Solar Cycle Variation of Suprathermal Heavy Ion Composition and Spectra during Quiet Times near 1 AU

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Abstract

We report on the annual variation of quiet-time suprathermal ion composition and spectral properties for C-Fe using Advanced Composition Explorer (ACE)/Ultra-Low Energy Ion Spectrometer (ULEIS) over the energy range 0.3 MeV/nuc to 1.28 MeV/nuc from 1998 through 2020. This extends the work of Desai et al. (2006) and Dayeh et al. (2009, 2017) to cover Solar Cycle 23's rising phase through Solar Cycle 24's declining phase. With 5 additional years of data, we show that the number of quiet-time hours strongly anti-correlates with the Sunspot Number (SSN) at better than the -0.9 level. We also show (1) a clear ordering of the cross correlation between abundance (normalized to O) and SSN as a function of solar wind M/Q; (2) the slope of X/O's abundance as a function of Fe/C decreases with increasing M/Q; and (3) discuss the trend of annual spectral indicies with respect to Oxygen's spectral index as a function of solar cycle and M/Q. The contrast between our abundance and spectral index results suggests that the source from which suprathermal ions are drawn or accelerated varies with solar activity and is tied to each element's chemistry, but he acceleration mechanism that governs the spectral shape does not.

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Abstract

- Annual variation of quiet-time suprathermal ion composition and spectral properties
  - C through Fe
  - 1998 through 2019
  - ACE/ULEIS
  - Energy range 0.3 MeV/nuc to 1.28 MeV/nuc
- Extends Desai et al. (2006) and Dayeh et al. (2009, 2017)

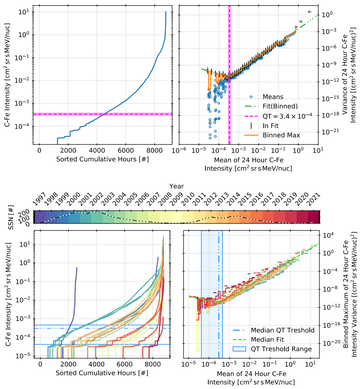
Results

- Number of quiet hours strongly anti-correlates with the annual Sunspot Number (SSN)
- Cross correlation between abundance (normalized to O) and SSN well ordered with solar wind M/Q
- Slope of X/O abundance as a function of Fe/C decreases with increasing M/Q
- Results are robust against our quiet time selection criterion

Key Takeaway

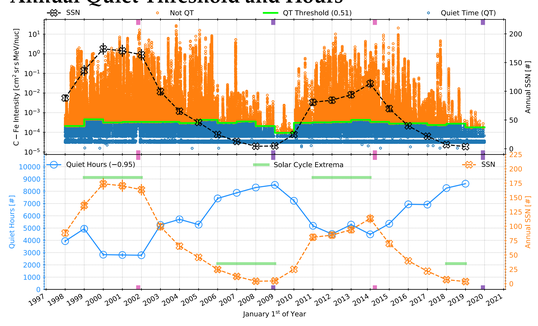
- Annual quiet time abundances vary with solar activity and are M/Q fractionated
- Annual spectral indices $\gamma \approx 2.5$, independent of solar activity and M/Q
- This contrast suggests that the source from which suprathermal ions are drawn or accelerated varies with solar activity and are tied to the element's chemistry, but the acceleration mechanism that governs the spectral shape does not

Quiet Time Selection



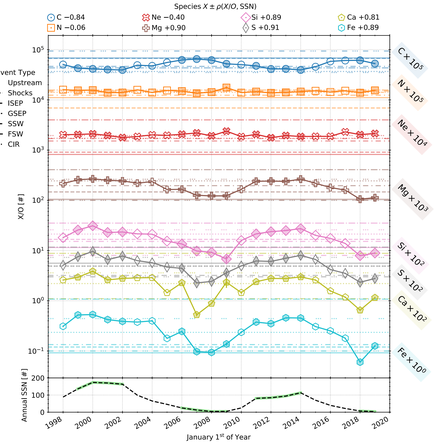
- (Top) Selection Method
  - Dayeh et al. (2017) developed a statistical method to identify quiet times
    - (Left) Total C-Fe Intensity vs. Sorted Cumulative Hours
    - (Right) 24-Hour Variance vs. its Mean
    - Quiet Time Threshold (QT) is the inflection
  - We fit the maximum of two power laws to identify the inflection with a confidence interval
    - Fits are applied to binned maximum
    - Subset of bins selected to reduce systematic bias
- (Bottom) Summary of fits for all years
  - Color in color bar
  - Shows 13-month smoothed SSN for visual reference
  - Trend with median of fit parameters and QT threshold range of values

Annual Quiet Threshold and Hours

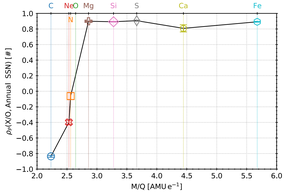


- (Top) Annual Quiet Threshold independent of annual SSN
- (Bottom) Strong anti-correlation between quiet hours and annual SSN ($\rho = -0.95$) likely due to solar activity's impact on non-quiet time periods
- Solar cycle extrema selected based on Normalized SSN (NSSN)
  - Scale annual SSN to maximum in its cycle
  - Converts SSN into amplitude-independent clock
  - Shown with green bars and partially filled markers
  - See Zhao et al. (2013)

Annual Abundances

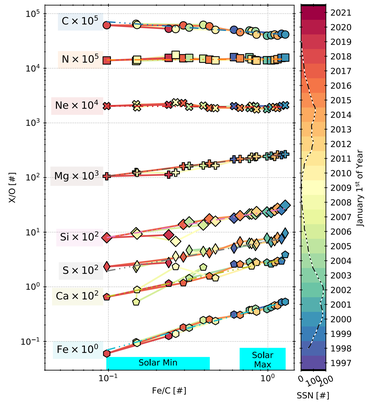


- (Bottom) Annual SSN
  - Solar cycle extrema years are highlighted
- (Top) Annual X/O abundances scaled by the value indicated at right
  - Solar cycle extrema are partially filled
  - Horizontal lines are event types (Desai et al. 2003)
  - Legend gives $\rho(X/O, SSN)$
  - Error bars are standard deviation of results across QT thresholds



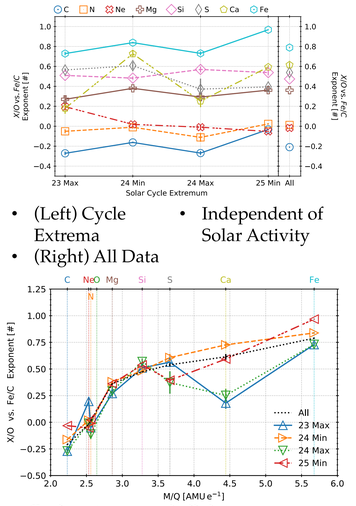
- ρ changes sign at Oxygen
  - $\rho(M/Q < 0) < 0$
  - $\rho(M/Q > 0) > 0$

Annual X/O vs Fe/C



- From X/O vs Fe/C, we study quiet time M/Q fractionation
- Fit each trend for all data along with solar cycle extrema
  - Extrema ranges highlighted at bottom

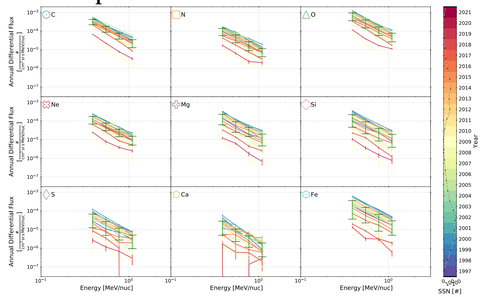
X/O vs Fe/C Slopes – Fractionation



- (Left) Cycle Extrema
- Independent of Solar Activity
- (Right) All Data

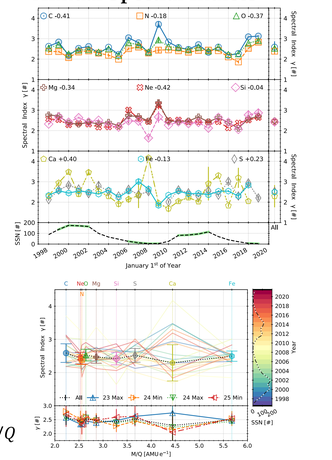
- Cycle extrema and all data
- Abundances are M/Q fractionated

Annual Spectra

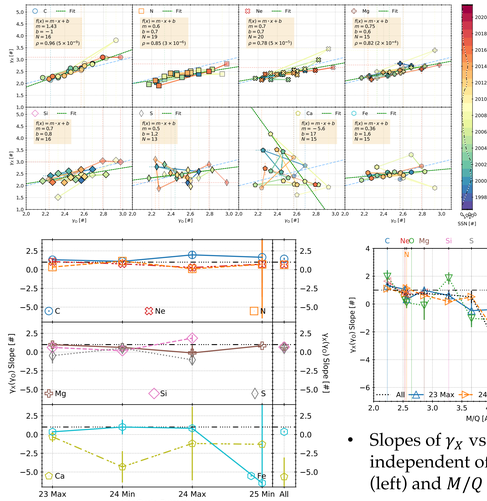


- (Left) Differential flux spectra
  - Ca is noisiest because of low counts
  - Year given by color bar
  - Includes 13-month smoothed SSN for reference
- (Right) Annual Spectral Indices
  - $\gamma \approx 2.5$ independent of solar activity (right, top) and M/Q (right, bottom), even selecting for solar cycle extrema

Annual Spectral Indices



Spectral Index Comparison with γ_O



- Annual γ_X vs γ_O
- Color bar gives marker and line year
- Semi-transparent markers are years with high uncertainty
  - Ca is noisiest because of low count statistics
- Inserts give trends
  - If correlation coefficient $\rho \geq 0.6$, it is included

- Slopes of γ_X vs γ_O are independent of solar activity (left) and M/Q (right)

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