \int \sigma_{ion}^{k,j}(E)\Phi_j(z,E,\mu)dE \qquad (3)$$

- Therefore, they are included in the Aeroplanet/electron transport system.

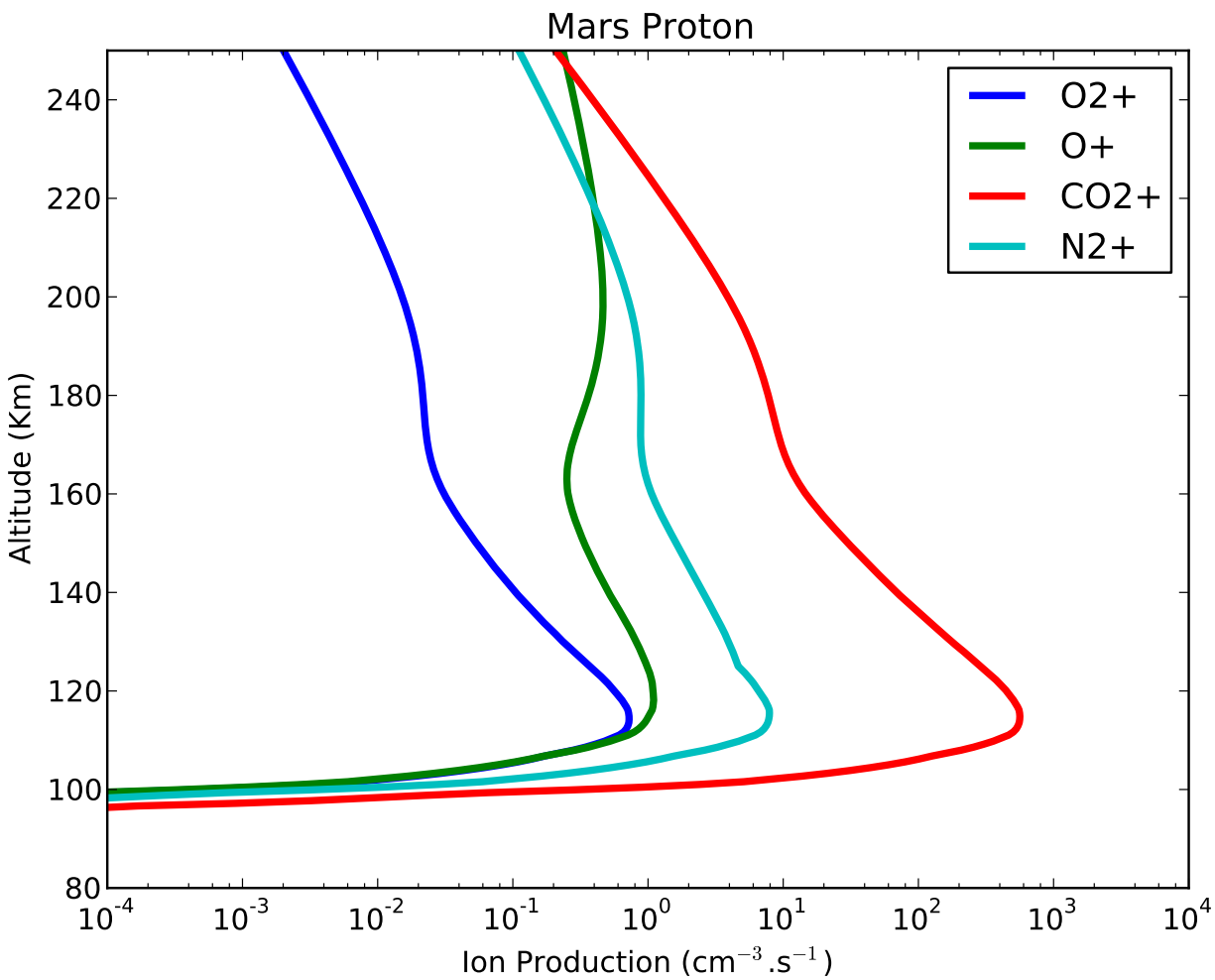
Proton Precipitations

The coupled H+/H transport equation

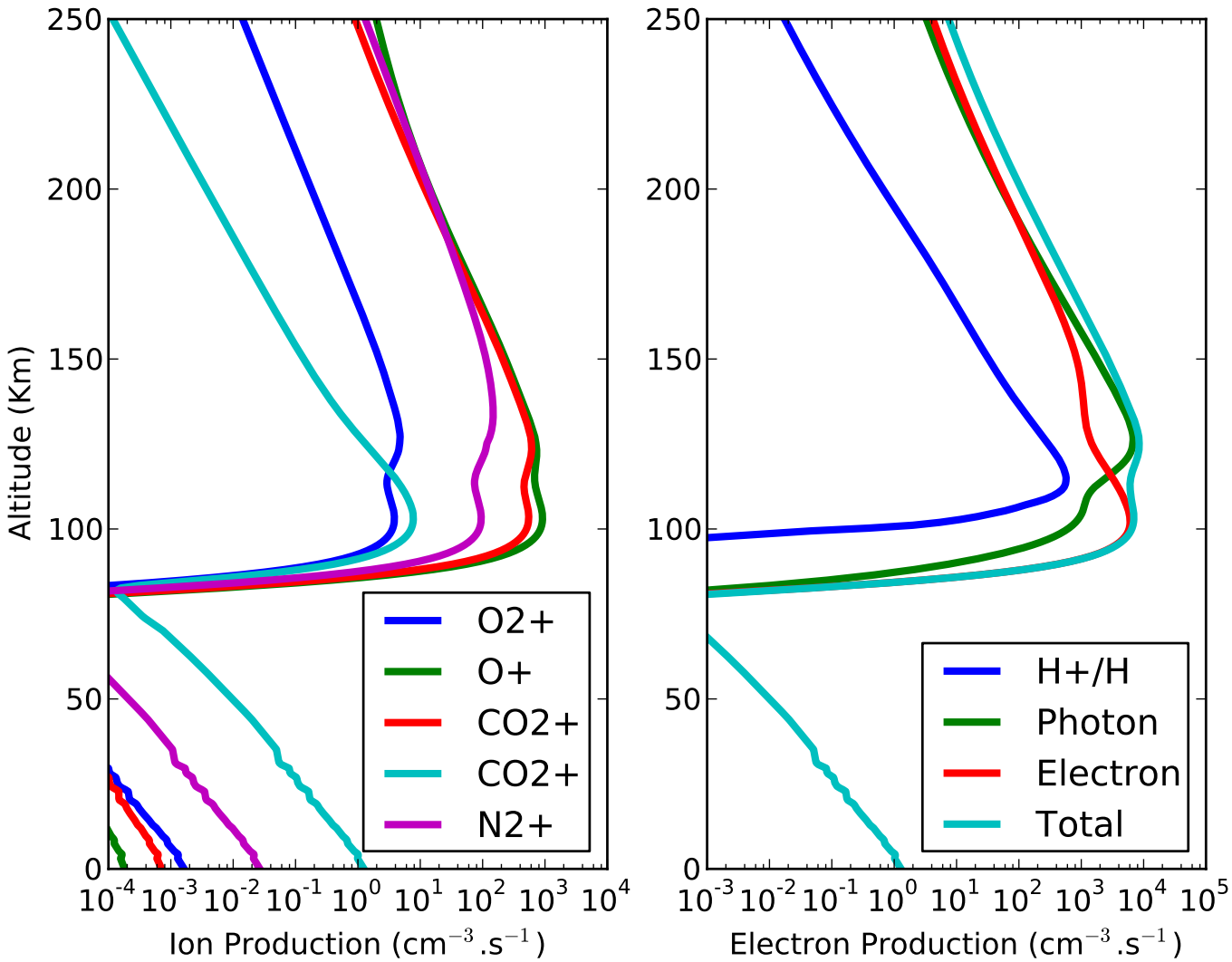


Proton Precipitations

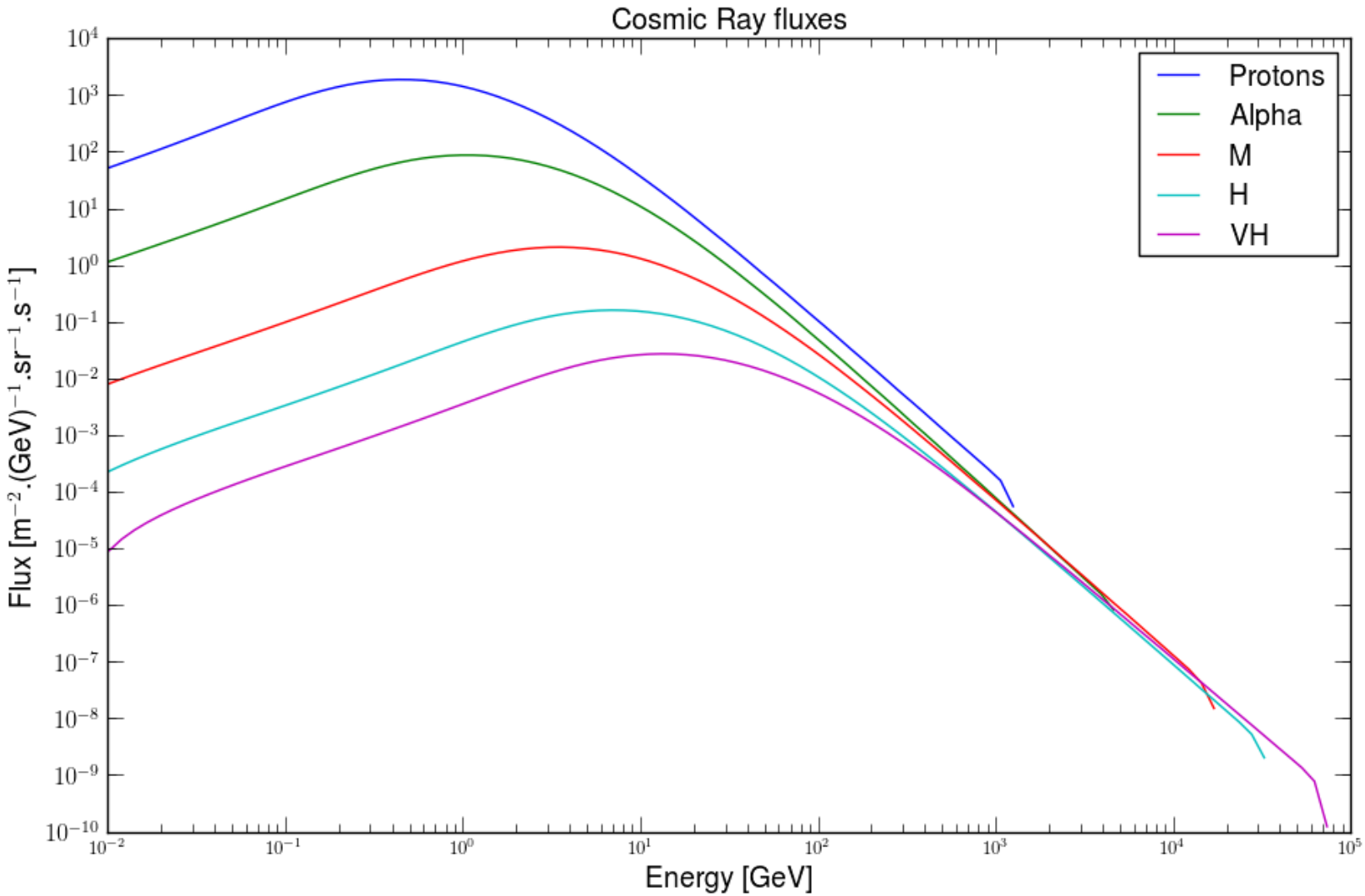
The effect of a 1 keV proton precipitation: the ion production



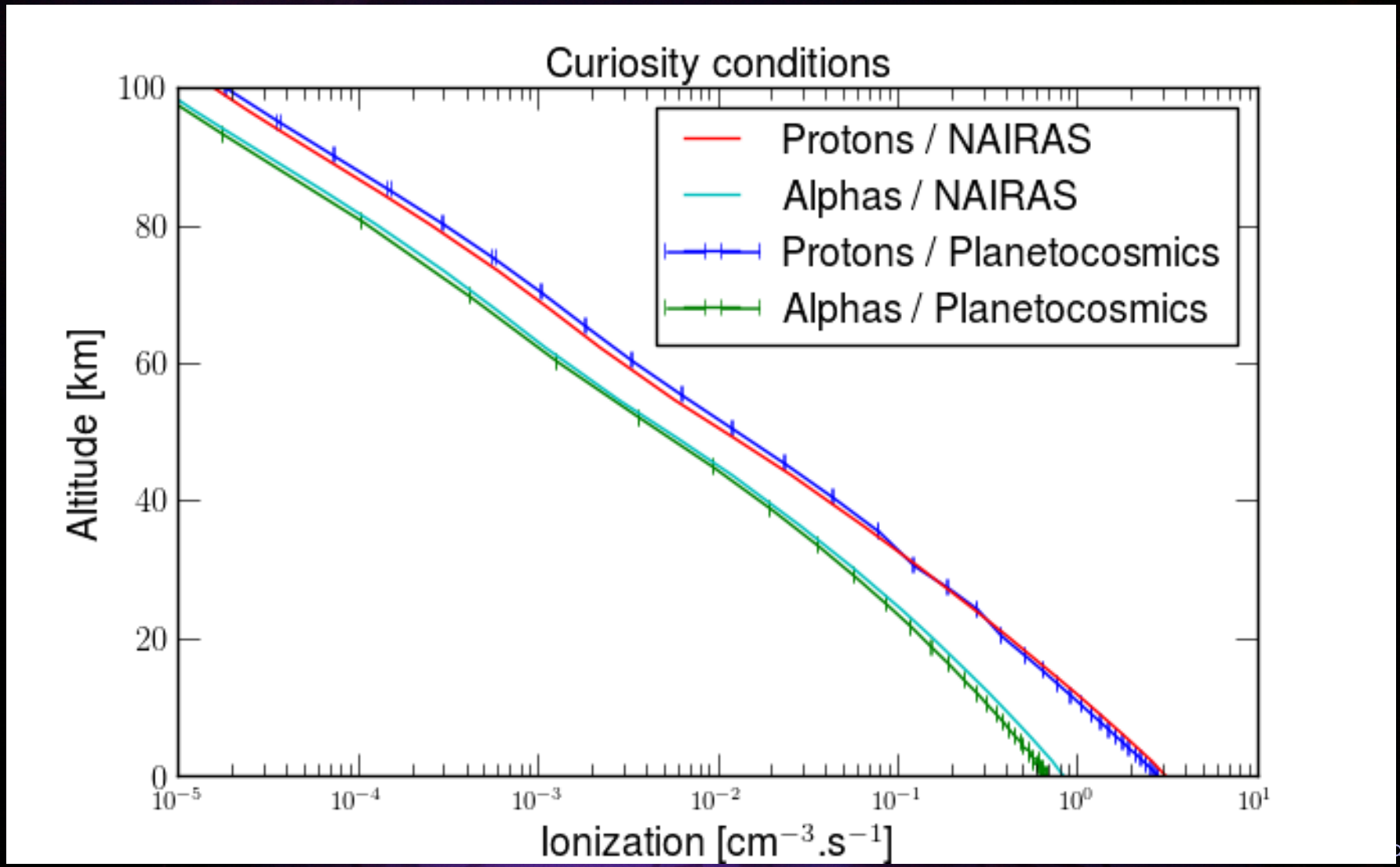
Computation of the ionization in the whole atmosphere



The cosmic ray spectra (Detail)



The cosmic ray ionization (comparison between NAIRAS and PLANETOCOSMICS)



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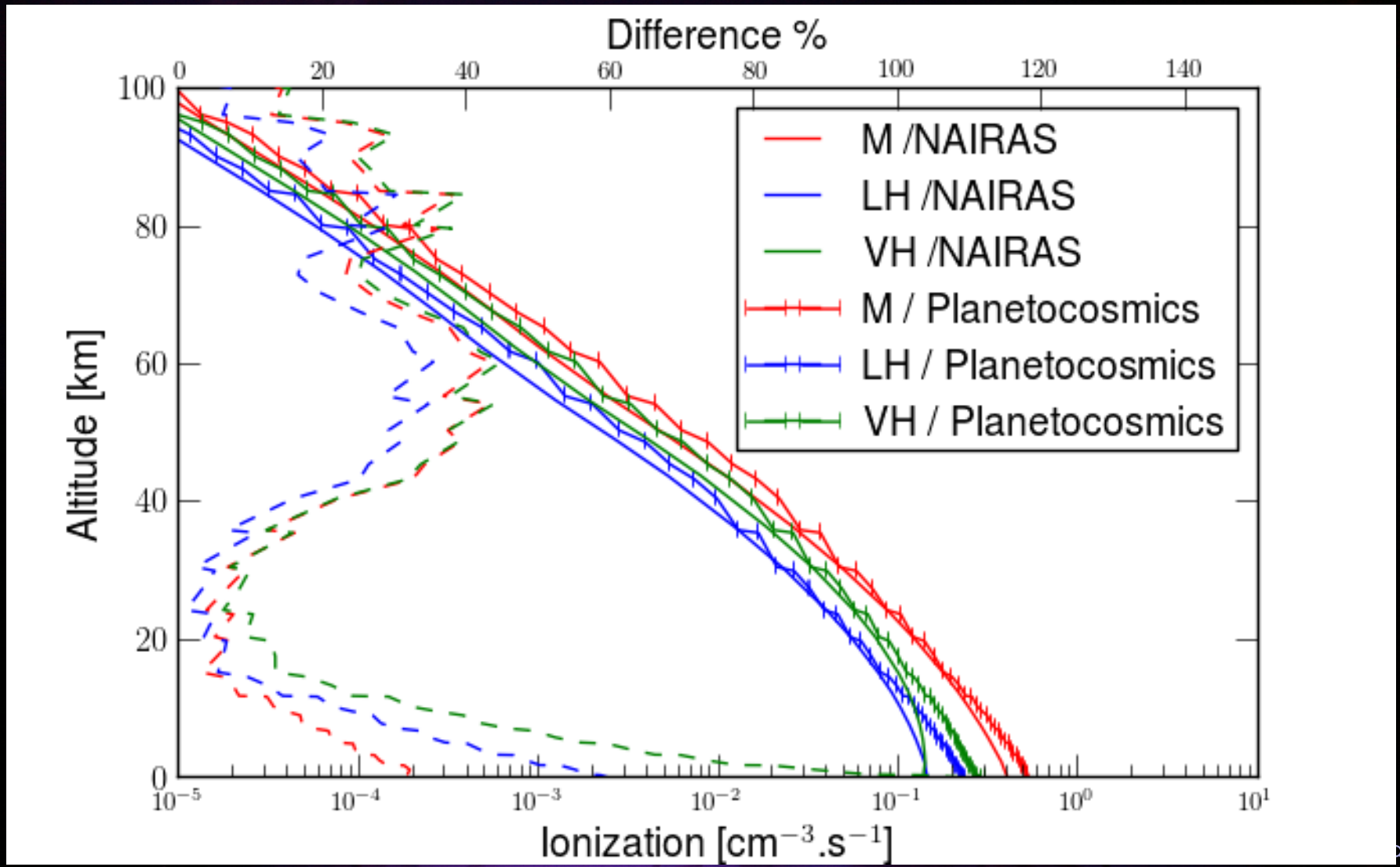
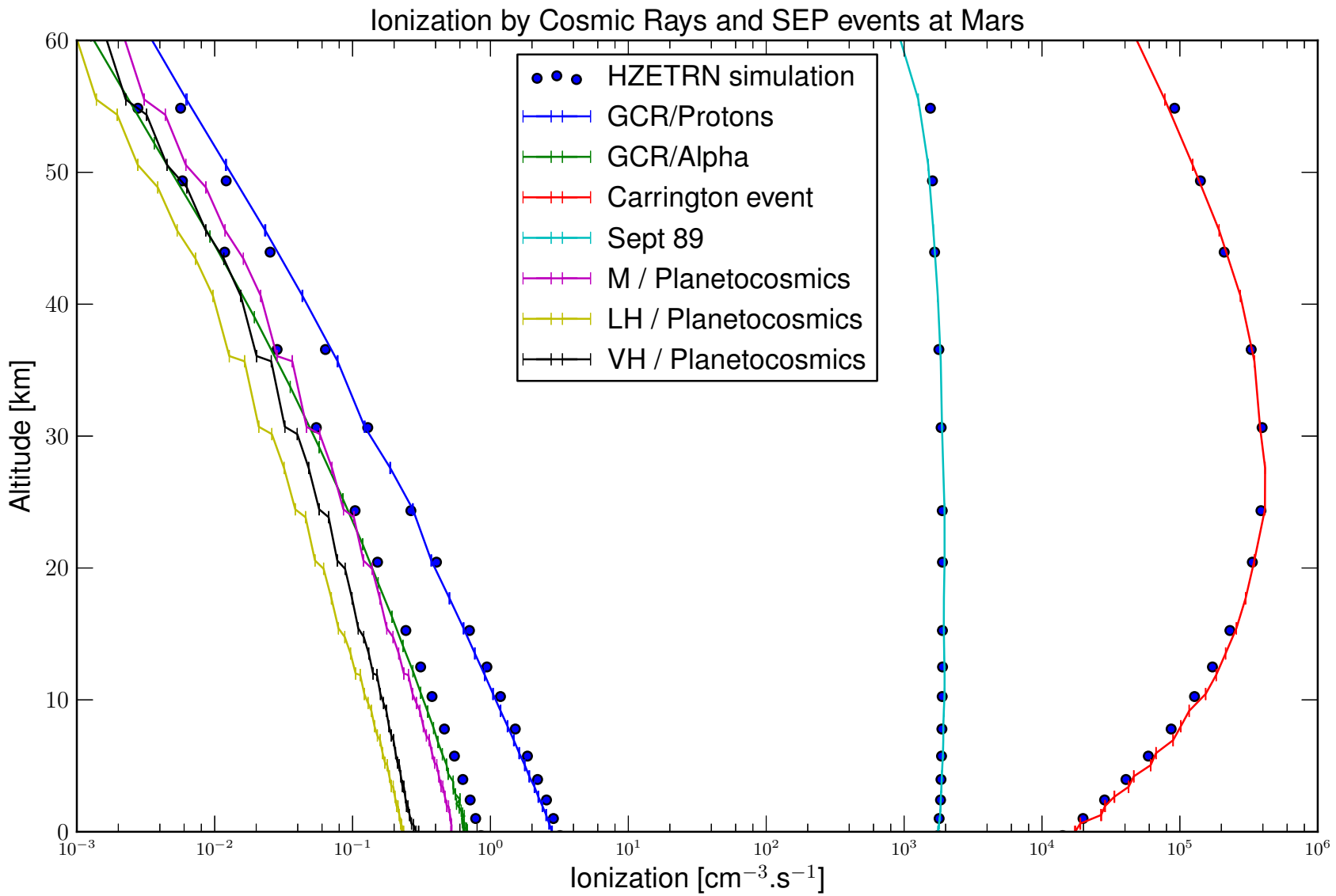
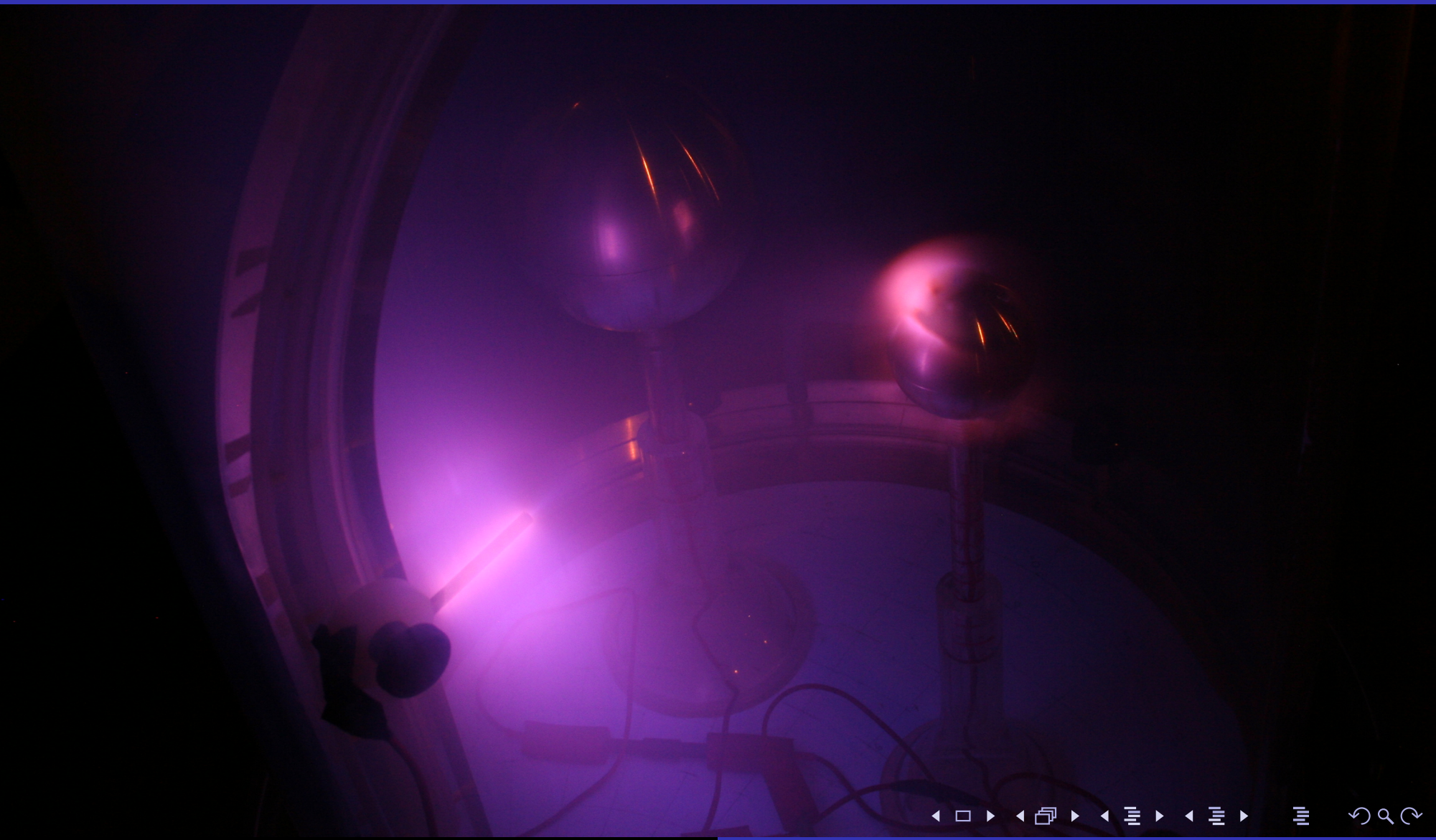


Solar energetic particle events



APPLICATIONS: computing the irradiation of astronauts/high latitude flights



The dose suffered by astronauts

SEP events

SEP event	Planetocosmics	HZETRN
Sept 89	69.0 mGy/day	65.0 mGy/day
Carrington	755 mGy/day	502 mGy/day
Oct 22	10.4 mGy/day	9.40 mGy/day
Oct 24	20.1 mGy/day	17.5 mGy/day
SPENVIS Oct 89 5min	147 mGy/day	124 mGy/day

Galactic Cosmic Rays

GCR family	Planetocosmics computation	HZETRN
Proton	0.11 mGy/day	0.107 mGy/day
Alpha	0.023 mGy/day	0.0295 mGy/day
M	0.017 mGy/day	0.0143 mGy/day
LH	0.008 mGy/day	0.00511 mGy/day
VH	0.009 mGy/day	0.00481 mGy/day
Total	0.1670 mGy/day	0.1607 mGy/day

Let's be careful about the units/doses/risks

Radiation dose

- 1 Gy = 1 J/kg
- 1 Sv = 1 Gy * QF (Quality factor)
- QF = 1 for protons, electrons, photons
- QF = 20 for alpha particles
- QF = 10 for neutrons

Let's be careful about the units/doses/risks

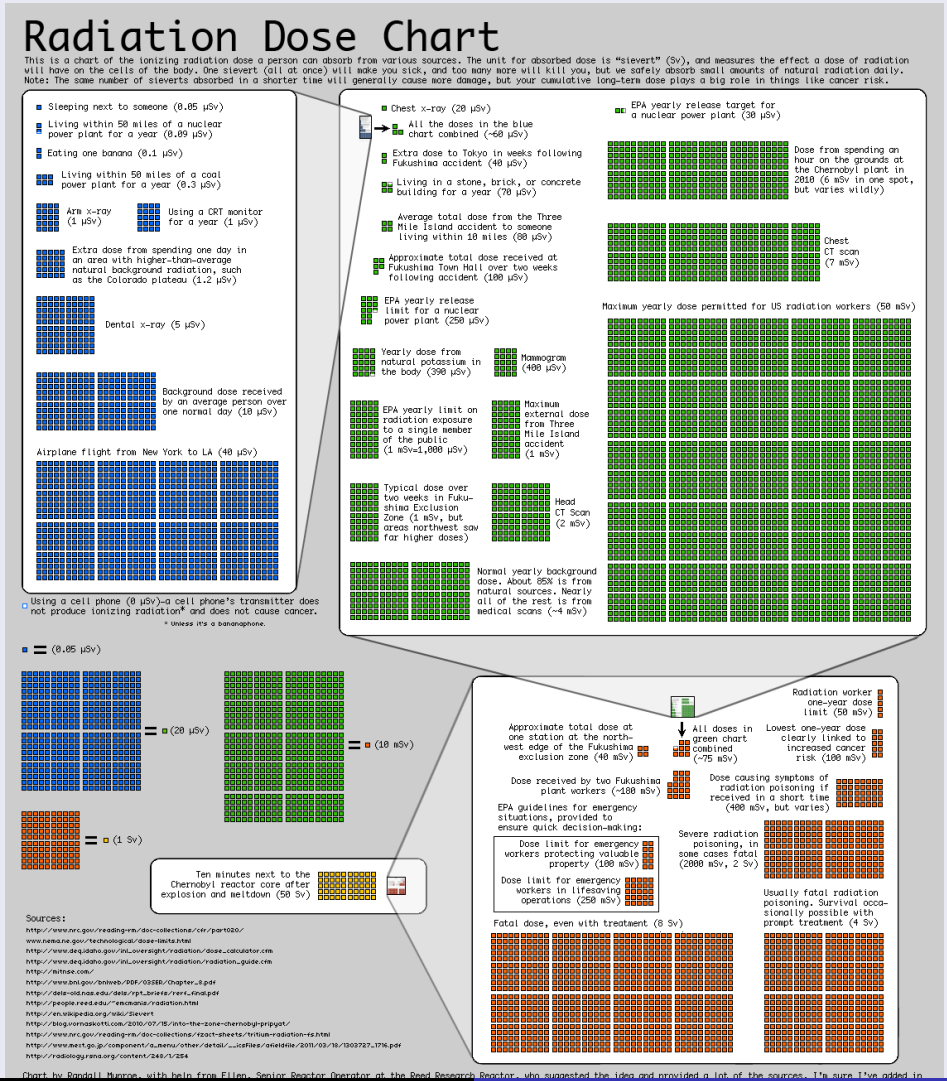
But those units are already simplified

- **Absorbed** Dose in tissue, water, Si, are all in Gy; but different
- The Sievert is used for **equivalent dose**, ambient dose equivalent, effective dose...
- The Sievert is what affects the **risk** of cancer, the biology!
- At same energy*, a neutron is more damaging than a proton

(See Mertens et al 2016: Space Weather. 2016 November ; 14(11): 921–934. doi:10.1002/2016SW001399. Overview of the Radiation Dosimetry Experiment (RaD-X) flight mission) (* in our range of energies, let's not be pedantic)

Let's be careful about the units/doses/risks

Radiation doses (and risks from XKCD / public domain)



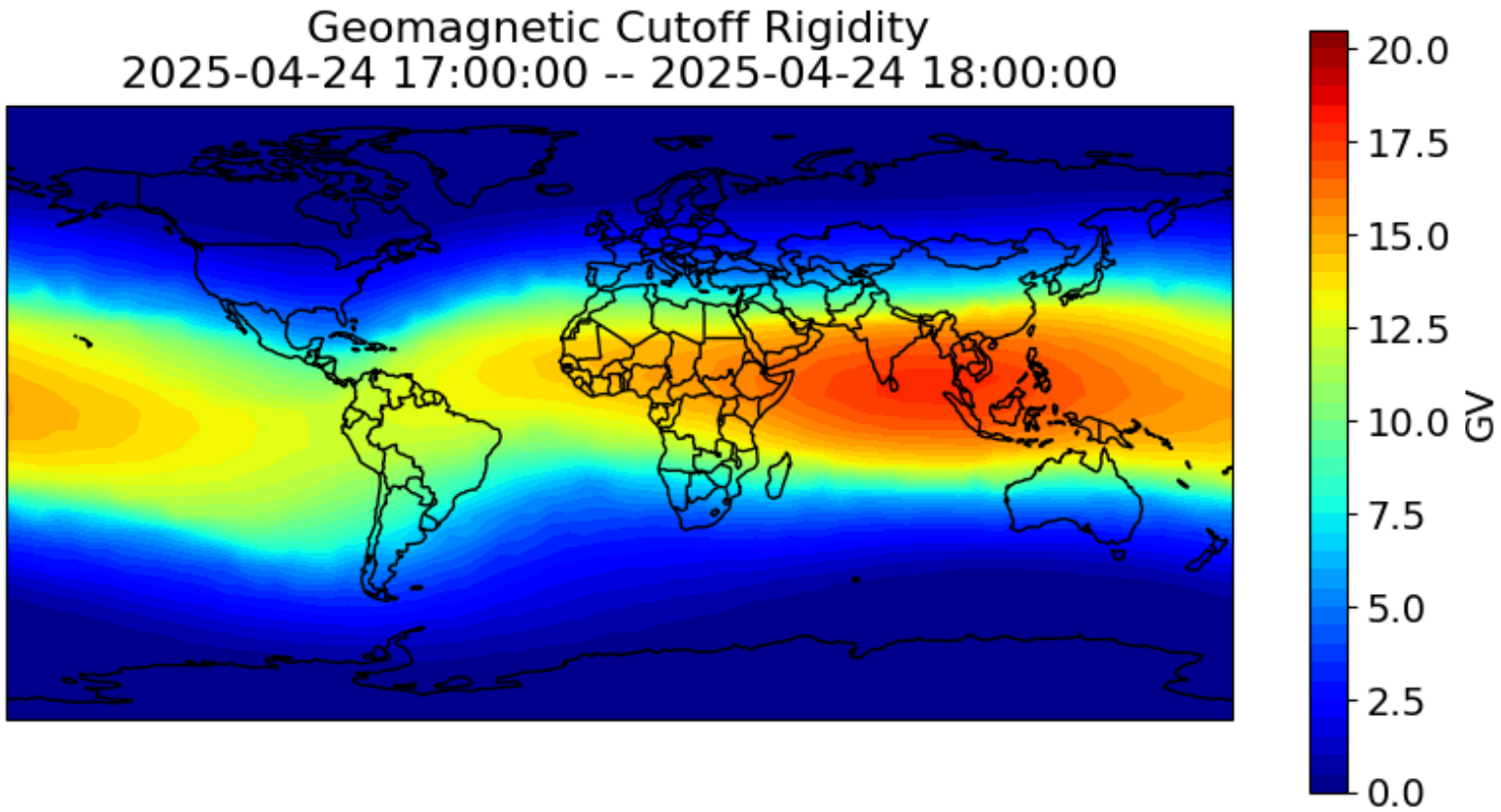
Is it dangerous to fly? NAIRAS

Tools used by our team

- The NAIRAS(Nowcast of Aerospace Ionizing RAdiation system) model (Mertens et al. 2013) for fast computation of GCR and SEP events.
- The PLANETOCOSMICS model (Desorgher et al.) for accurate computation of GCR and SEP events.
- The AEROPLANETS model (Gronoff et al.) for fast and accurate computation of low energy events (photons, electrons (keVs), protons (up to MeV)).

Comparison of the NAIRAS and PLANETOCOSMICS models: the NAIRAS model is fast, but has approximations on the physics, whereas PLANETOCOSMICS is more accurate, but much slower (Monte-Carlo model)

Is it dangerous to fly? NAIRAS



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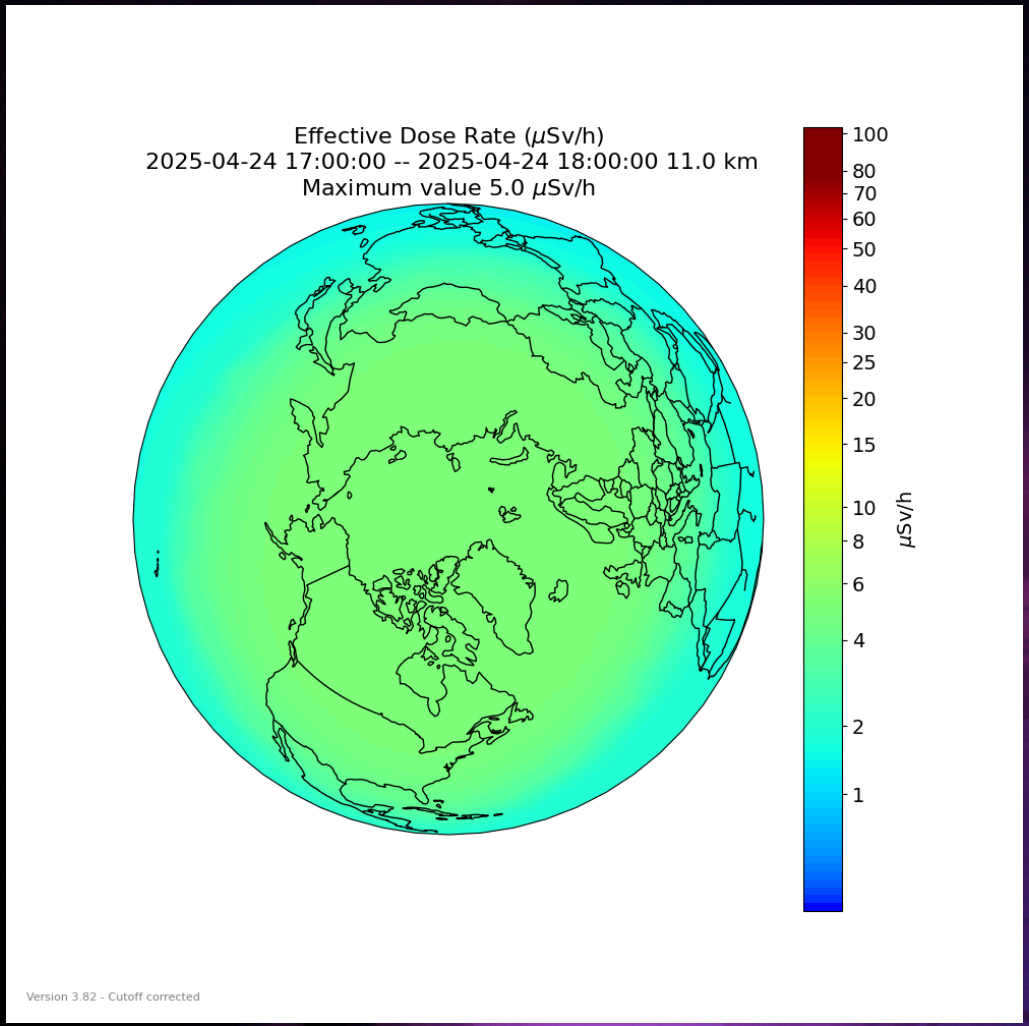

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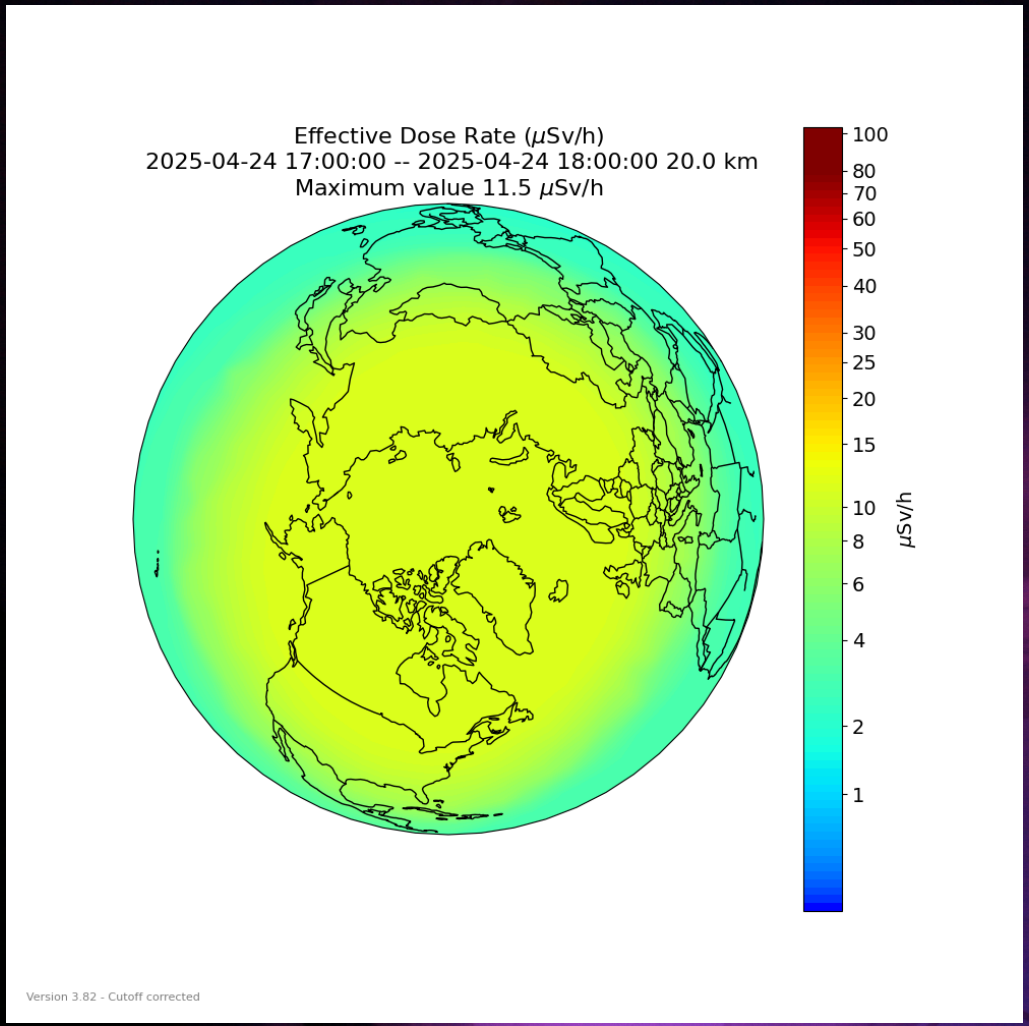

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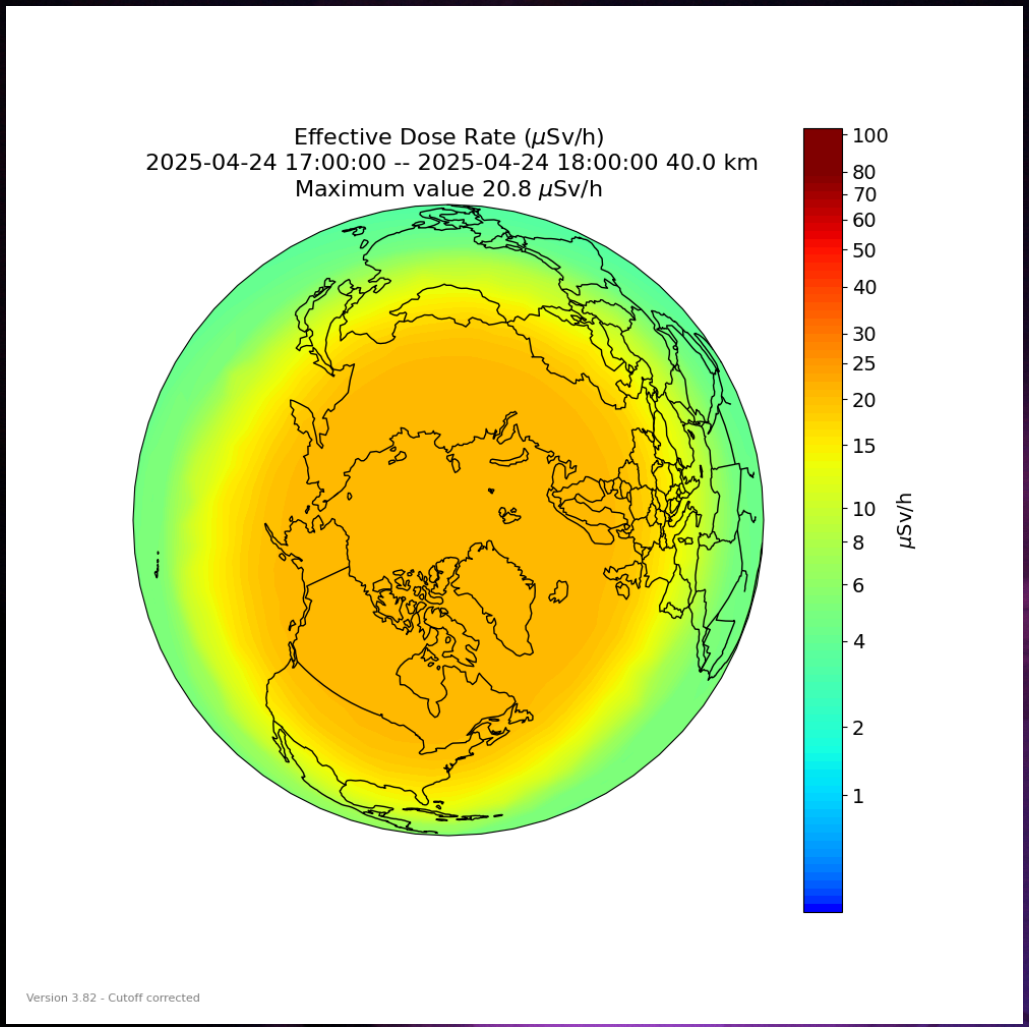

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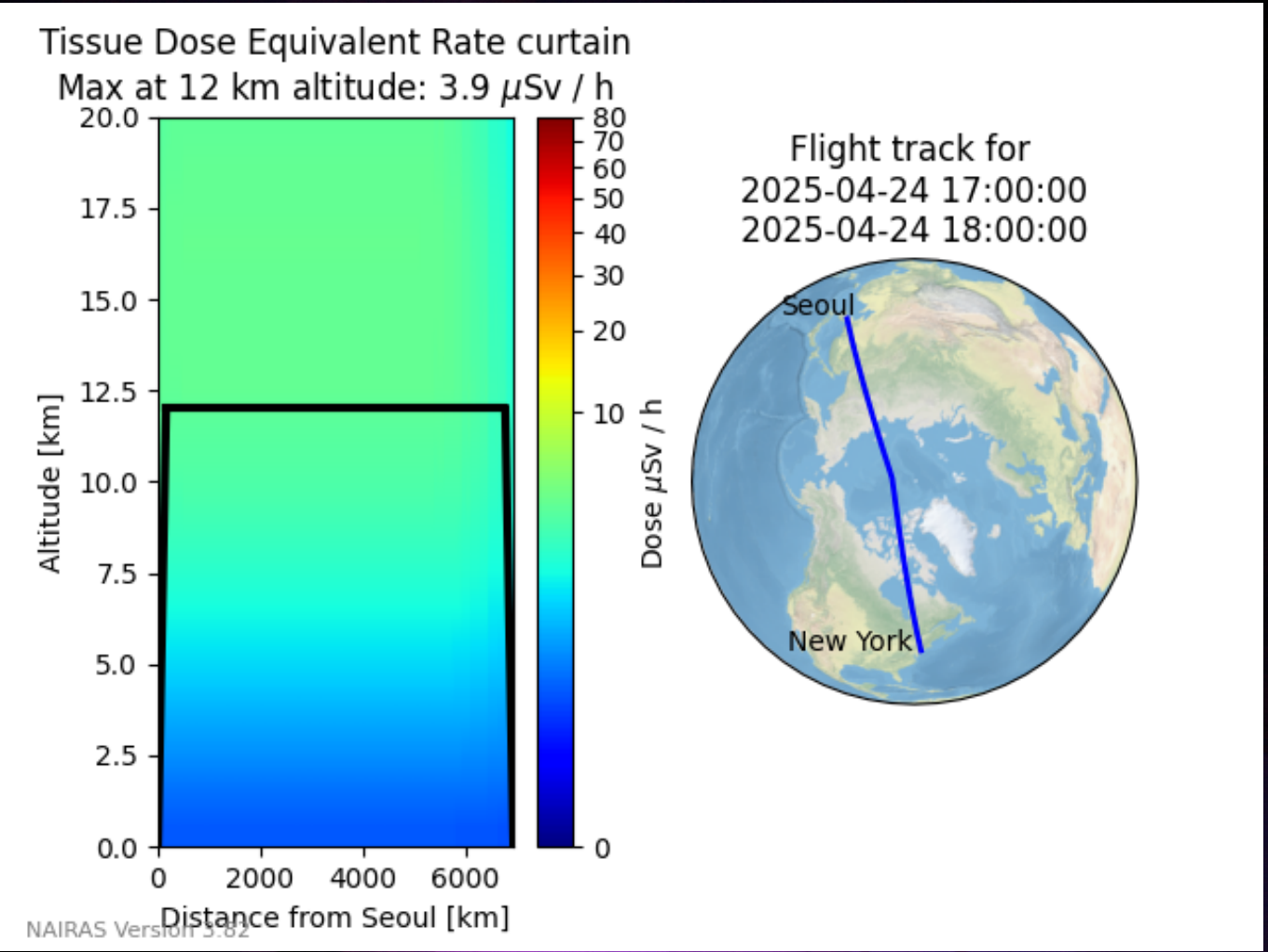
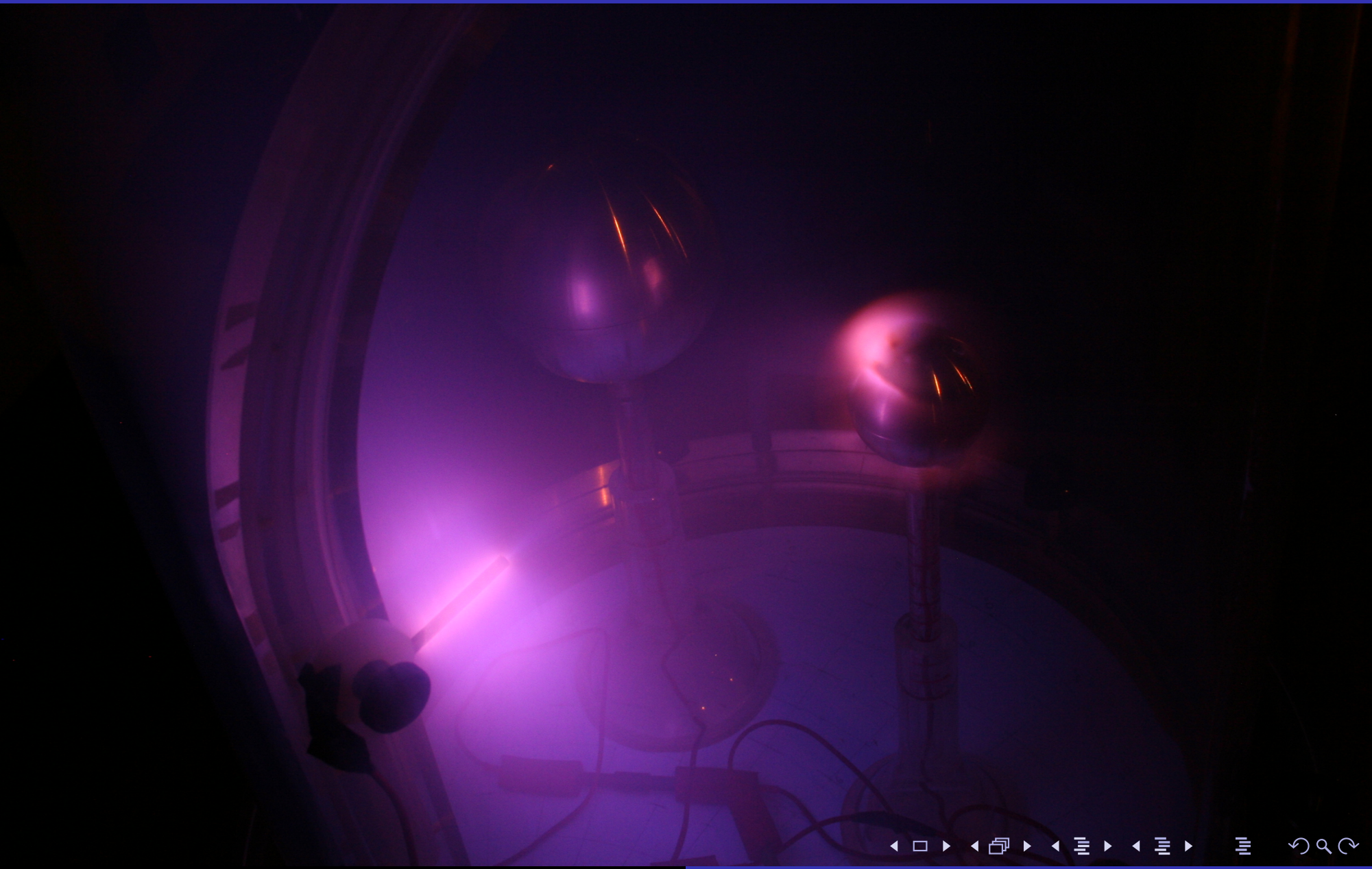


Is it dangerous to fly? NAIRAS

NAIRAS at CCMC

- This is the "realtime" version
- Time in UTC, about 2h from "actual" time
- (1h for satellite data to come, 1h to process)
- Prediction is under development (ROSES-Heliophysics-O2R)
- Also used for the ISS and space flight (GCR/SEP/radiation belts)

APPLICATIONS: the color of the aurora

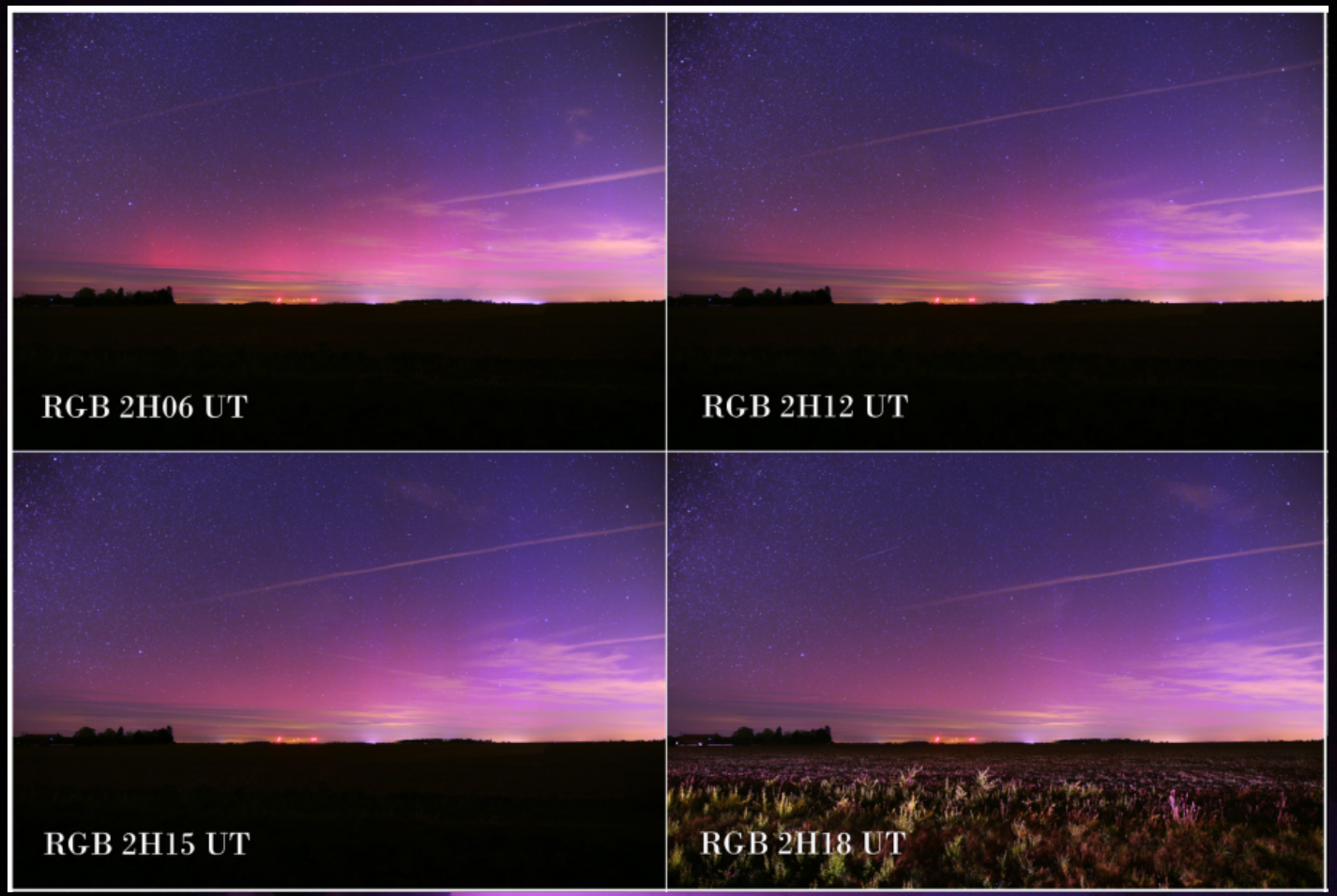


The color of the aurora

The color of the aurora

- The color of the aurora is due to the different ionization/excitation processes
- The main colors are:
  - Green: O(1D) at 557.7 nm
  - Red: O(1S) at 630.0 nm
  - Blue: N2+ at 427.8 nm
  - Violet: N2+ at 391.4 nm (careful about purple)
  - Rose: N2 (bands)

The sunlit aurora (Image: Emmanuel Beaudouin)

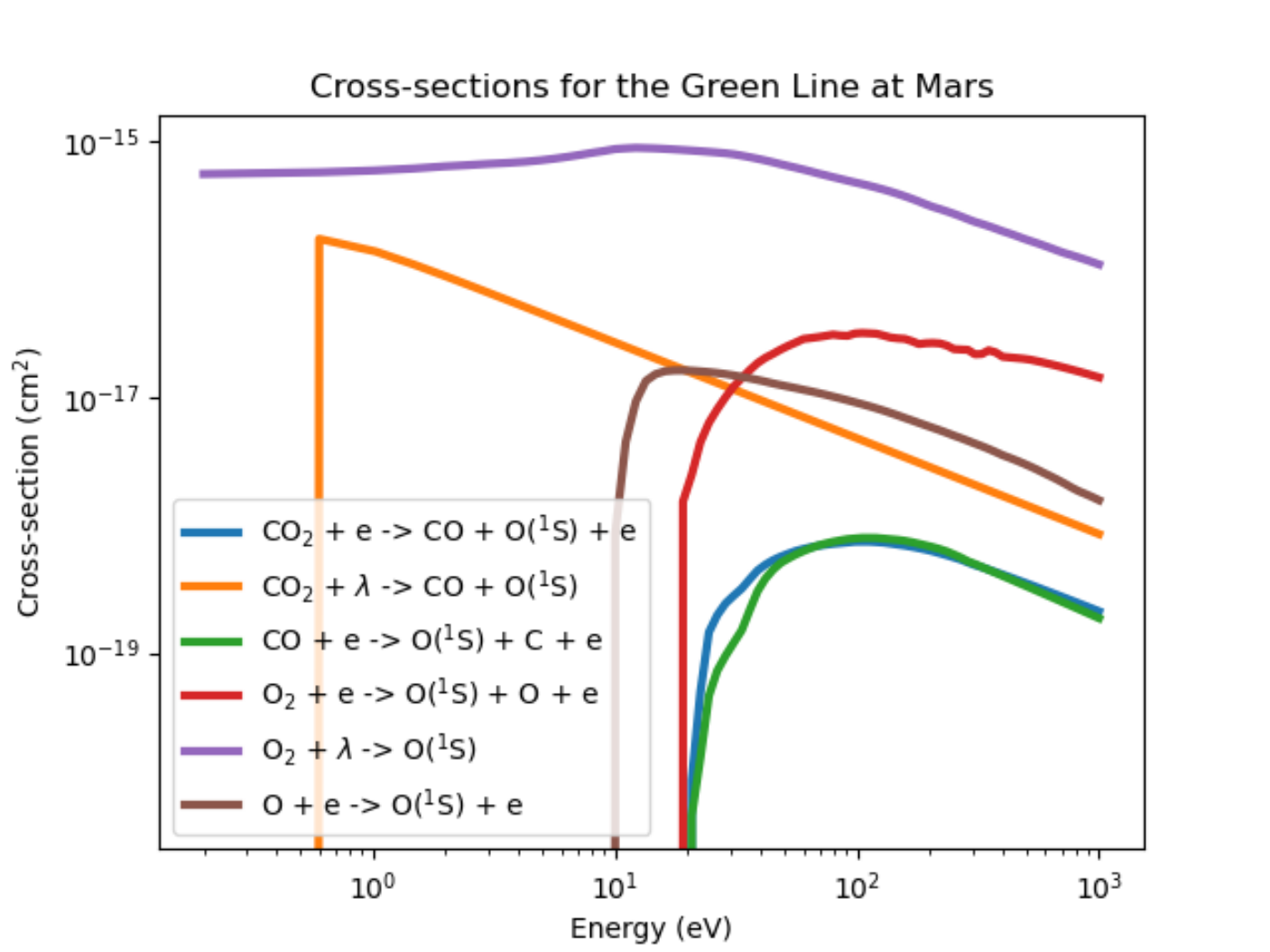


The sunlit aurora (Image: Emmanuel Beaudouin)

The sunlit aurora

- The sunlit aurora is due to the scattering of the sunlight by N2+ (from the aurora)
- Contrarily to usual aurora, the top is blue; while it is usually red (and the bottom is green, or blue/rose/violet if very intense)

Computing the aurora on other planets



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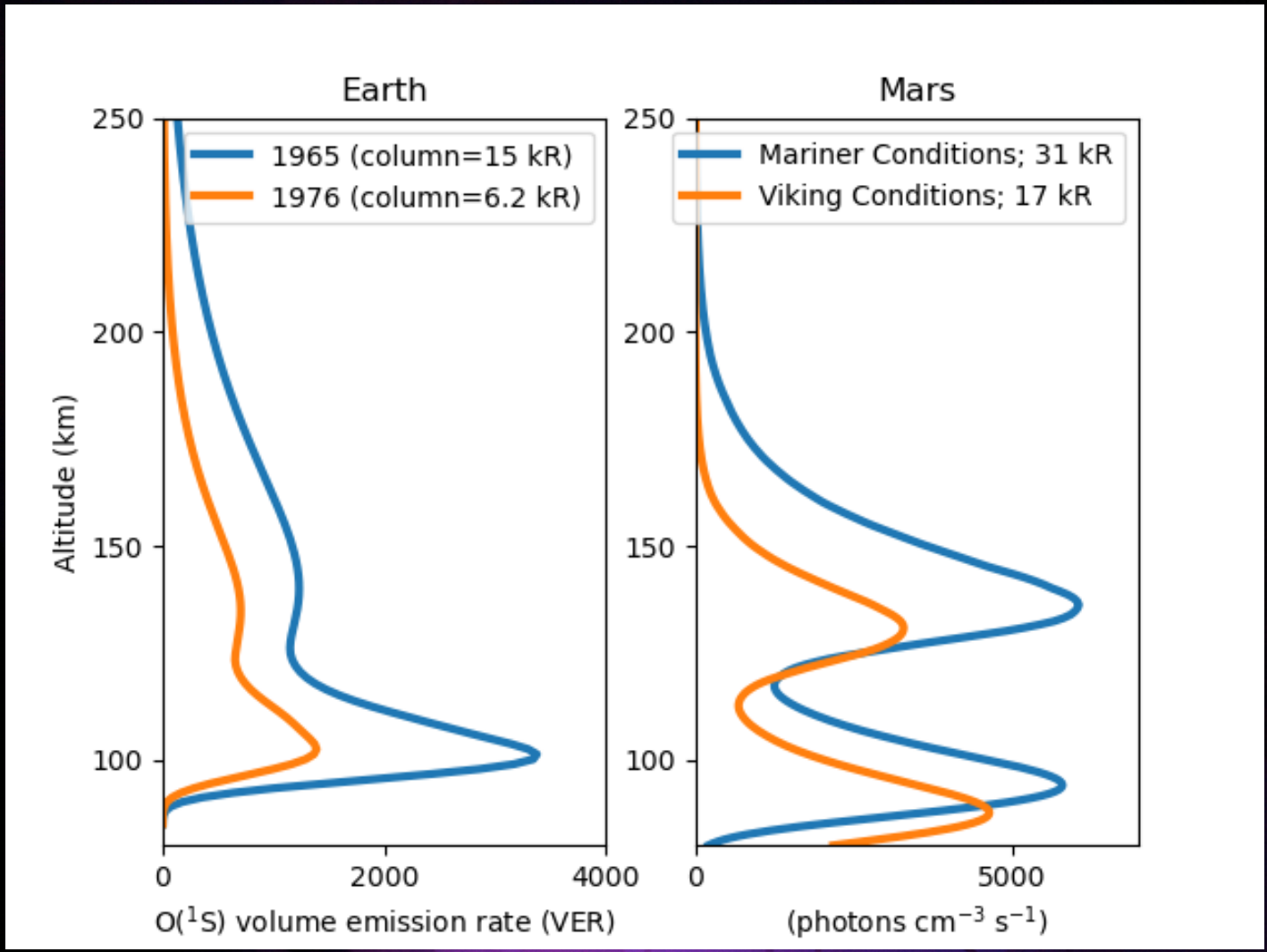
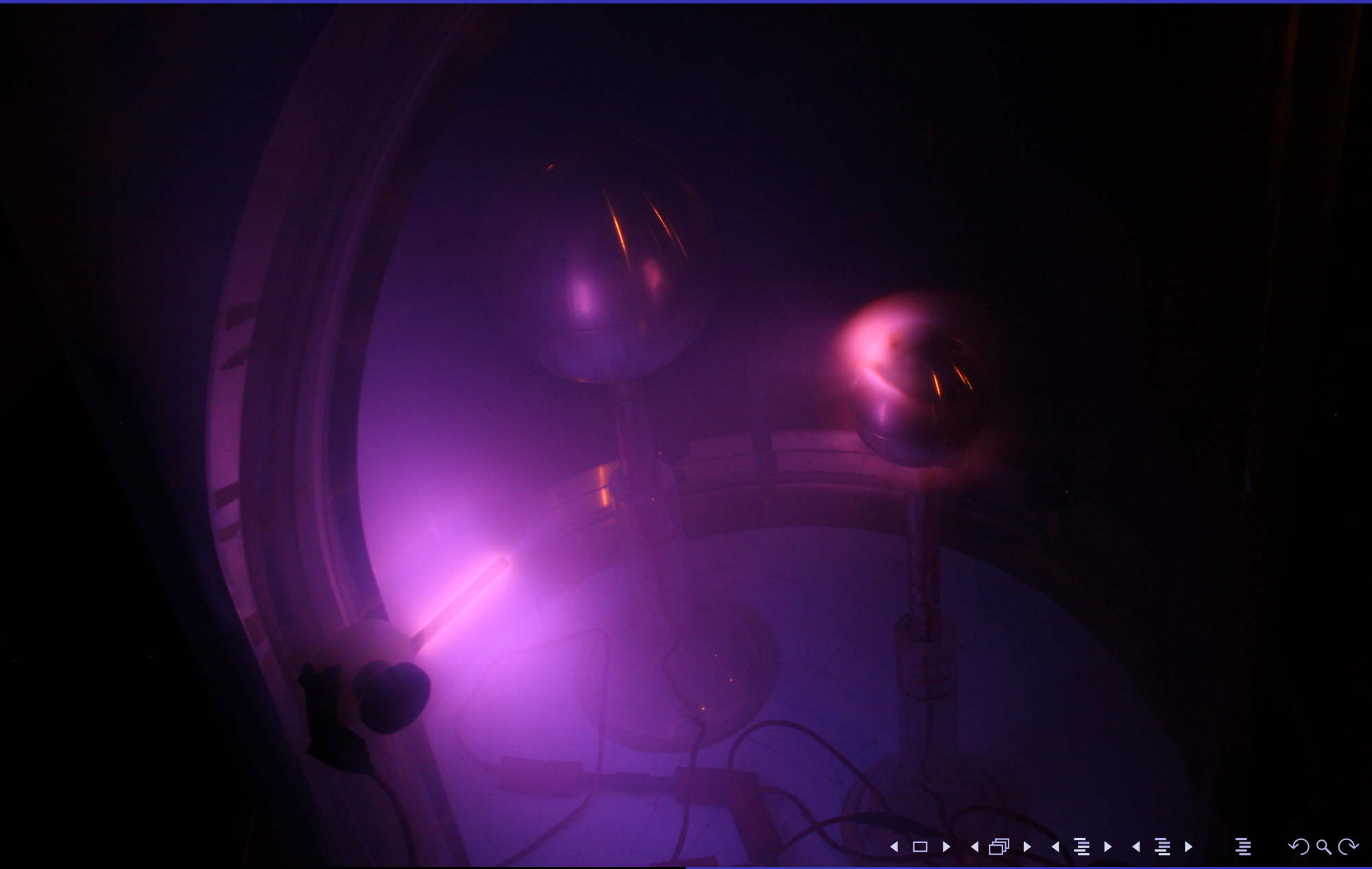


Computing the aurora on other planets

The aurora

- The aurora is due to the precipitation of electrons and protons
- The aurora is a good indicator of the magnetosphere
- The aurora is a good indicator of the solar wind
- The aurora is a good indicator of the atmosphere
- There is also some chemistry involved
- https://authors.elsevier.com/a/1kvfg_6DS4Vu5C

Natural wonders



Natural wonders

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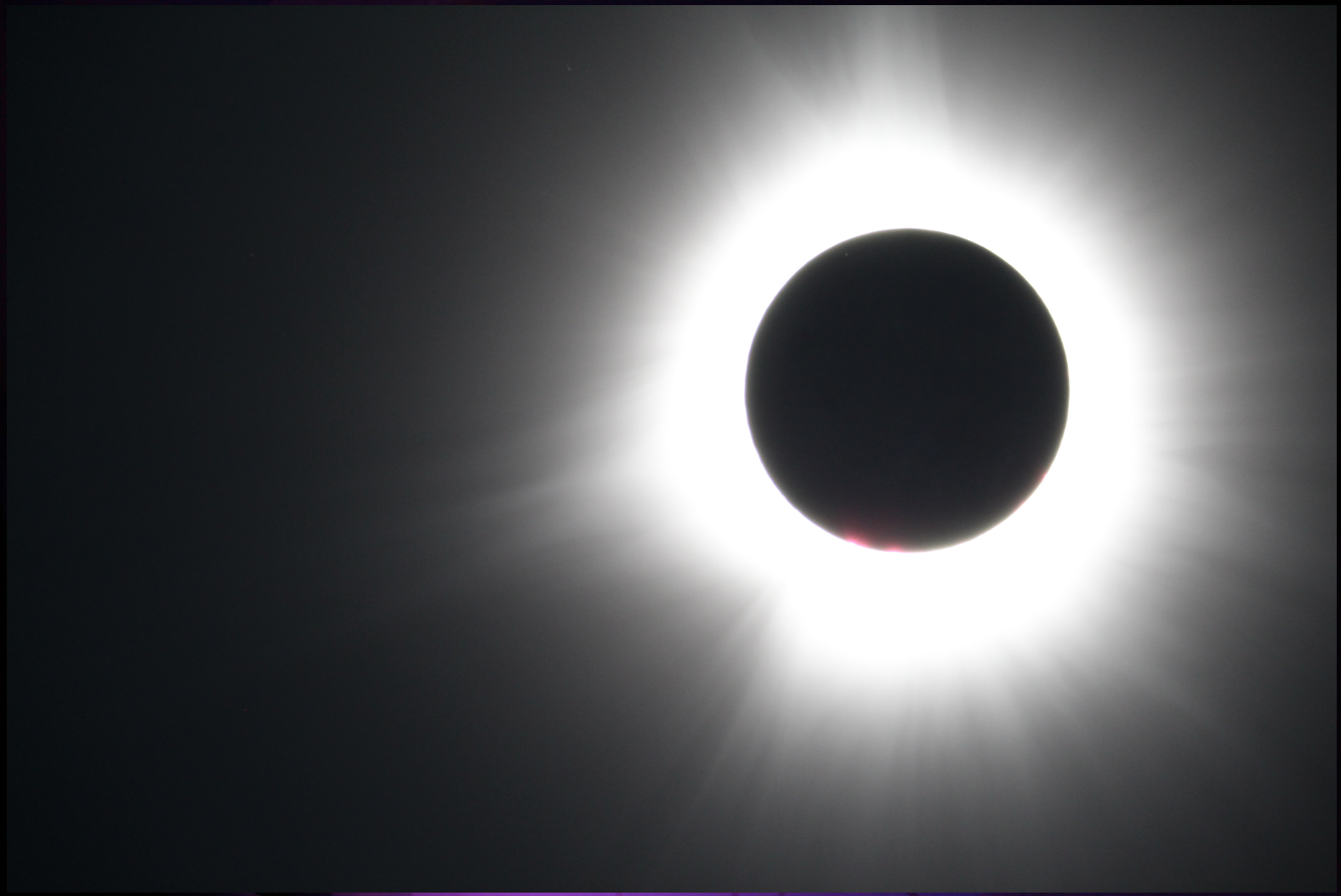

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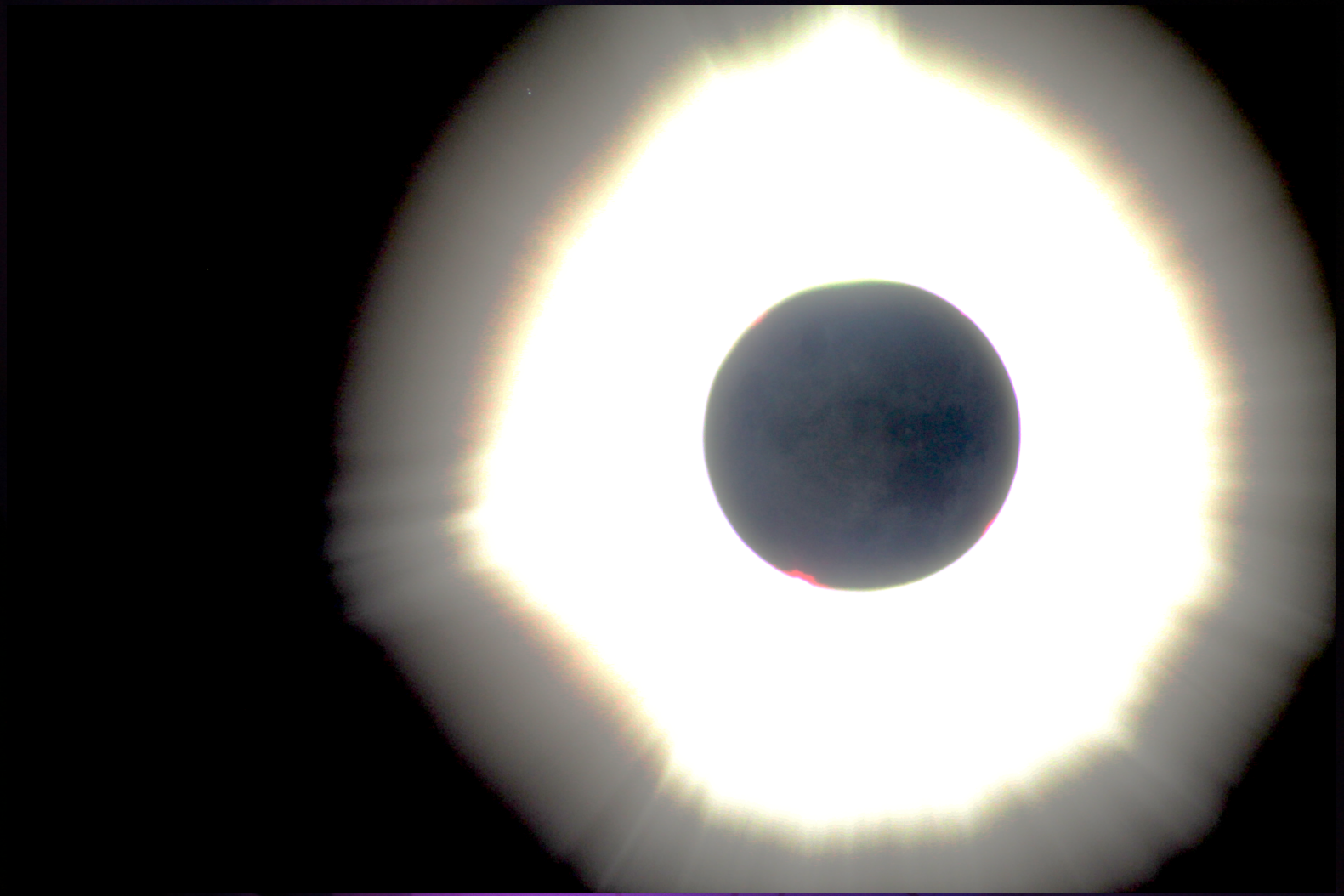

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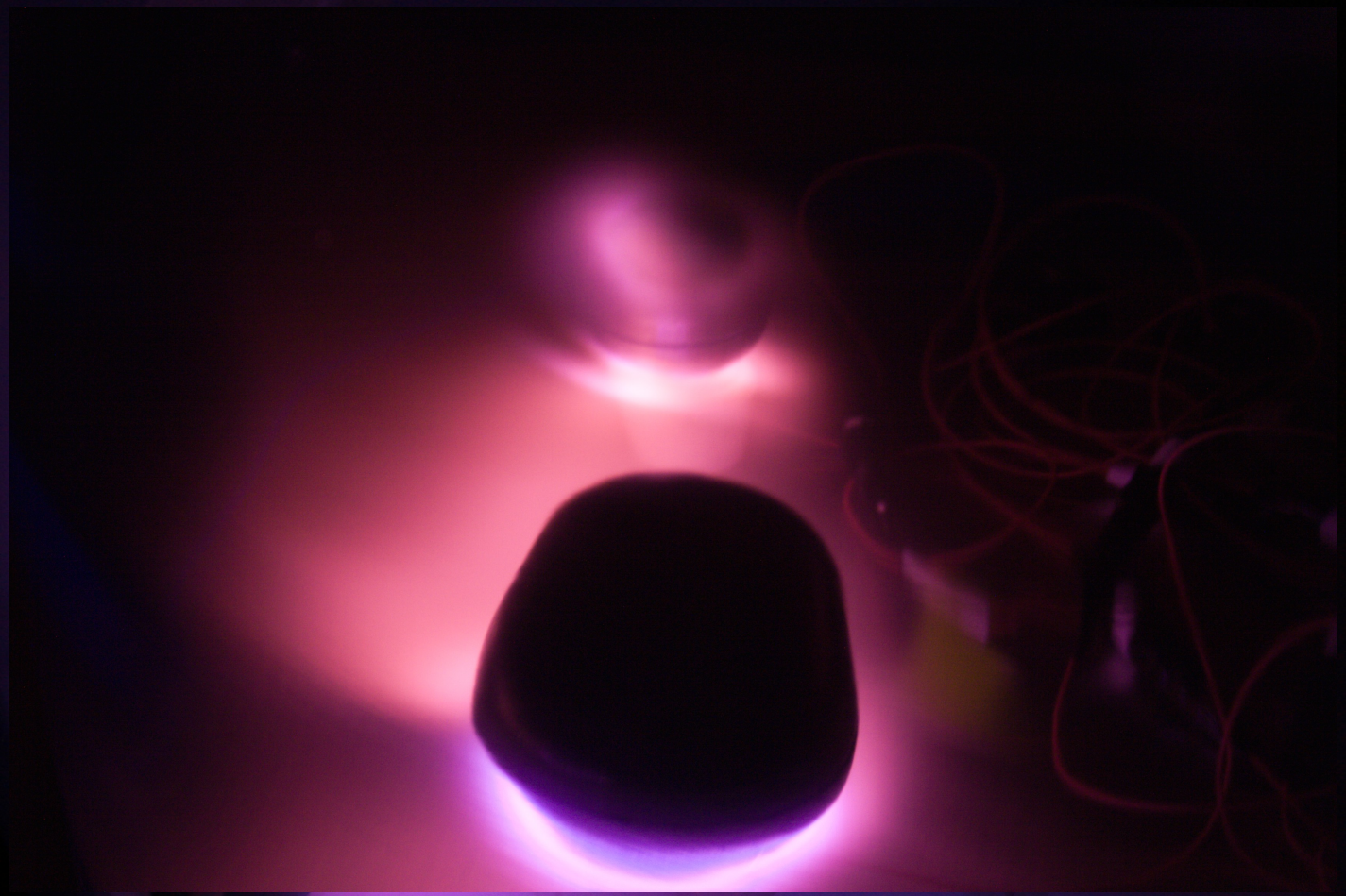
Extra: the Planeterella



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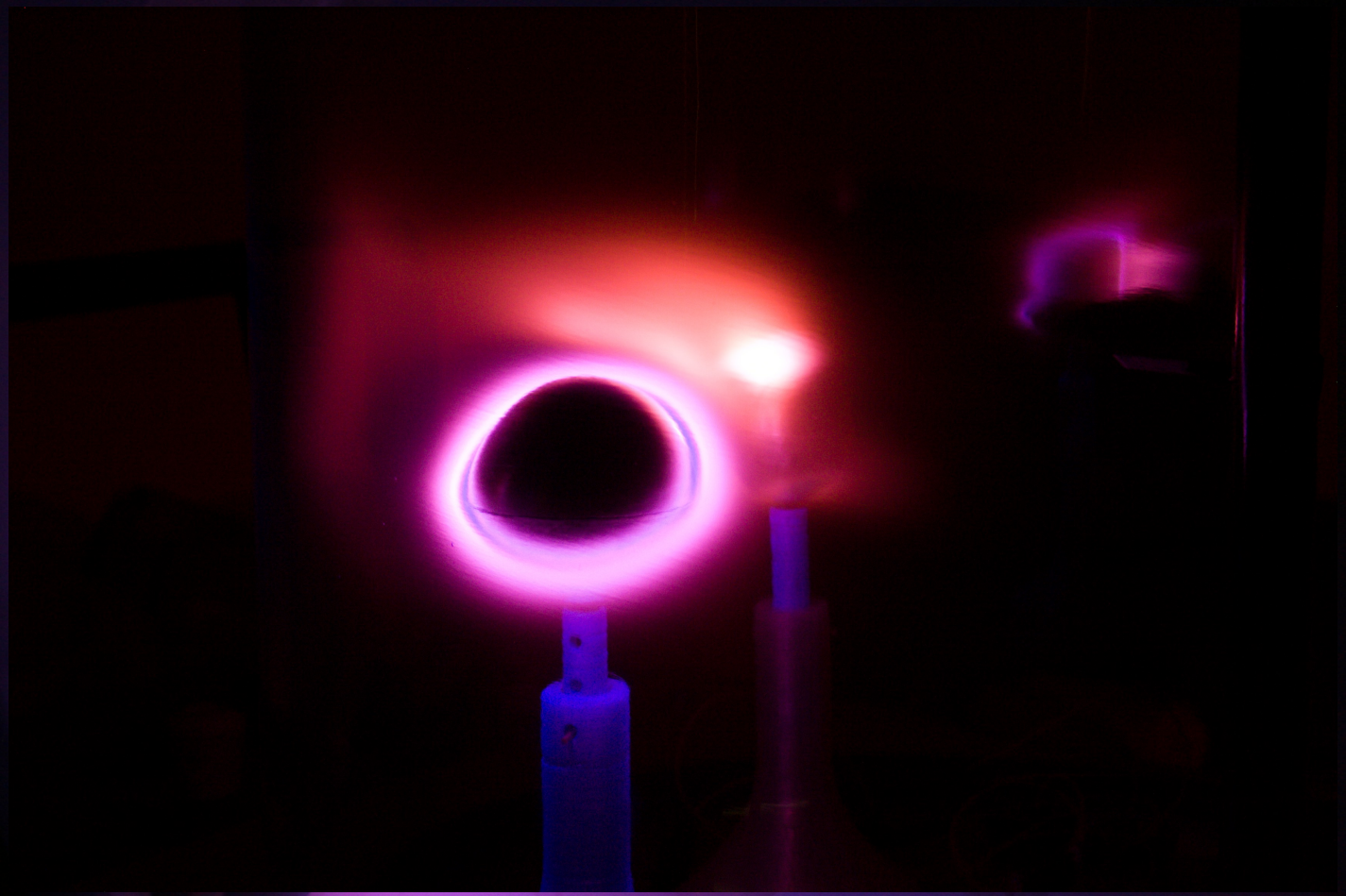

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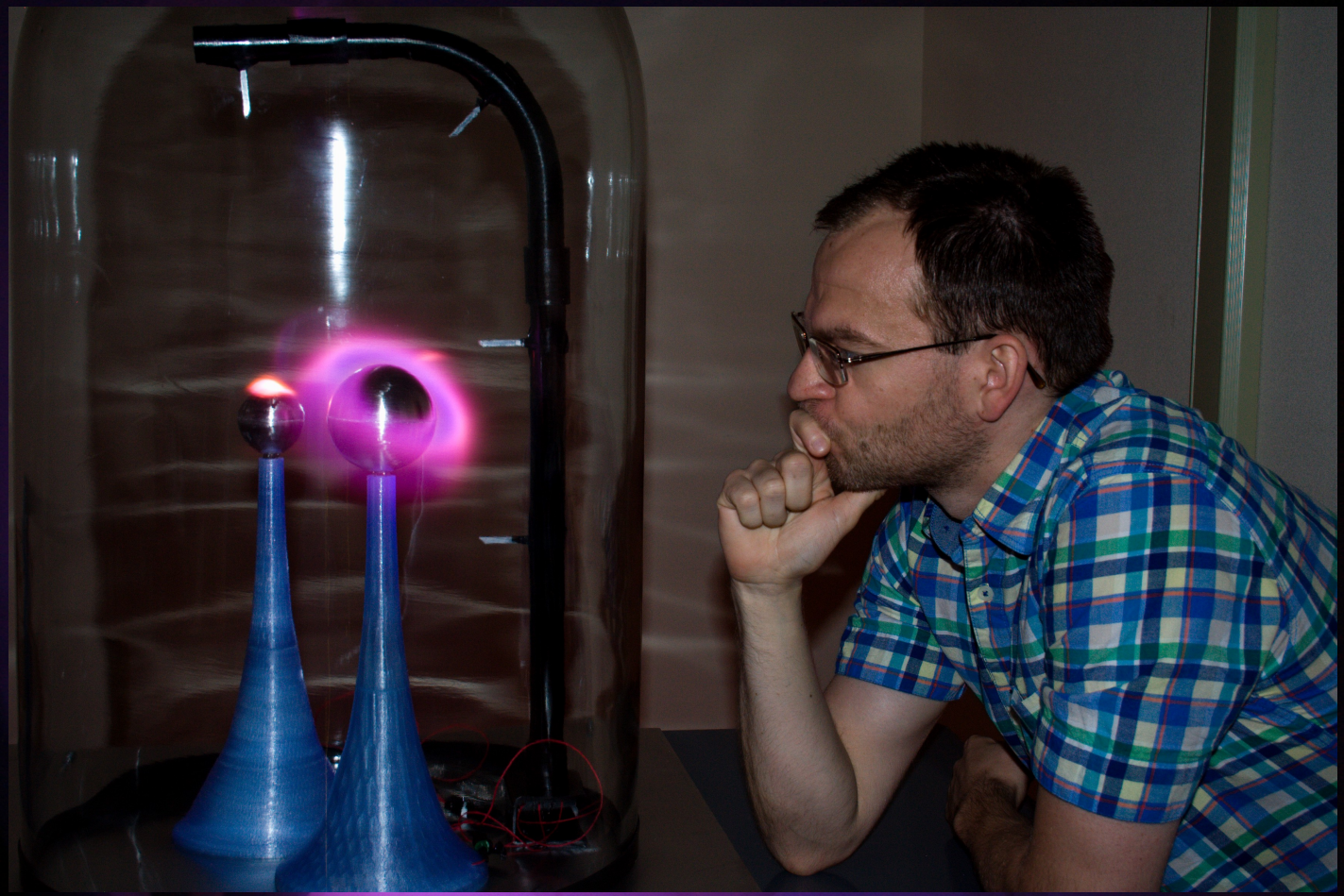

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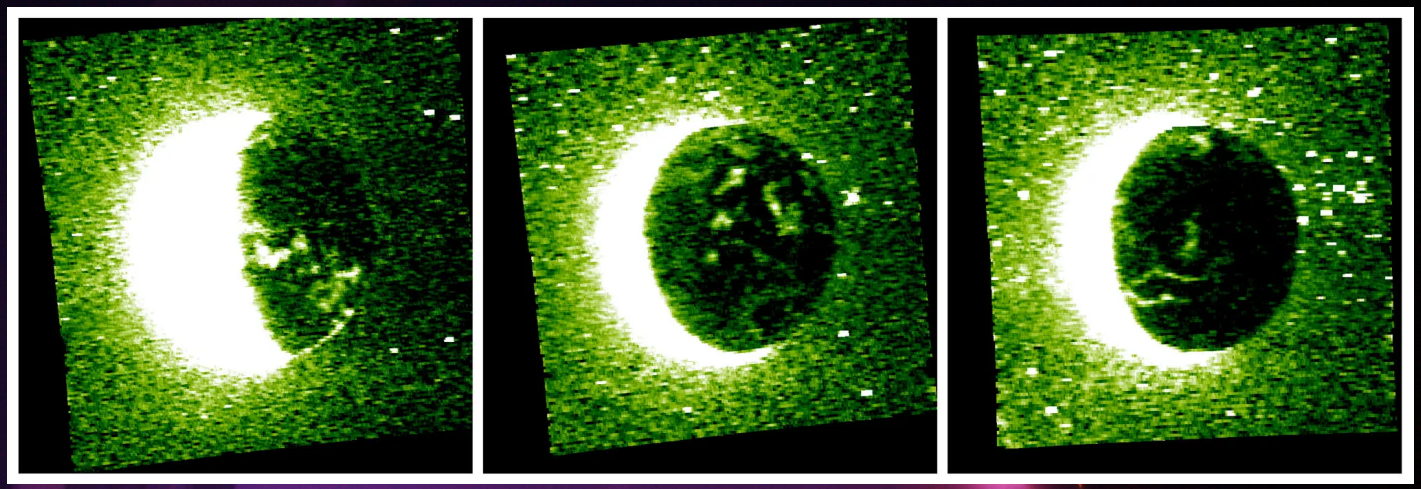

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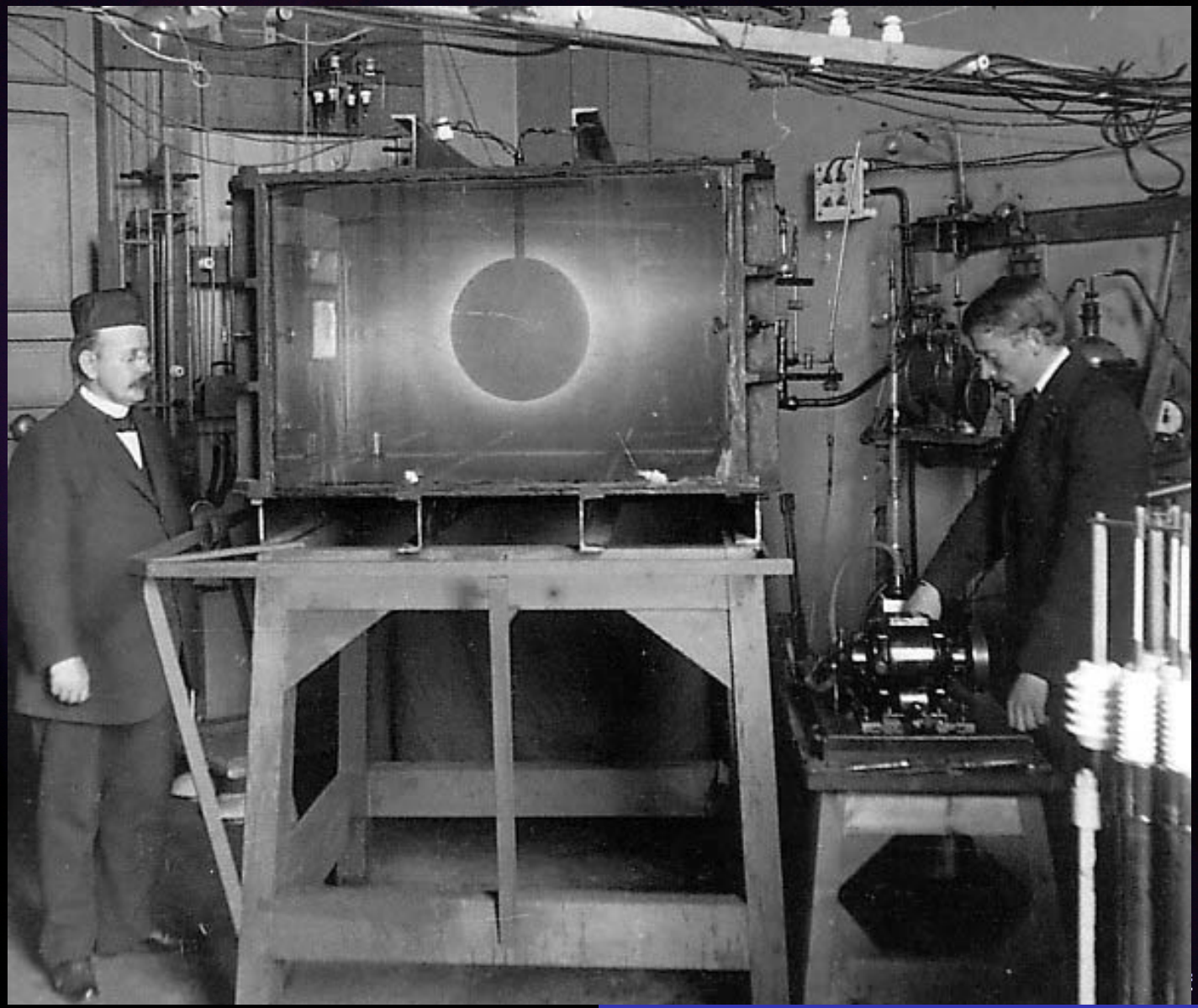

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Thank you

for your attention