# Comparison of Terrestrial and Martian TEC at Dawn and Dusk during Solstices

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# Motivation

- The Earth and Mars are arguably the most similar of the solar planets
  - They are both inner, rocky planets
  - They have similar axial tilts
  - They both have ionospheres that are formed primarily through EUV and X-ray radiation
- Planetary differences can provide physical insights

# Total Electron Content (TEC)

- The Global Positioning System (GPS) measures TEC globally using a network of satellites and ground receivers
- MIT Haystack provides calibrated TEC measurements
  - Available from 1999 onward
  - Includes all open ground and space-based sources
  - Specified with a 1˚ latitude by 1˚ longitude resolution with error estimates

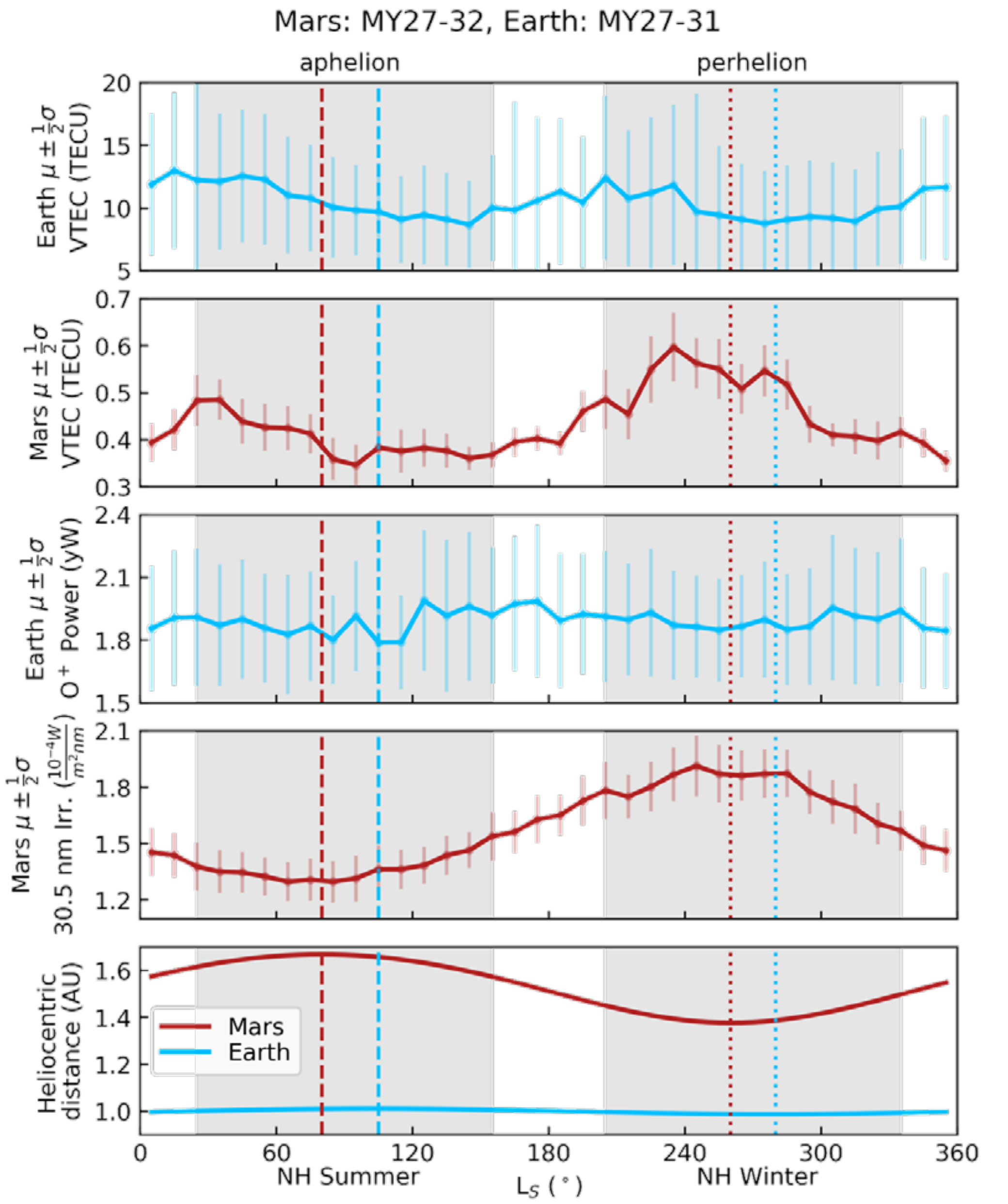
- The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) measures the TEC between the Martian surface and Mars Express
- Mars Express has an inclination of 86.9˚ and a period of 7h, allowing observations of all locations and times
- TEC is available for solar zenith angles (SZA) greater than 75˚

Rideout and Coster (2006) doi:10.1007/s10291-006-0029-5, 2006.

Picardi and Sorge (2000), In: Proc. SPIE. Eighth International Conference on Ground Penetrating Radar, vol. 4084, pp. 624–629.

# Data Selection

- Both Earth and Mars data are grouped by Martian Year (MY)
  - Earth: 04 July 2005 – 30 July 2013, MY 27-31
  - Mars: 04 July 2005 – 17 June 2015, MY 27-32
  - A partial MY 27 is used at Earth to ensure identical solar cycle coverage at both planets
- Seasons centred about solstices
  - NH Winter/SH Summer: 205˚ < $L_S$ < 335˚
  - SH Winter/NH Summer: 25˚ < $L_S$ < 155˚
  - Seasonal range was chosen to improve planetary coverage at Mars and include data with similar solar irradiance conditions



# Data Selection

## Earth

North: 15˚ < $\varphi$ ≤ 60˚

South: -15˚ > $\varphi$ ≥ -60˚

Longitude regions have similar magnetic magnitudes and orientations

SZA: 50˚-90˚, 90˚-135˚ before and after solar local noon

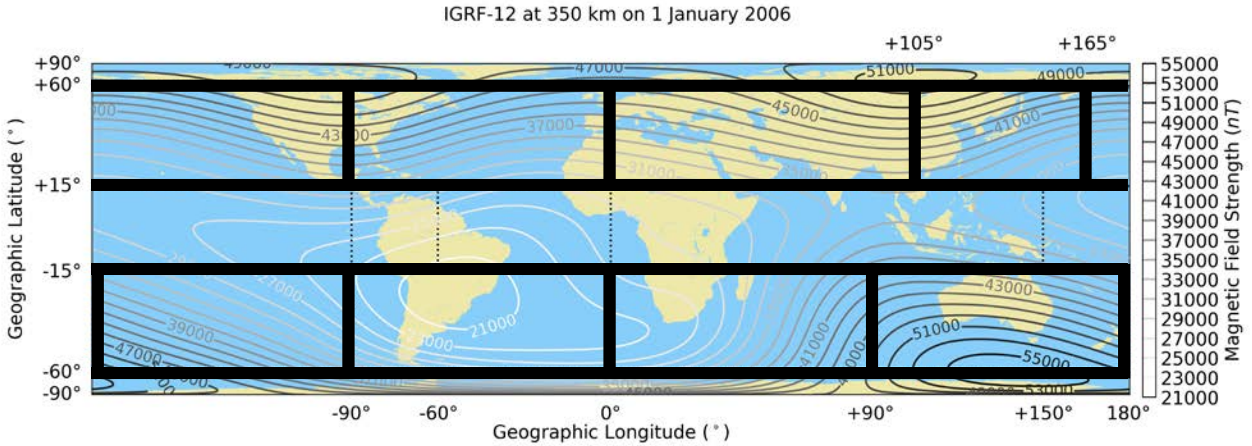
## Mars

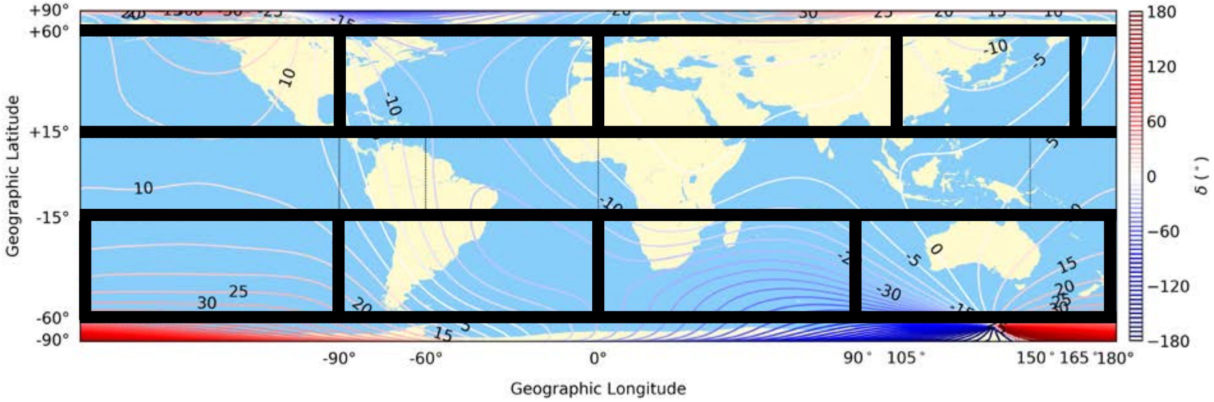
North: 0˚ < $\varphi$

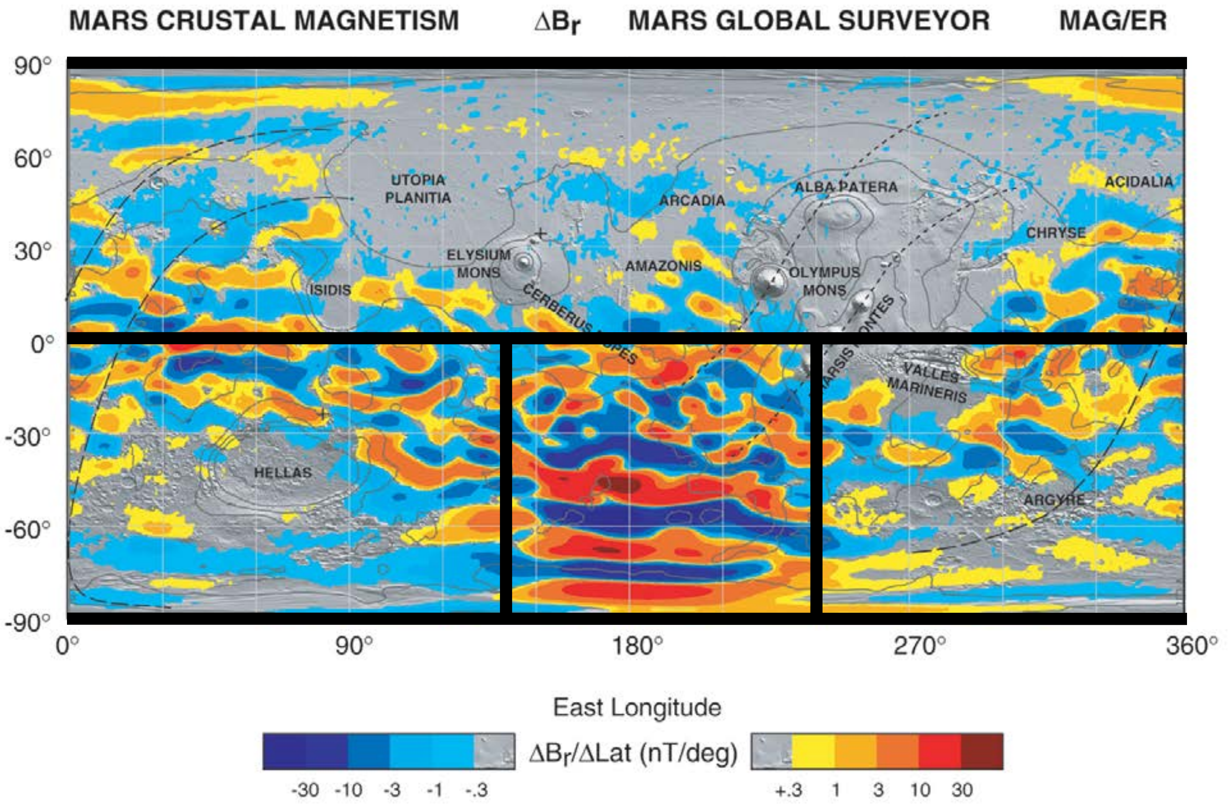
South: 0˚ > $\varphi$

Southern hemisphere divided into regions with and without crustal fields

SZA: 50˚-90˚, > 90˚ before and after solar local noon



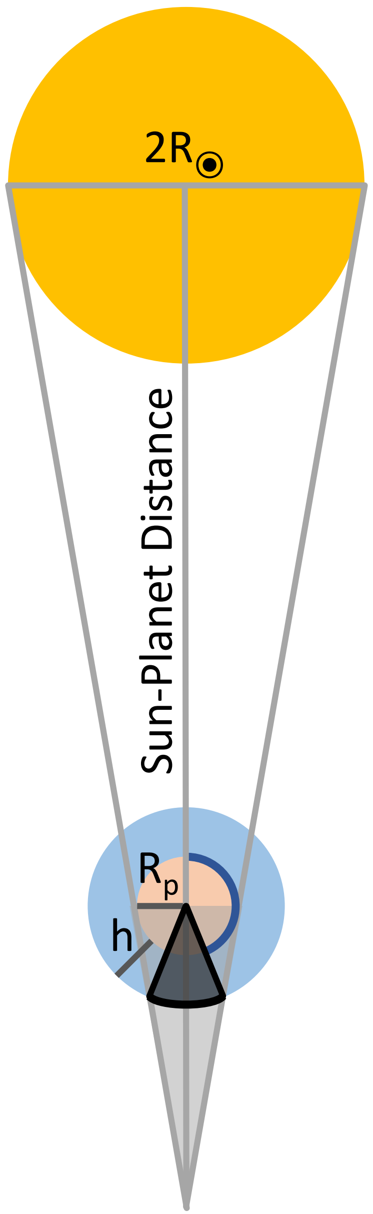




Connerney, J. E. P. et al., (2005) Proc. Natl. Acad. Sci. USA, 102, No. 42, 14970-14975.

# Data Selection

- Four Solar Zenith Angle (SZA) regions were chosen based on the location of the solar terminator
- Negative SZA defined as those before noon
- The SZA of the solar terminator ($\chi$) was determined using the location of the planetary umbra at typical ionospheric altitudes
  - At Earth and Mars, we calculated $\chi$ for typical altitudes for the peak ion production and the height of the peak ion density
  - At Mars we also calculated $\chi$ at the typical altitude where the photochemical ionosphere ends
  - $\chi$ calculated using the intersection of the right circular cones and spheres →

| SZA Region | Earth | Mars |
|---|---|---|
| Pre-dawn | -135˚ ≤ SZA ≤ -110˚ | -135˚ ≤ SZA < -105˚ |
| Dawn | -102˚ ≤ SZA ≤ -50˚ | -105˚ ≤ SZA ≤ -50˚ |
| Dusk | 50˚ ≤ SZA ≤ 102˚ | 50˚ ≤ SZA ≤ 105˚ |
| Night | 110˚ ≤ SZA ≤ 135˚ | 105˚ < SZA ≤ 135˚ |




Not to scale

# Linear Fitting

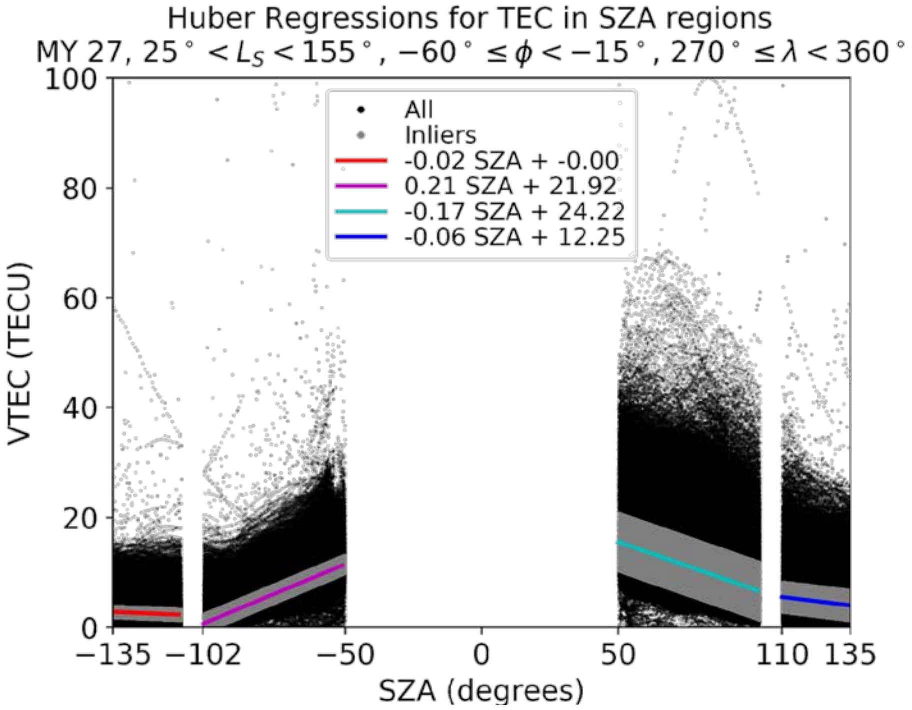
- Huber method is used to identify inliers and perform a linear fit for each MY, season, spatial region, and SZA sector
- The Huber Regressor optimizes the squared or absolute loss for the samples, as appropriate, by optimising $\sigma$ and $\varepsilon$:

$$|(y - X'w) / \sigma| < \varepsilon : \text{squared loss}$$

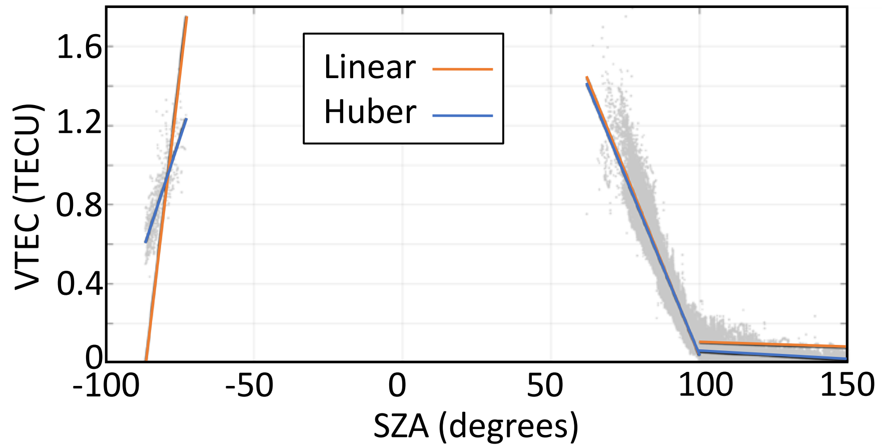
$$|(y - X'w) / \sigma| > \varepsilon : \text{absolute loss}$$

  - $\varepsilon$ - controls the number of points considered outliers, and must be greater than 1.0 (used 1.35)
  - $\sigma$ - scaling factor
  - X - dependent variable (SZA)
  - y - independent variable (VTEC)
  - w - weight (inverse of the VTEC error) CHECK
- The linear fit is not heavily influenced by the outliers
- Unlike other robust fitting methods, the Huber method will return the same set of inliers and outliers for the same initial conditions
- Only use fits with at least 50% coverage of the SZA region

Earth

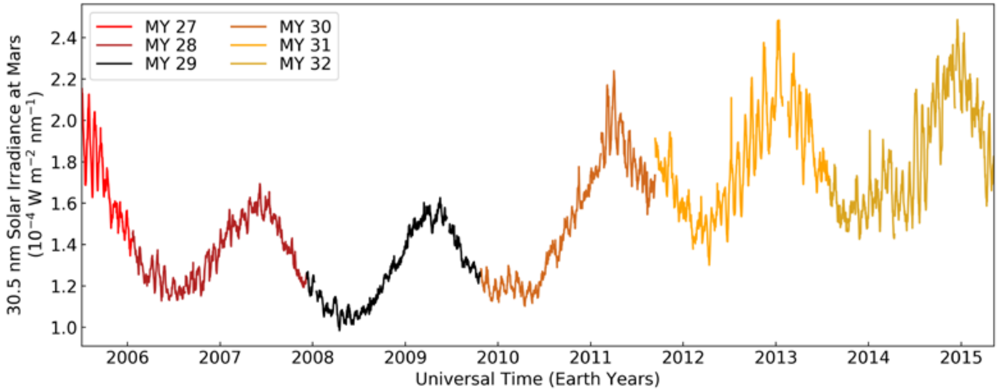


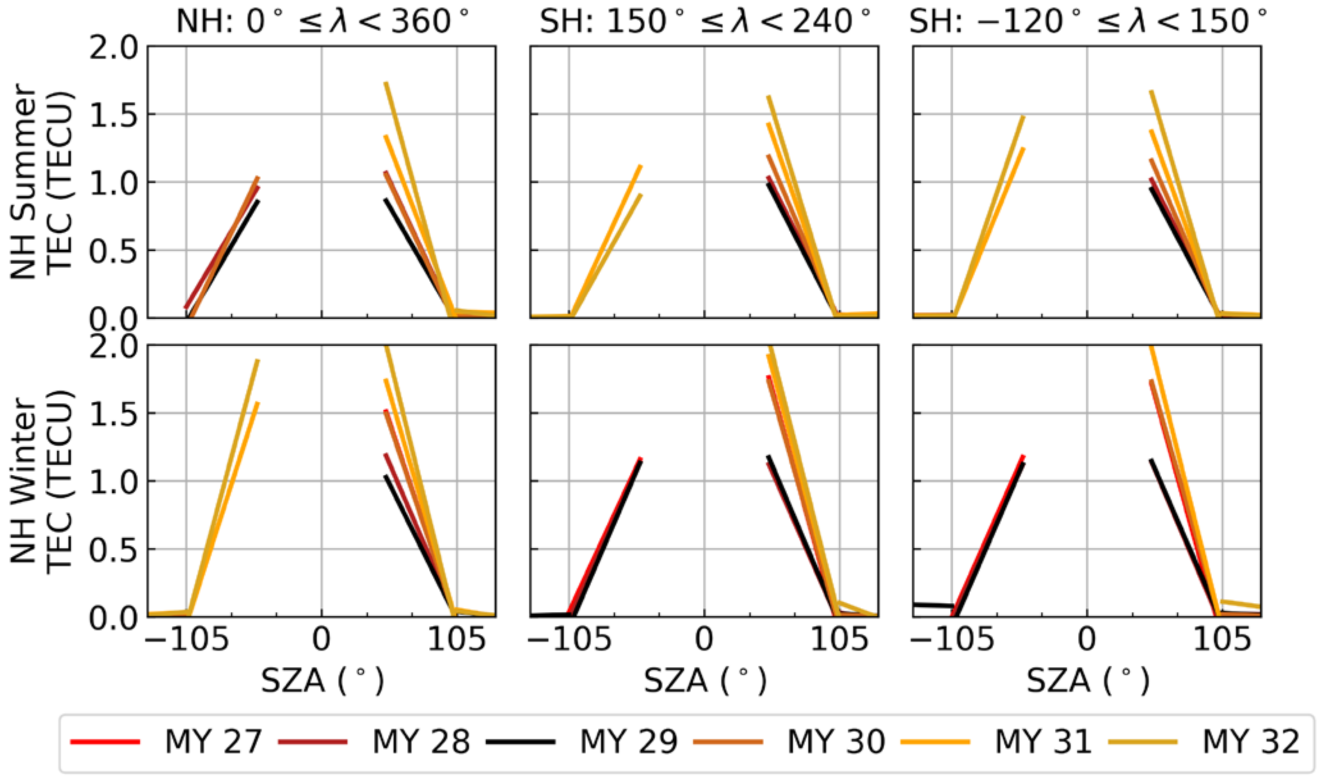

Mars

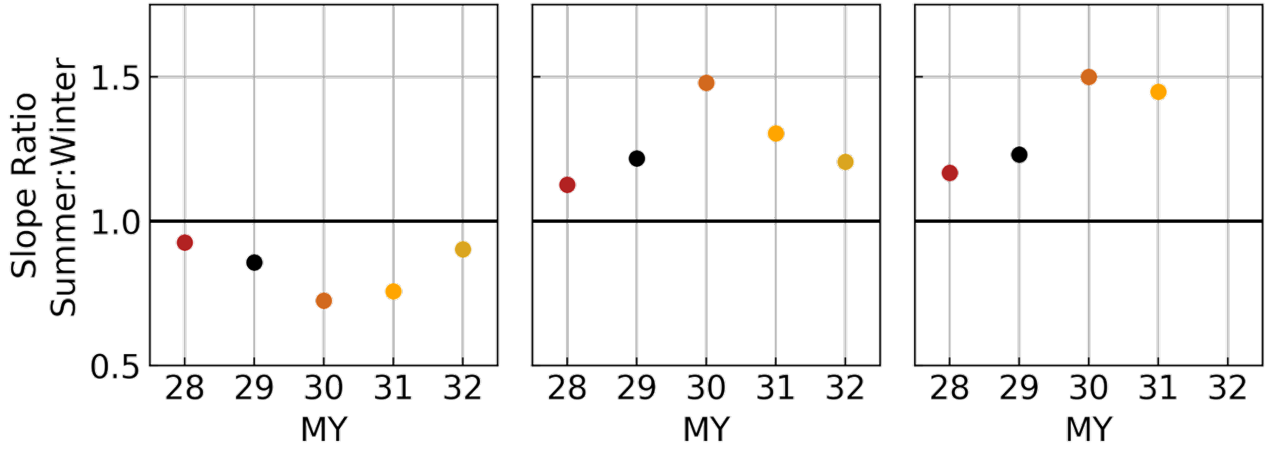


# Martian Variations

- Ion production and loss are controlled by SZA in all regions
- The rate of ion production and loss increases with increasing solar irradiance
  - Evident in solar cycle and heliocentric distance
  - Seasonal influence is secondary to heliocentric distance
- The presence or absence of crustal magnetic fields do not appear to influence the TEC
- Heliocentric distance has more influence over slopes than season

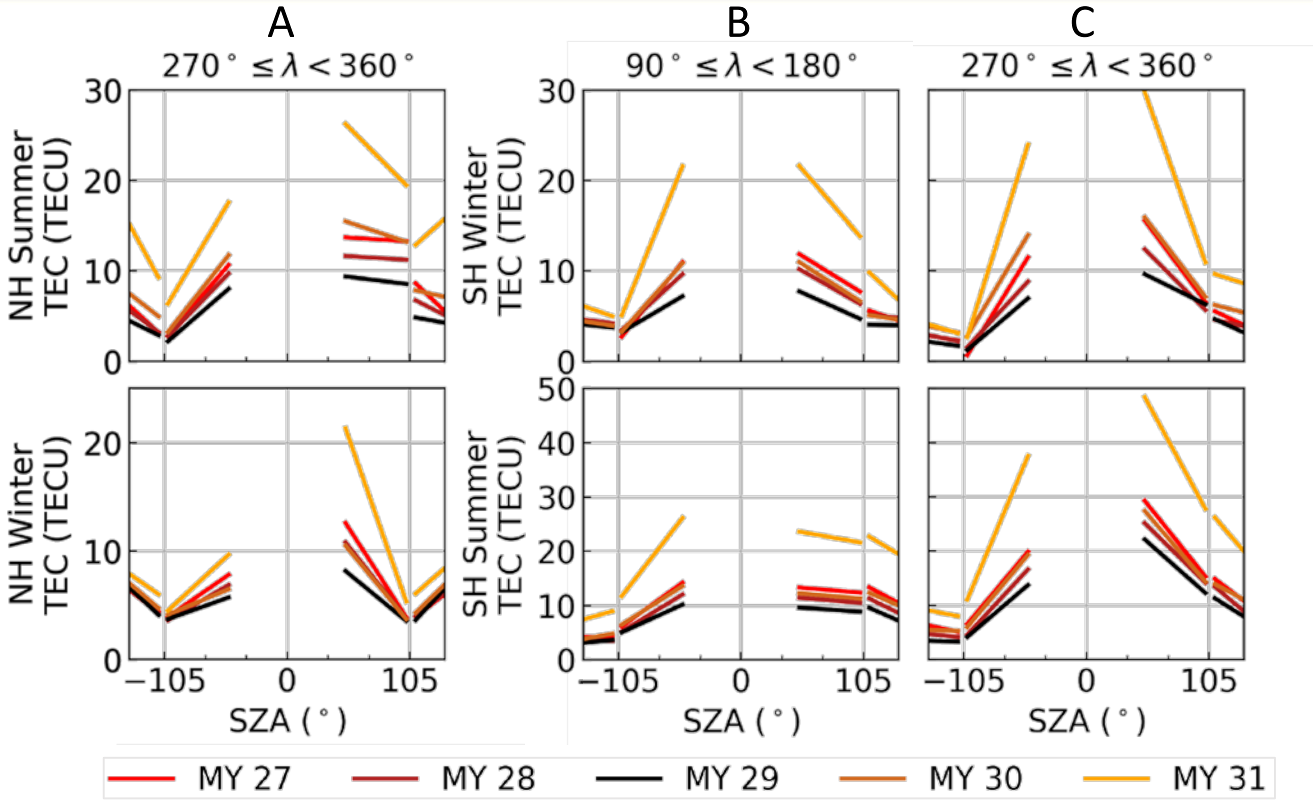


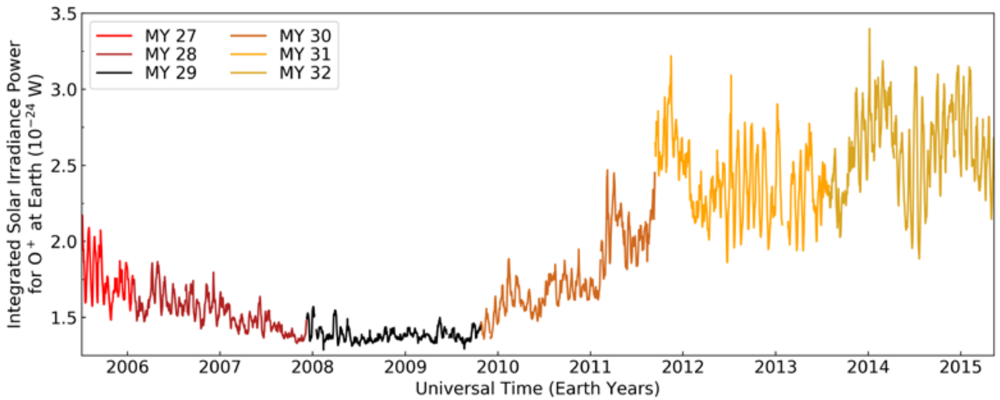



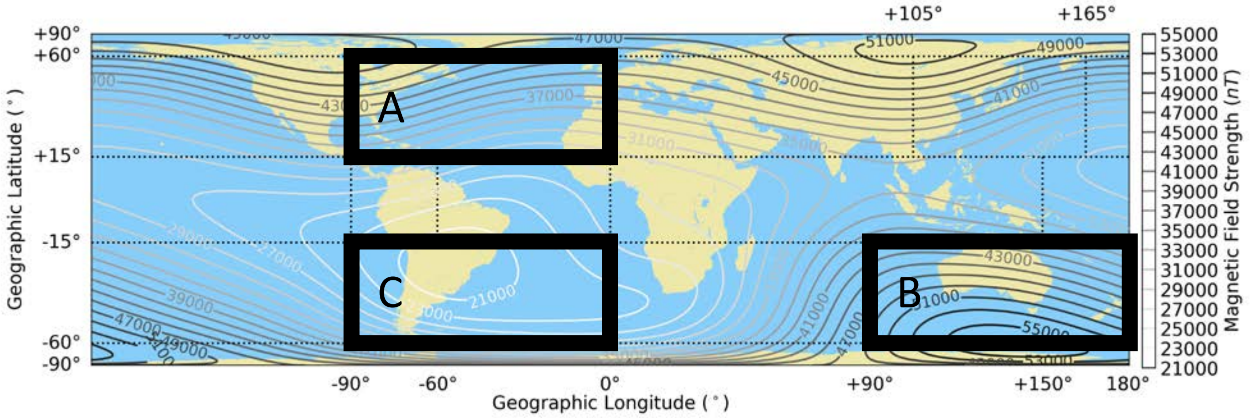



# Terrestrial Variations

- In the mid-latitude *F* region, the morning ion production is more simply controlled than the afternoon ion loss
- Solar cycle variations show increasing slope magnitude at dusk and dawn (± 50˚-90˚ SZA) with increasing solar activity
- Season and magnetic field configuration influence the SZA region where the ion loss rate is greatest
  - Electric fields and neutral winds can work to lift or lower the *F* region, reducing or increasing ion loss
  - Plasmasphere acts as an evening, ionospheric plasma source
  - Annual anomaly appears to affects SZA region with most rapid ion loss
- Region containing the South Atlantic Anomaly consistently shows strong SZA control of ion production and loss



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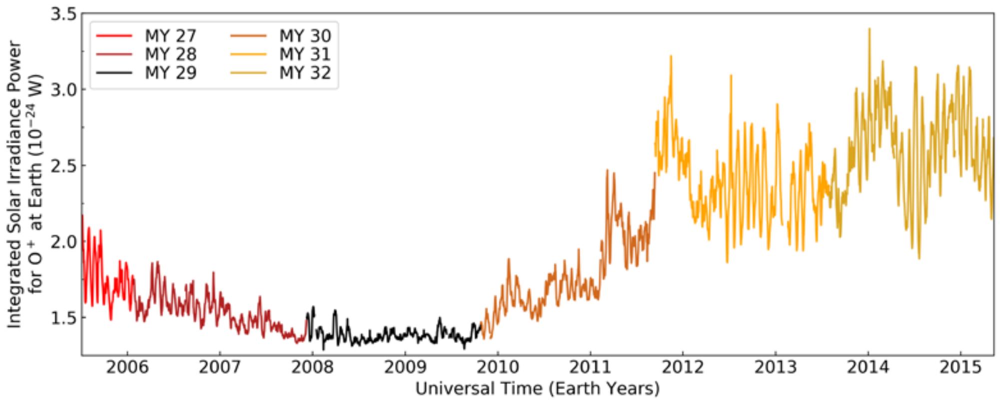
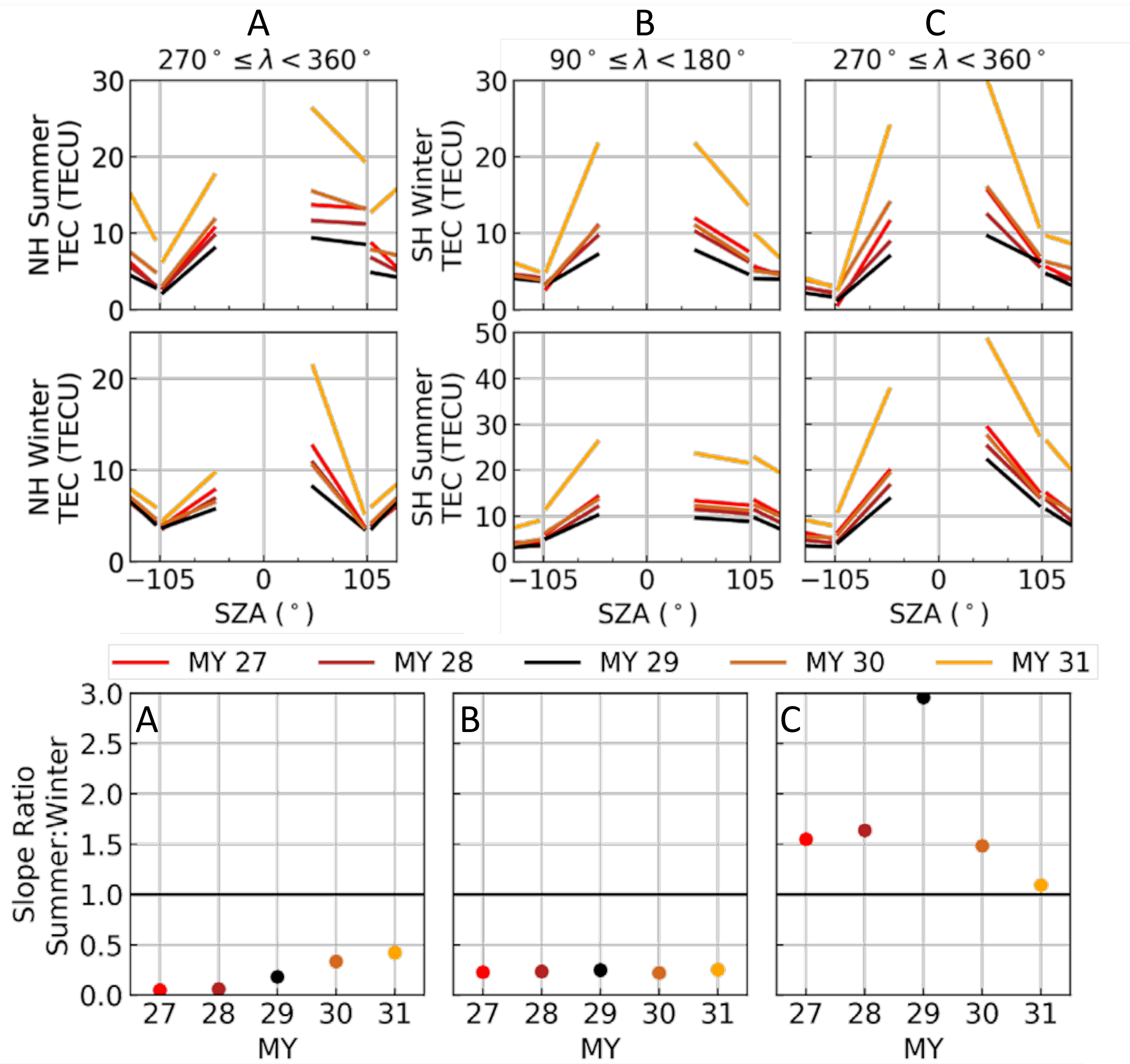
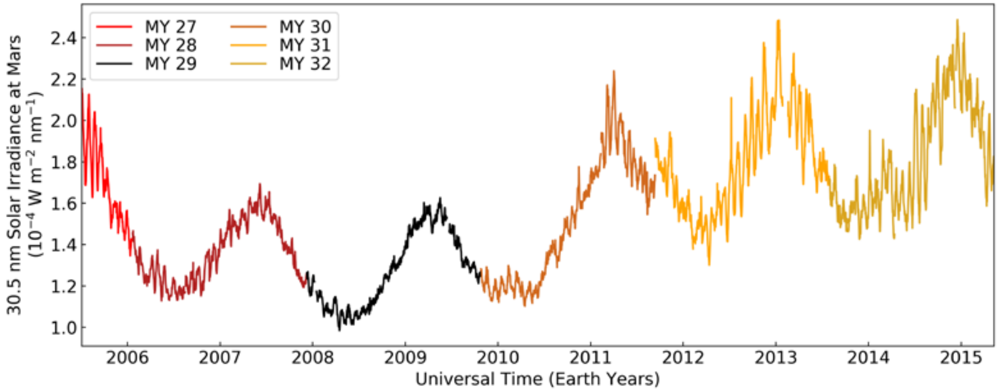
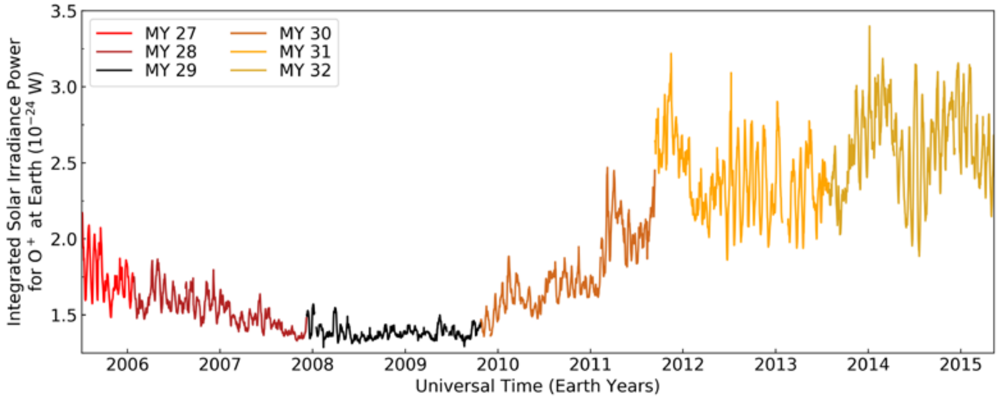


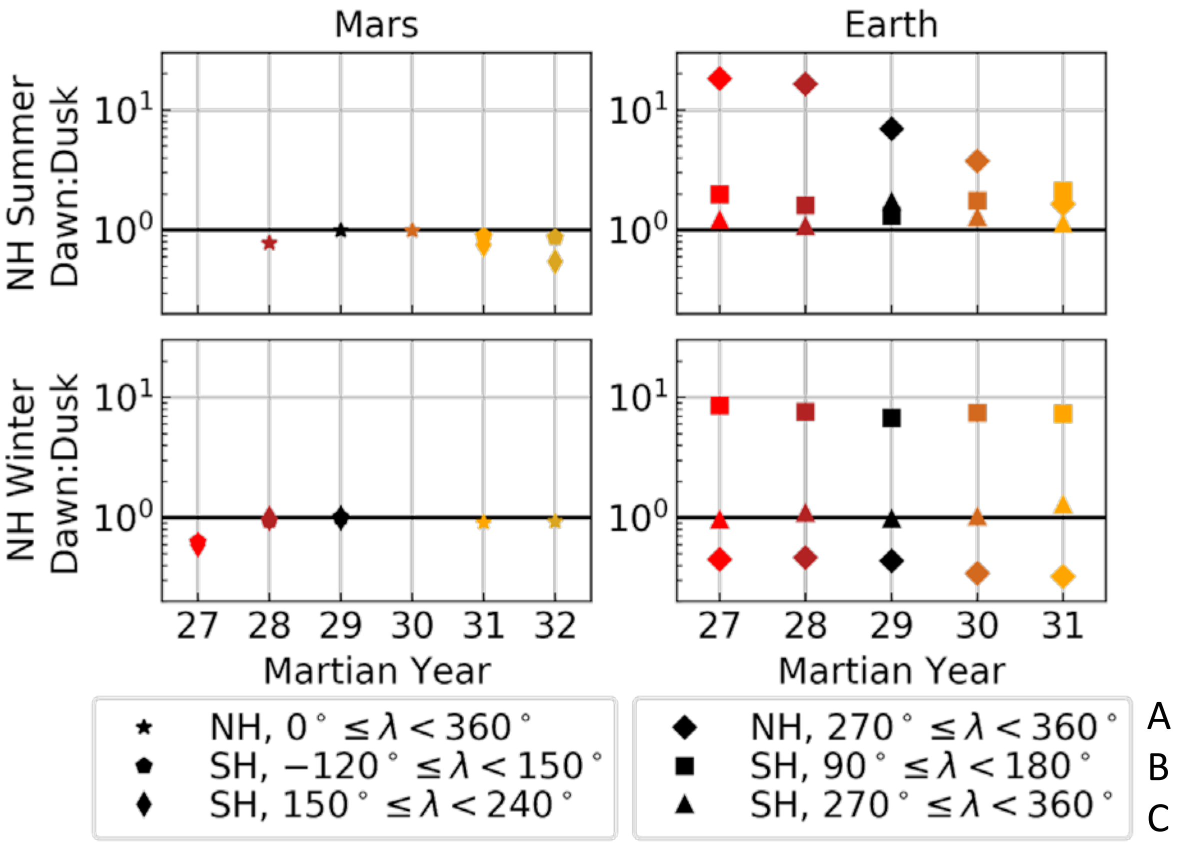



# Comparing Earth and Mars

- Ratio between dawn and dusk slopes (50˚-90˚ SZA) show no consistent solar cycle variation
- Ratios at Mars and in the terrestrial South American region (▲ or C) lie near unity
- Ratios in the other Earth regions show strong seasonal variations, with local winter values closer to unity



# Conclusions

- Ion production at dawn dominates at both Mars and Earth
- Ion loss at dusk is dominated by recombination at Mars, but transport plays an important role in the mid-latitude *F* region at Earth
  - Thermosphere plays an important role in determining the efficacy of solar irradiance
  - The orientation (and possibly strength) of the magnetic field affects the relative importance of plasma transport and ion production and loss
  - Greater solar irradiance increases the importance of ion production and loss processes
    - The influence of transport processes are easier to see at low levels of solar activity
- Solar cycle increases the rate of ion production and loss, but does not affect the relationship between the dawn and dusk slopes in regions not dominated by transport

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