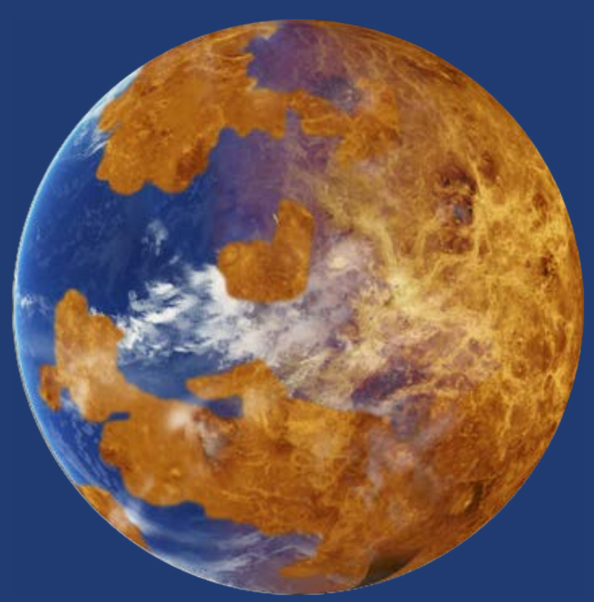

Key Unknowns for Venus Atmospheric Evolution 2: Consequences of a Venus-Like Magnetosphere for Hydrodynamic Xenon (heavy) Ion Escape

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Key Takeaways

- A photo-ionized hydrogen polar wind may drive Xenon fractionation at Earth [Zahnle+ 2019].
- An analogous "Venusian polar wind" can exist at Venus, which could fractionate the atmosphere via similar processes.
- DaVINCI will measure isotopic fractionation at Venus; we identify what additional new measurements of the Venusian upper atmosphere are needed to contextualize these.

1. Fractionation of Xenon at Earth via polar wind

- Terrestrial Xenon is heavily fractionated compared to the lighter noble gases and meteoritic sources.
- Escape of Xenon as an ion provides an avenue for this fractionation:
  - Strong early EUV conditions (>x10 current day) drive substantial H escape and polar wind-like escape of H^+ produced by photoionization.
  - Xenon ions (produced via photoionization and charge exchange with H^+) are dragged up and away to space by collisions with polar wind H^+.
  - Gravity drives the fractionation of escaping Xe^+.
- Ions flow along magnetic fields: thus Earth's dipole magnetosphere leads to H^+ and Xe^+ outflow at the polar regions.

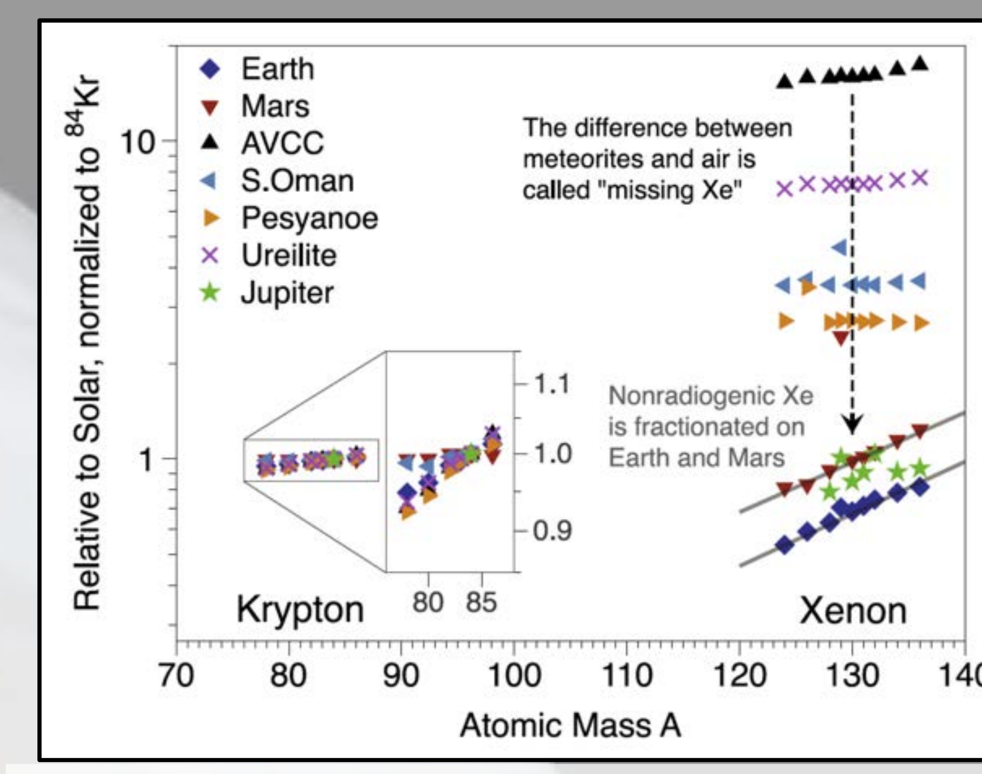

Figure 1: From Zahnle+ 2019. **Measurements of the Earth's upper atmosphere have been crucial in understanding the isotopic fractionation of terrestrial Xe.**

2. Polar wind analogy at Venus

- Venus does not posses a global dipole magnetic field, but polar wind like escape can still occur.
- Solar wind magnetic field drapes around the planet: this produces physical conditions in the magnetotail equivalent to those in the polar regions at Earth.
- The escape of H^+ down the tail could drive the loss and fractionation of heavy ions in a similar fashion to Earth's polar wind.
- PVO and Venus EXpress observed H^+ and O^+ escaping down the Venusian magnetotail. These missions were not capable of distinguishing higher mass ions nor identifying the driving mechanisms of this escape.

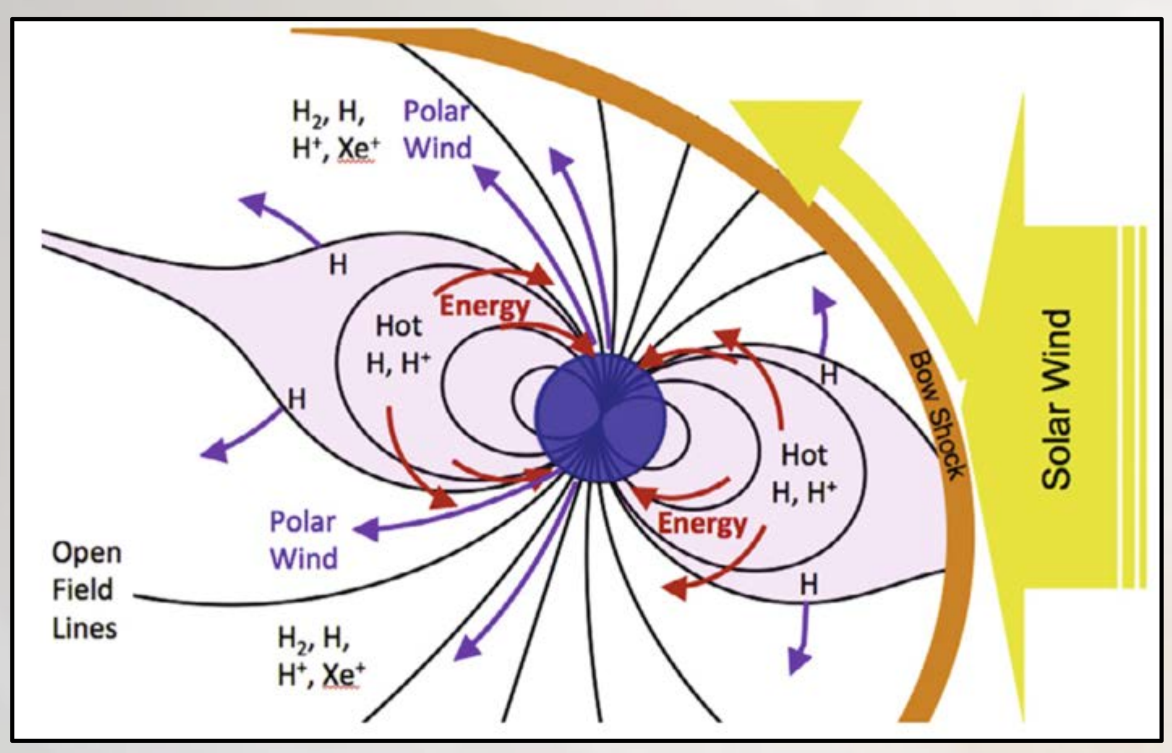

Figure 2: From Zahnle+ 2019; depiction of the polar wind region at Earth. Magnetic fields at the poles are ~vertical and "open" (connect to the solar wind), allowing Xe^+ to escape (ions travel along magnetic field lines).

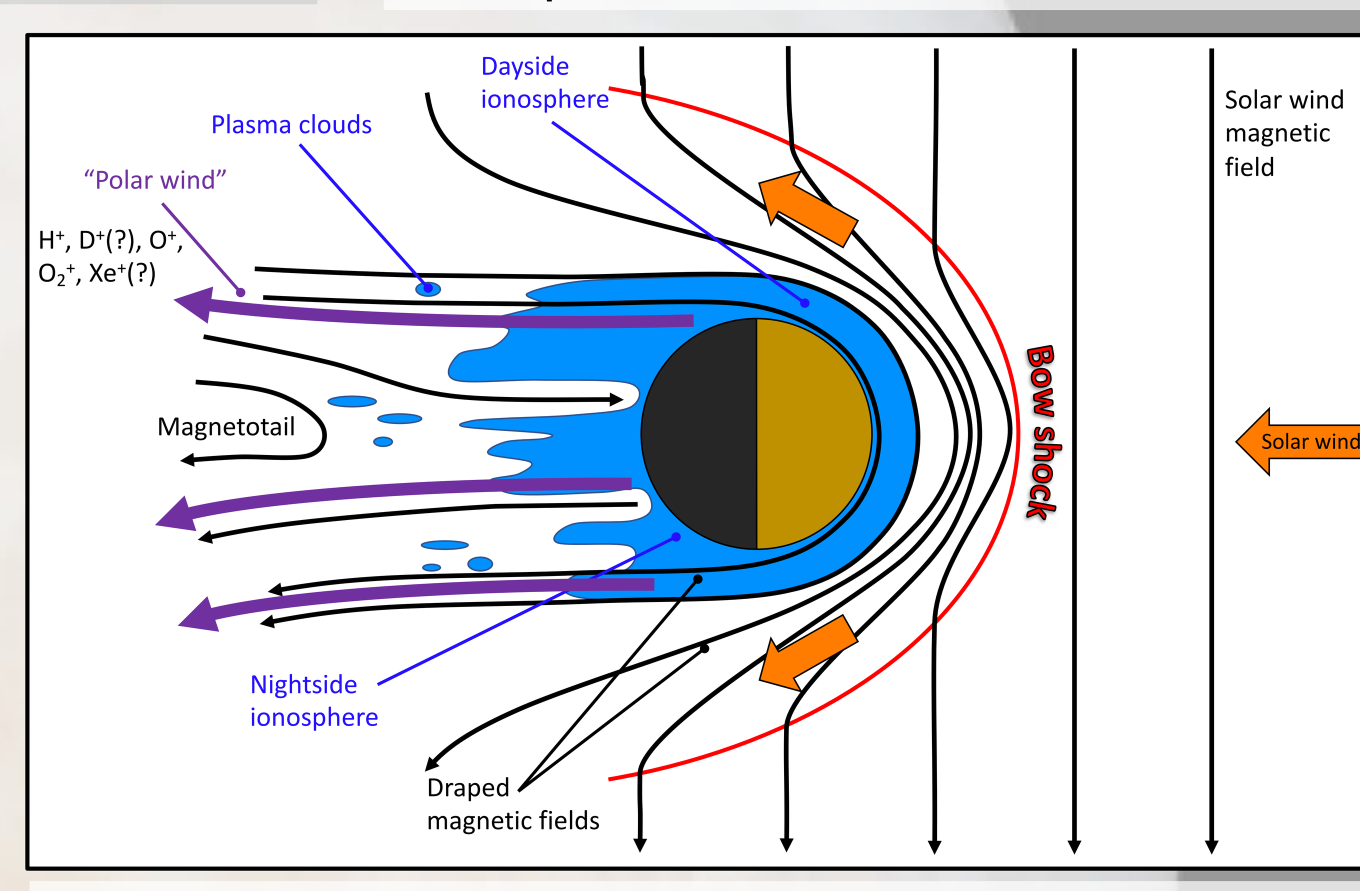

Figure 3: depiction of the Venusian polar wind analogy. The solar wind magnetic field drapes around Venus, producing ~vertical magnetic fields on the nightside. Ions can thus escape down the magnetotail region, in a fashion analogous to that depicted at the polar regions in Figure 2.

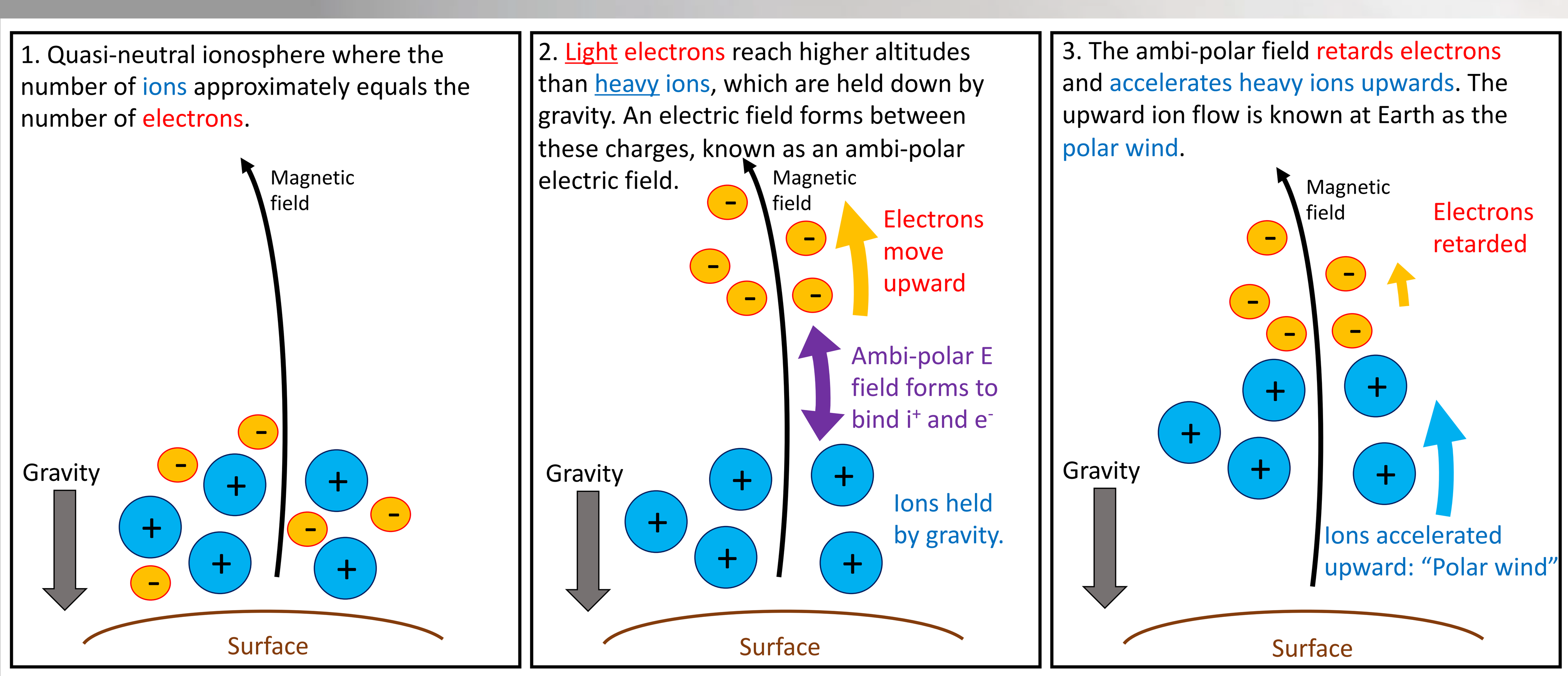

Figure 4: Cartoon depiction of how the polar wind forms. The underlying physics is the same at Earth and Venus.

3. The physics of the polar wind

- In planetary ionospheres, relatively heavy ions reside close to the ground due to gravity, while lighter electrons can reach higher altitudes.
- This creates a separation of charge and thus an electric field, known as an ambi-polar electric field.
- The ambi-polar field pulls electrons downward, and accelerates ions upwards. This upwards acceleration can be enough for the ions to escape, especially lighter ions such as H^+.
- Electrons and ions travel along magnetic fields. Escape confined to polar regions at Earth, but can be global at Venus (Figures 2 and 3).
- "Magnetic topology" defines the regions that a magnetic field line connects to. The polar wind requires access to both an ion reservoir below (ionosphere) and space above (the solar wind) – known as "open" topology.

5. What measurements are needed from future Venus missions?

Aspect and motivation	Quantities	Instrument
Photochemistry: drives upper atmospheric structure, composition and energetics.	Major neutrals and ions in the upper atmosphere.	Mass spectrometer (capable of measuring winds?).
Magnetic topology: information on where magnetic field lines connect to.	Magnetic field and suprathermal (>3eV) electrons.	Magnetometer, electrostatic analyzer.
Ion and electron heating: what mechanisms transfer energy to the charged particles so that they can escape to space.	Ion and electron distribution functions.	Electrostatic analyzers.
Solar EUV and solar wind: constrain energy input to Venus and global configuration of the Venusian polar wind region (magnetotail).	Solar EUV, solar wind magnetic field and velocity.	EUV monitor, magnetometer, electrostatic analyzer.
High cadence sampling: Venus' magnetosphere and ionosphere are highly dynamic over spatial scales <10s km.	Cadences of =<1-5 s. Full range of local time, latitude, etc.	Mass spectrometer, electrostatic analyzers, magnetometer.

4. Discussion: contextualizing upcoming DaVINCI measurements of the lower atmosphere

- **DaVINCI will measure isotopic fractionation in the lower atmosphere at Venus.**
- **We need to know the physics of the system to interpret these. This includes measurements of the upper atmosphere.**
- **Here we suggest that a mechanism involving collisions between outflowing H^+ and heavier ions (that may drive fractionation of these heavy species) merits further investigation.**
- **Once we understand outflow and the processes that control it today, we can start to think about how it worked in the past under more extreme solar conditions.**