Why are there Ionospheres?

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What is an ionosphere?

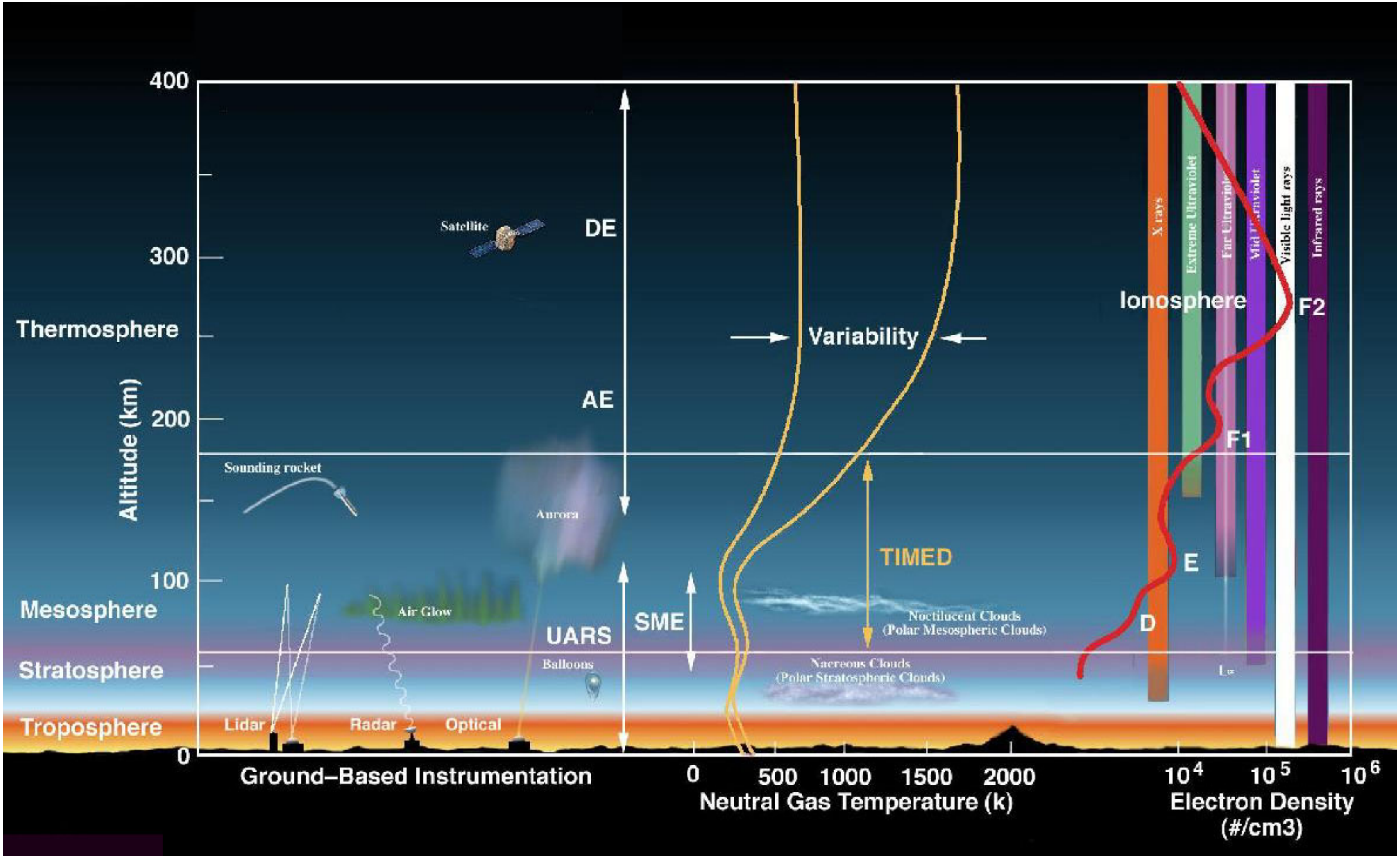
- Type in chat

What is needed to make an ionosphere?

- Raise hand…and I’ll call on you.
- If no one hazards an idea in 5 seconds, I’ll call on “volunteers” (if in person, would give a NASA sticker for those who volunteer).


PHOTO-IONIZATION
Free Electron Released
+ve Charged Atom

Earth's Ionosphere



Conceptual Framework

- Can organize Iono Physics in a number of ways.
- Regions and Processes
  - ionosphere, thermosphere, equatorial, polar
  - ionization, recombination, wave-particle interactions
- Energy and momentum transfer
  - (EM, waves, collisions, excitation, chemistry)
- Techniques
  - Ground and Space-based Observations
  - In Situ and Remote Sensing
  - Physics-based vs Empirical
    - GTIM and IRI

Ionospheres

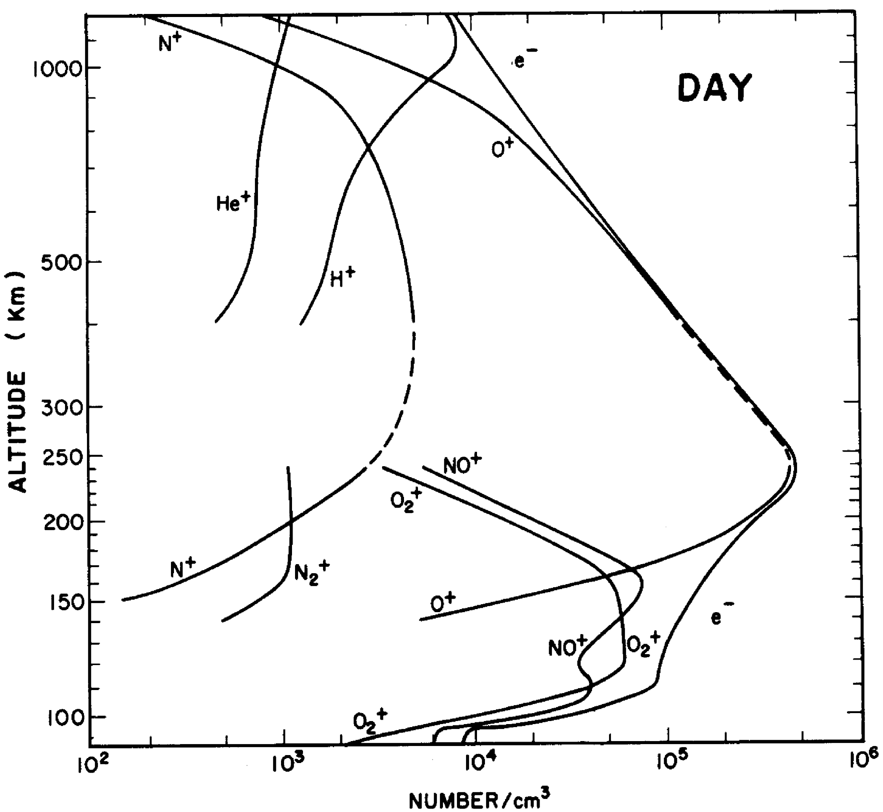
- Note that for much of what has been discussed so far in the HSS, we can neglect most terms in momentum equation and other complications (e.g., ideal MHD, equilibrium etc.)
- Ionospheres often don't allow you to neglect too many terms (gravity, viscosity, collisions, chemistry, neutrals, radiative processes, vertical motion, Electric Fields, …are important)

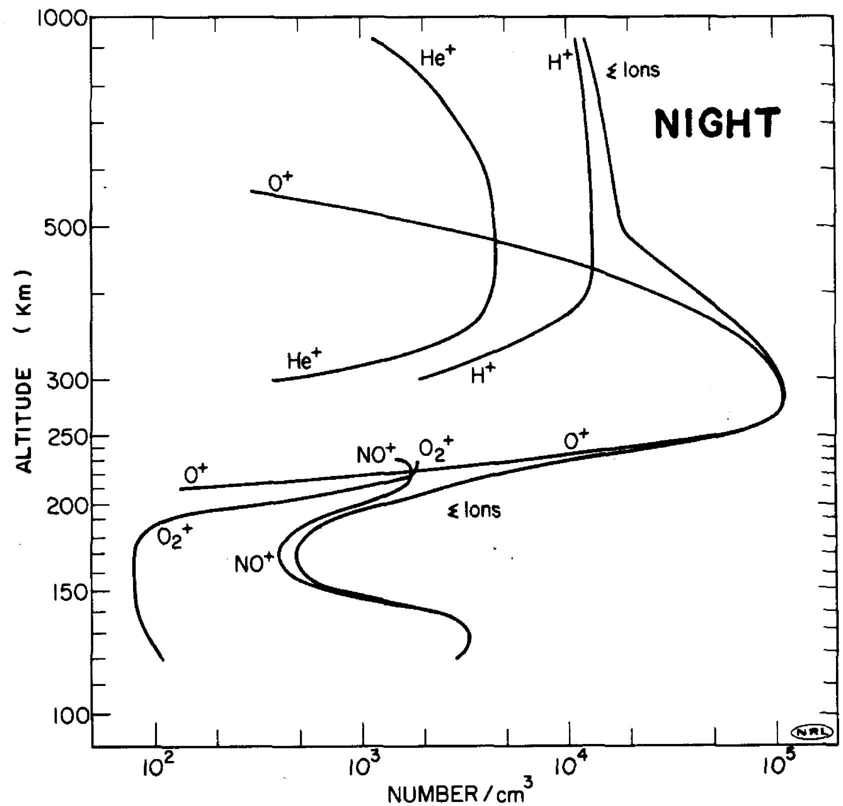
Continuity Equation

- $\frac{dN_i}{dt}$ = Source – Loss + Transport

- Type in chat some source and loss terms for ion density

Ionospheric Composition





Transport

- What equation describes transport?

- What are some of the terms important for ionospheric transport?

Gyration Dominated Plasma Transport

- Charged particle gyroradii are very small compared the vertical size of ionospheric layers
- In the upper ionosphere the ions and electrons are tied to the magnetic field lines
- Transport is gyration dominated: particles can only move along field lines
- Transport equations

$$\frac{\partial m_s n_s}{\partial t} + \nabla \cdot (m_s n_s \mathbf{u}_s) = m_s S_s - L_s m_s n_s$$

$$m_s n_s \frac{\partial \mathbf{u}_s}{\partial t} + m_s n_s \left(\mathbf{u}_s \cdot \nabla\right) \mathbf{u}_s + \nabla p_s - m_s n_s \mathbf{g} - q_s n_s \left(\mathbf{E} + \mathbf{u}_s \times \mathbf{B}\right) = \sum_t m_s n_s \overline{\nu}_{st} \left(\mathbf{u}_t - \mathbf{u}_s\right)$$

$$\frac{3}{2}\frac{\partial p_s}{\partial t} + \frac{3}{2}\left(\mathbf{u}_s \cdot \nabla\right) p_s + \frac{5}{2} p_s \left(\nabla \cdot \mathbf{u}_s\right) + \nabla \cdot \mathbf{h_s} = \sum_t \frac{m_s n_s \overline{\nu}_{st}}{m_s + m_t} \left[3k\left(T_t - T_s\right) + m_t \left(\mathbf{u}_t - \mathbf{u}_s\right)^2\right]$$

- Consider the case of strong magnetic field: B⇒∞. Momentum equation

$$\pm \Omega_{cs} u_{s\perp} = \sum_t \overline{\nu}_{st} \left|\mathbf{u}_t - \mathbf{u}_s\right|$$

- If collision frequency is small, there can be no perpendicular transport

$$\mathbf{u}_s = u_s \mathbf{b}$$

Field-Aligned Transport

- Continuity equation

$$\frac{\partial m_s n_s}{\partial t} + m_s n_s u_s \left(\nabla \cdot \mathbf{b}\right) + \left(\mathbf{b} \cdot \nabla\right)\left(m_s n_s u_s\right) = m_s S_s - L_s m_s n_s$$

$$\left(\nabla \cdot \mathbf{b}\right) = \left(\nabla \cdot \frac{\mathbf{B}}{B}\right) = -\frac{1}{B}\frac{\partial B}{\partial s}$$

$$\frac{\partial}{\partial t}\left(\frac{m_s n_s}{B}\right) + \frac{\partial}{\partial s}\left(\frac{m_s n_s}{B} u_s\right) = \frac{m_s S_s}{B} - L_s \frac{m_s n_s}{B}$$

  – Flux tube area: 1/B

- Momentum equation

$$m_s n_s \frac{\partial u_s}{\partial t} + m_s n_s u_s \frac{\partial u_s}{\partial s} + \frac{\partial p_s}{\partial s} - m_s n_s g_{\|} - q_s n_s E_{\|} = \sum_t m_s n_s \overline{\nu}_{st}\left(u_{t\|} - u_s\right)$$

- Energy equation

$$\frac{3}{2}\frac{\partial}{\partial t}\left(\frac{p_s}{B}\right) + \frac{3}{2}\frac{\partial}{\partial s}\left(u_s \frac{p_s}{B}\right) + p_s \frac{\partial}{\partial s}\left(\frac{u_s}{B}\right) + \frac{\partial}{\partial s}\left(\frac{h_s}{B}\right) =$$
$$\frac{m_s n_s}{B}\sum_t \frac{\overline{\nu}_{st}}{m_s + m_t}\left[3k\left(T_t - T_s\right) + m_t\left(\mathbf{u}_t - \mathbf{u}_s\right)^2\right]$$

Ambipolar Electric Field

- Steady-state electron momentum equation

$$m_e n_e u_e \frac{du_e}{ds} + \frac{dp_e}{ds} - m_e n_e g_\parallel + e n_e E_\parallel = \sum_t m_e n_e \overline{\nu}_{et} \left(u_{t\parallel} - u_e \right)$$

- Simplify
  - Neglect gravity
  - Neglect collisions

$$\frac{dp_e}{ds} + e n_e E_\parallel = 0 \qquad \rightarrow \qquad E_\parallel = -\frac{1}{e n_e} \frac{dp_e}{ds}$$

  - This is the ambipolar (or polarization) electric field
- Ion momentum equation

$$m_i n_i u_i \frac{du_i}{ds} + \frac{dp_i}{ds} - m_i n_i g_\parallel - e n_i E_\parallel = -\overline{\nu}_{in} m_i n_i u_i$$

  - Low-speed approximation

$$u_i = -\frac{1}{\overline{\nu}_{in} m_i n_i} \left[\frac{dp_i}{ds} - m_i n_i g_\parallel - e n_i E_\parallel \right]$$

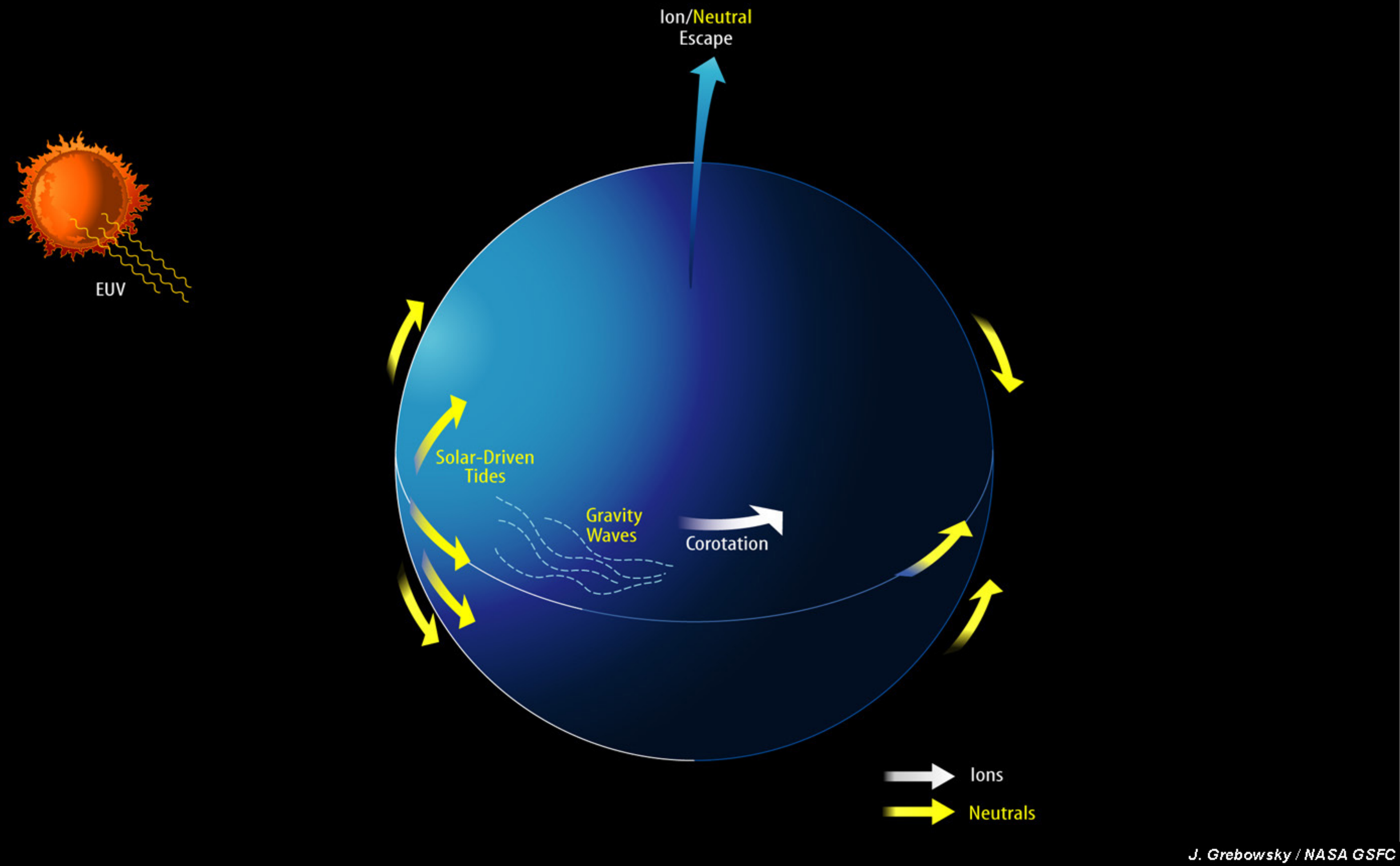
  - Substituting the ambipolar electric field

$$u_i = -\frac{1}{\overline{\nu}_{in} m_i n_i} \left[\frac{d(p_i + p_e)}{ds} - m_i n_i g_\parallel \right]$$

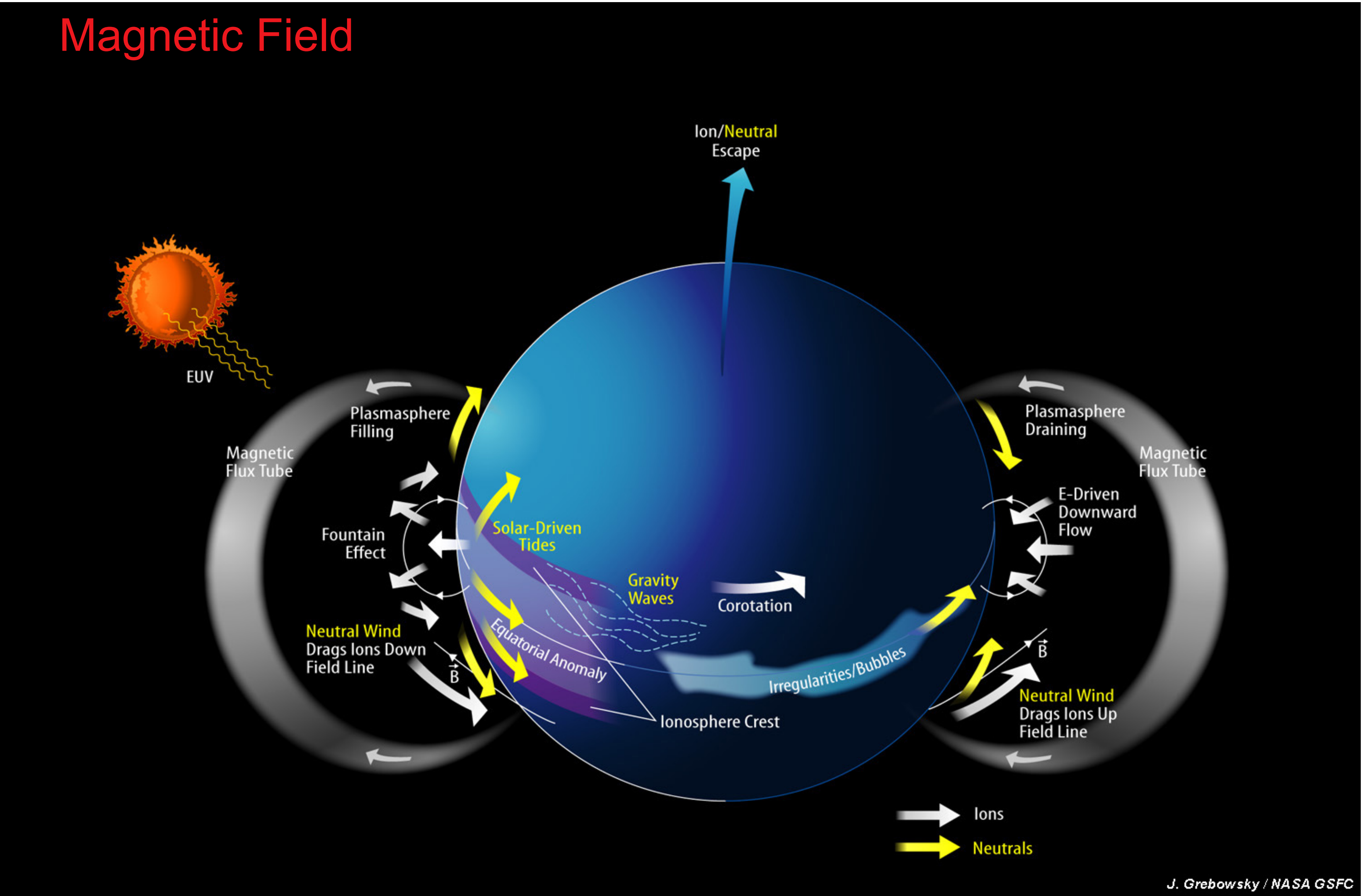
- Diffusive equilibrium (isothermal)

$$n_i = -\frac{k(T_e + T_i)}{m_i g} \frac{dn_i}{dz} \qquad n_i = n_{i0} \exp\left(-\frac{z - z_0}{H_i} \right) \qquad H_i = \frac{k(T_e + T_i)}{m_i g}$$

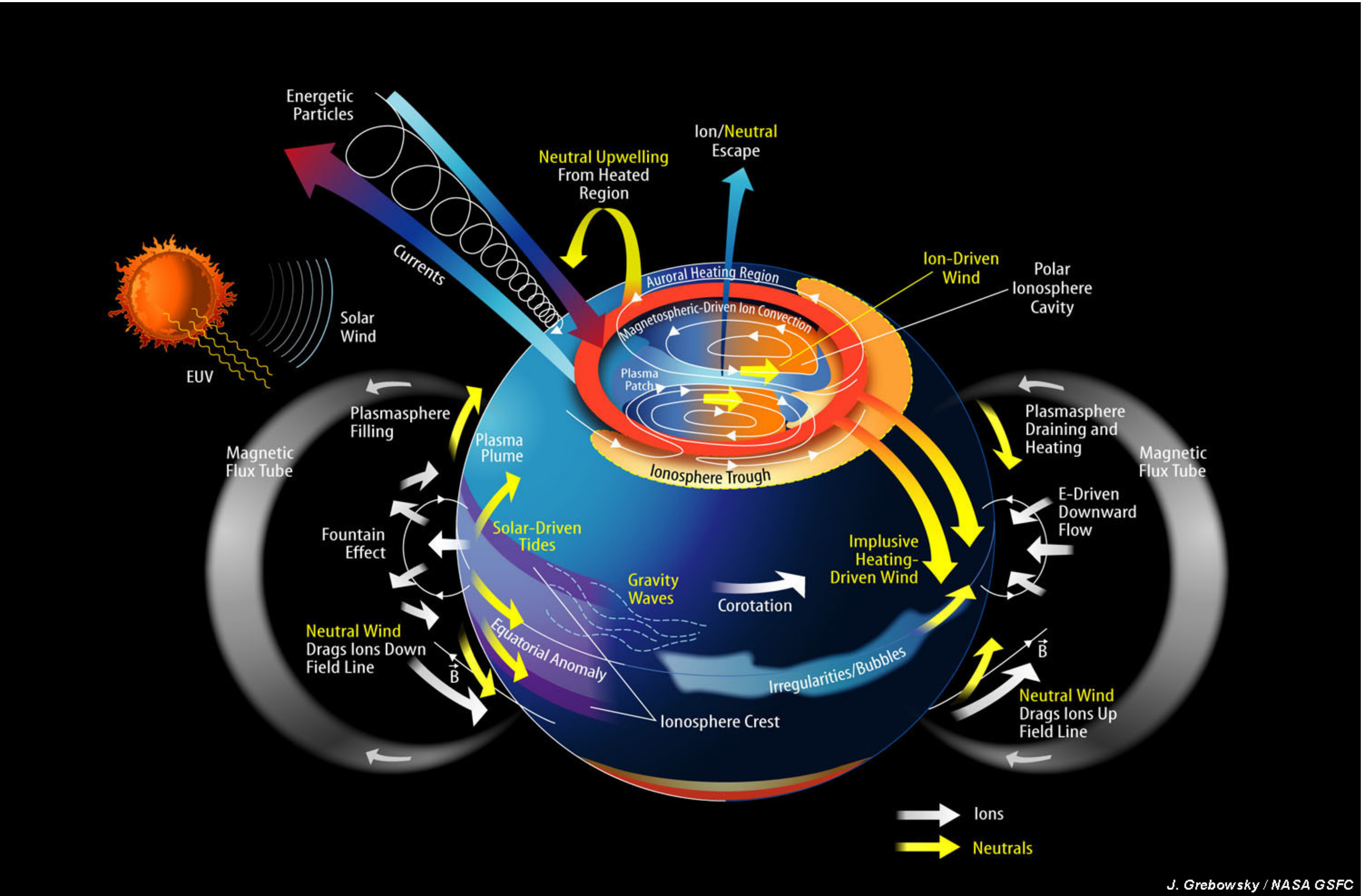
Solar EUV Effects
No Magnetic Fields



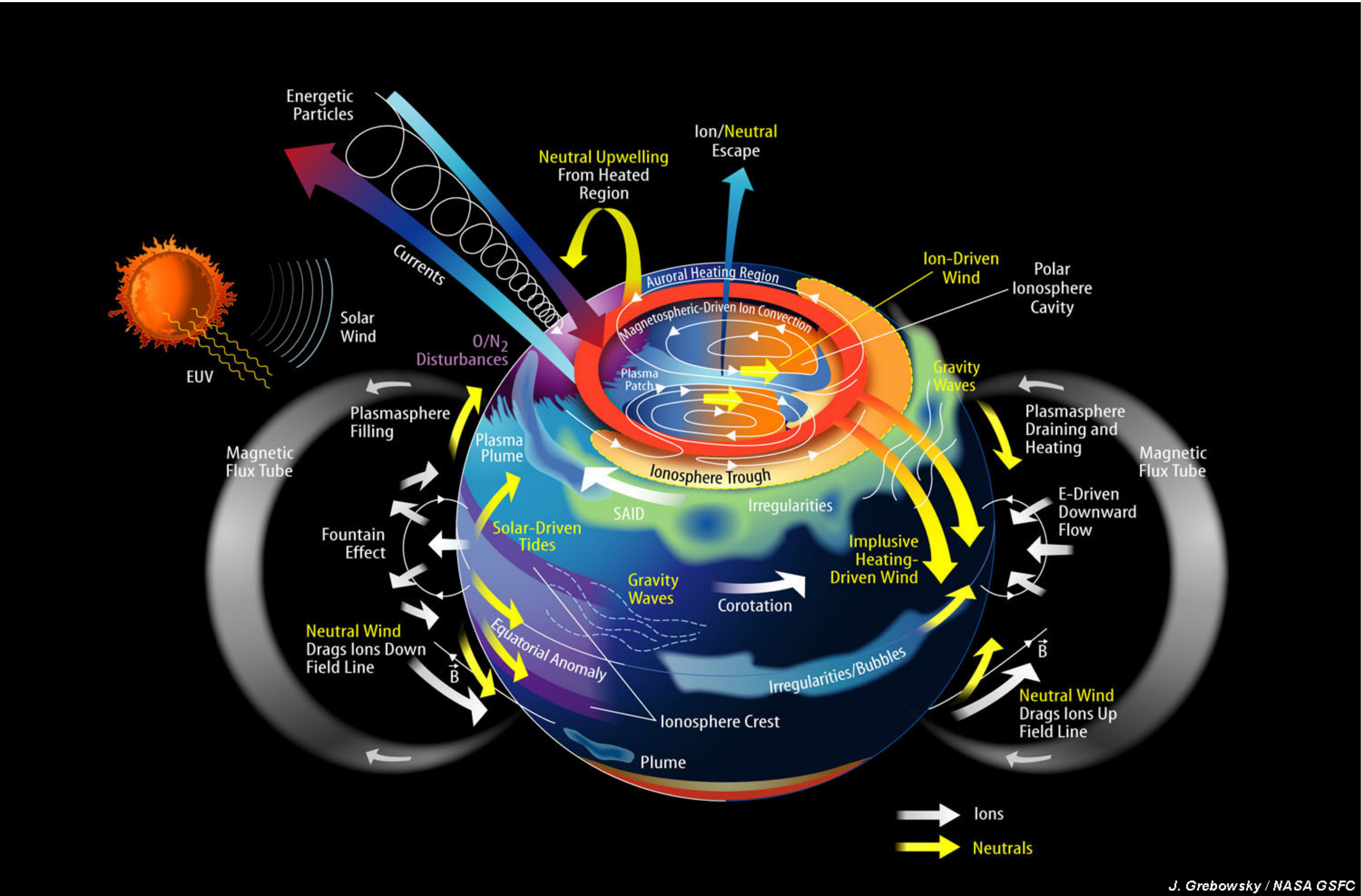
Addition of Earth's Magnetic Field



Addition of Solar Wind And IMF



Addition of Geomagnetic Storms



Ionospheres

- Any gravitationally bound atmosphere with EUV and/or energetic particle flux provides ionization will form an ionosphere.
- Density structure depends on Source and Loss (incoming EM and particle flux, neutral density (scale height – composition, temp, and gravity), chemistry) and transport (presence (strength and configuration) or absence of magnetic field, Poynting Flux/FAC, Joule heating, EM coupling (dynamo and ExB)

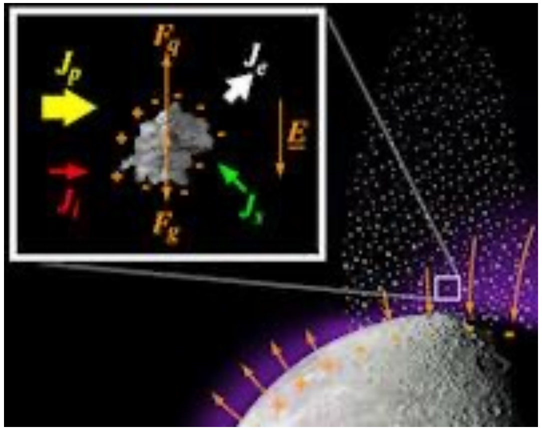
Does the Moon have Ionosphere?

- How could you know?
- If so, what is the dominant charged particle?

Moon Dust!

- Radio waves refract through lunar ionosphere - discovered by Apollo

- Stubbs et al., (2011) showed it was charged lunar dust!



doi: 10.1016/j.pss.2011.05.011.