Lyman-alpha Variability During Solar Flares

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Abstract

The chromospheric hydrogen Lyα line at 1216Å is the brightest emission line in the solar spectrum, and yet studies of solar flares at this wavelength have been scarce in the literature over the past 50 years. The study of Lyα is important for understanding space weather effects as changes in the Sun's Lyα output can drive changes in the dynamics and composition of planetary atmospheres. Lyα is also a significant radiator of solar flare energy, providing an important diagnostic of energy release and transport processes. Milligan et al. (2020) published a statistical study of ~500 M- and X-class flares using GOES/EUVS data, showing that although the Lyα irradiance increases by only a few percent during large events, it can radiate up to 100 times more energy than the corresponding X-rays. Flares that occurred closer to the solar limb, however, were found to exhibit a smaller Lyα enhancement relative to those on the disk due to opacity and/or foreshortening effects. It was also shown that impulsive Lyα emission, not X-rays, can induce currents in the E-layer of Earth's ionosphere. A follow-up study now includes B- and C-class flares, which although not readily observable in disk-integrated measurements, can be investigated using a superposed-epoch analysis. Despite increases of <1% above the solar background in the summed time profiles, a clear centre-to-limb variation was found in agreement with larger events. These findings should serve as a baseline for the advent of new Lyα flare observations and advanced numerical simulations that will become available during Solar Cycle 25.

Lyα Flare Observations

GOES-15 has been monitoring the full-disk, solar irradiance in broadband (~100Å) Lyα at 10.24s cadence with its EUV Sensor (EUVS, E-channel) since 2010. The data are calibrated to SORCE/SOLSTICE data, but assume an underlying quiet-Sun spectrum. As Earth's geocorona is opaque to Lyα photons, a dip in the Lyα time series is visible once per orbit (Figure 1). Any flares that occurred within these dips have been omitted from this study. At present, only data taken between April 2010 and June 2016 have been released.

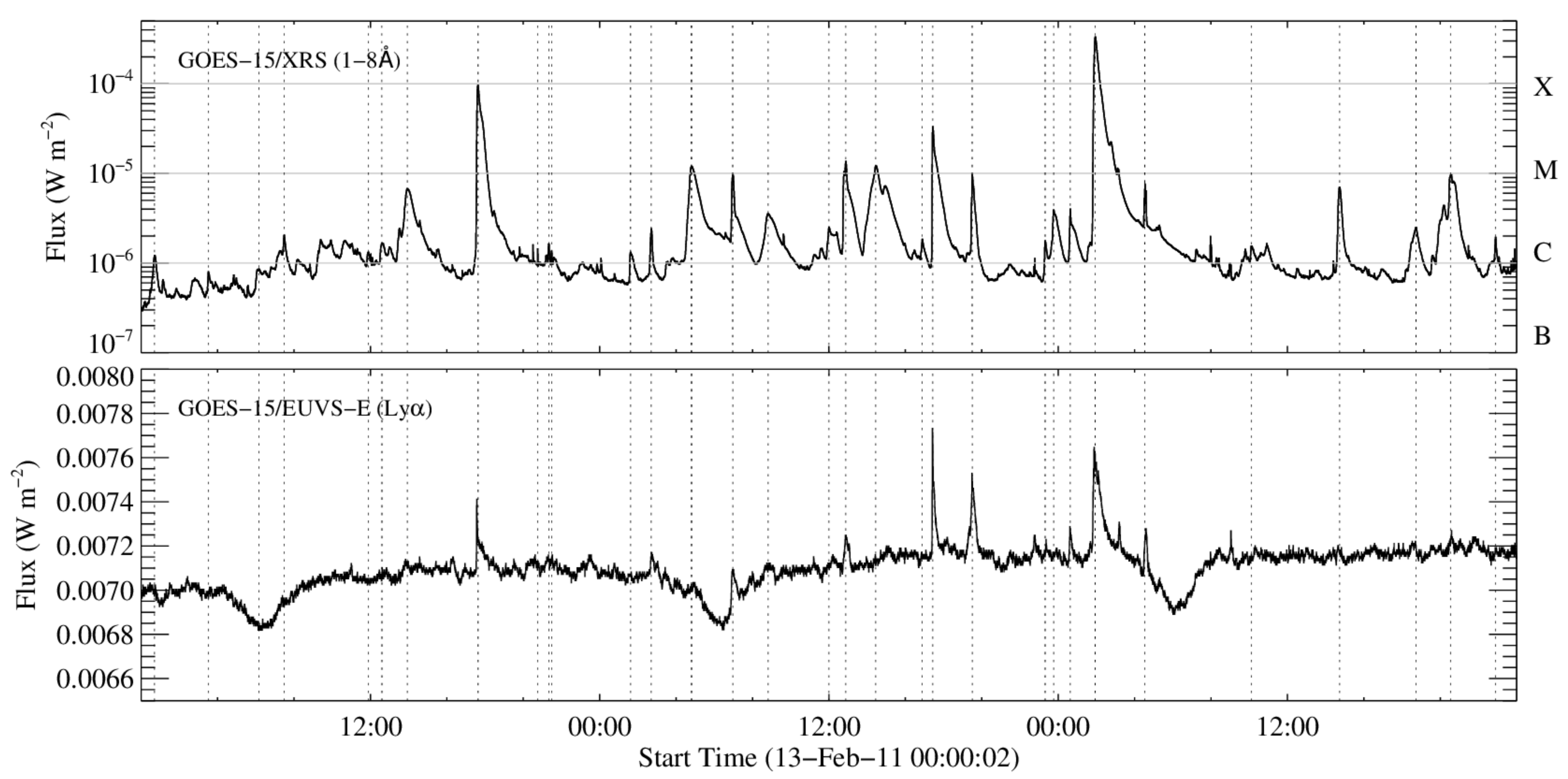

Figure 1: Three days of GOES-15 data from February 2011 in both X-rays (top panel) and Lyα (bottom panel). Only the largest (>M-class) flares produced readily visible responses in the Lyα line. The dips in the bottom panel are due to geocoronal absorption as GOES-15 peers through the Earth's atmosphere once per orbit.

Lyα Contrast and Energetics

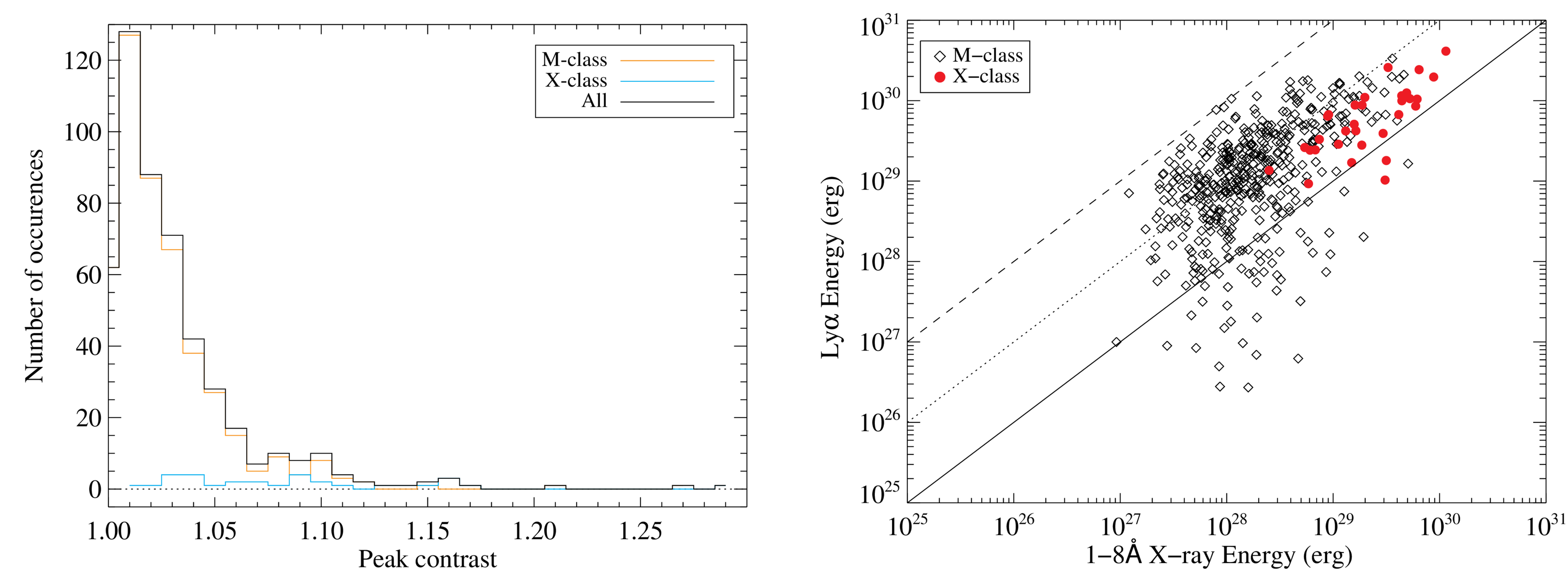

Figure 2: Left: Histogram of flare contrast in Lyα. Most flares exhibited a <10% enhancement above background, with a maximum of ~30%. Right: Energy radiated in Lyα against that of X-rays. Lyα emits up to 100x more energy than X-rays for most M-class flares (black diamonds), while X-class flares (red solid circles) are up to 10x stronger.

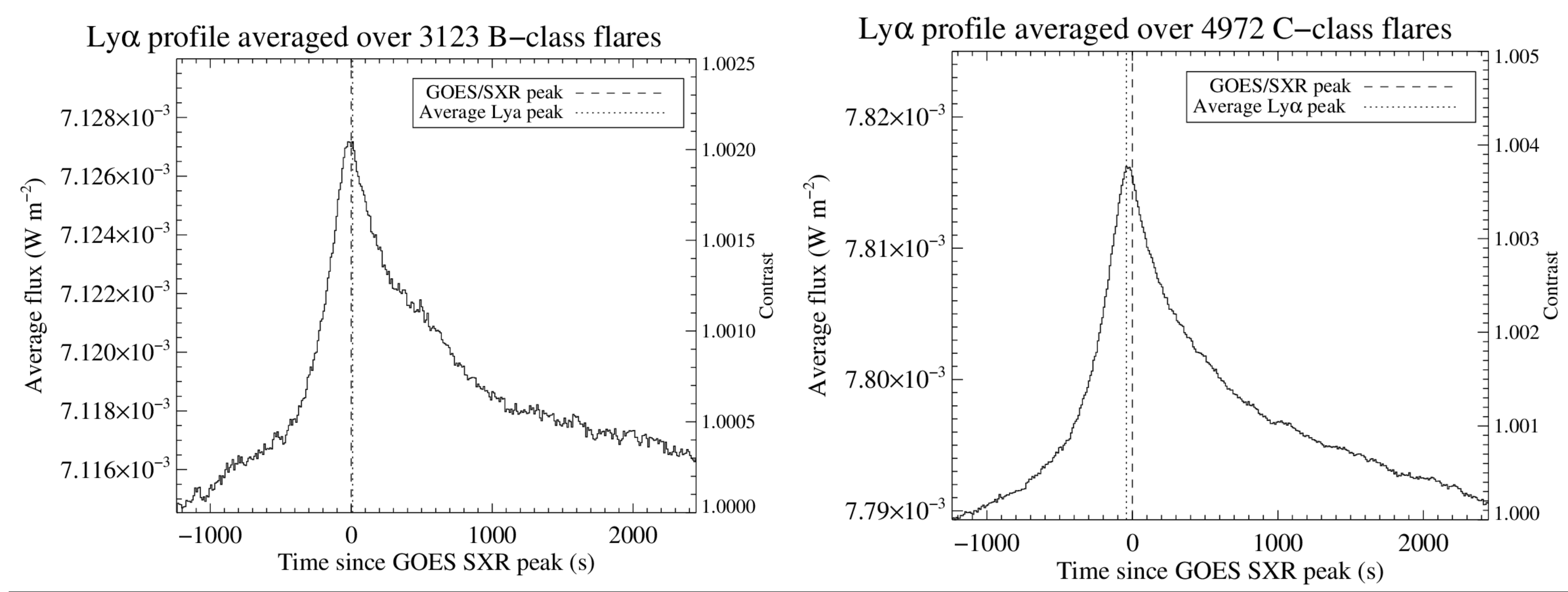

Figure 3: Left: Lyα profile from the average of 3123 B-class flares entered on their peak SXR times. The average contrast was 0.2% and the profile peaks at the time of peak X-ray emission. Right: Same lightcurve for 4972 C-class flares. The average contrast was 0.35% and the profile peaked ~40s before the SXR peak. This analysis was repeated for 453 M- (1.5%; -51s) and 31 X-class flares (4%; -72s), but are not shown here.

Ionospheric Response to Lyα

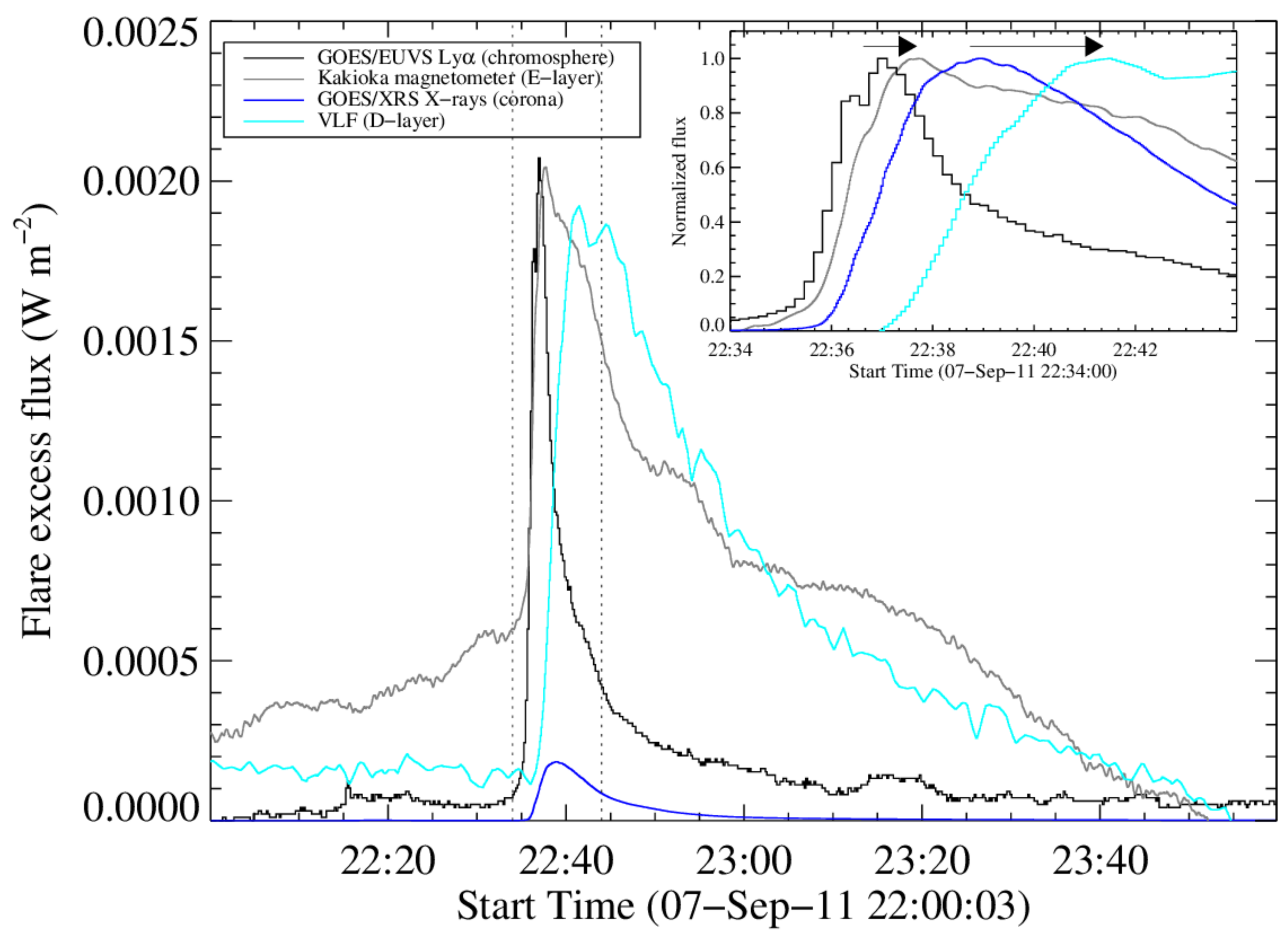

Figure 4: Plot of solar flare emission and the associated response of the terrestrial ionosphere. The inset shows each profile normalised to their respective maxima. Impulsive Lyα emission (black) correlates well with the induced currents in the E-layer as measured in magnetometer data (grey). The more gradual soft X-ray emission (blue) lags this response but appears to lead the D-layer response (cyan) from VLF measurements.

Lyα Center-to-Limb Variation

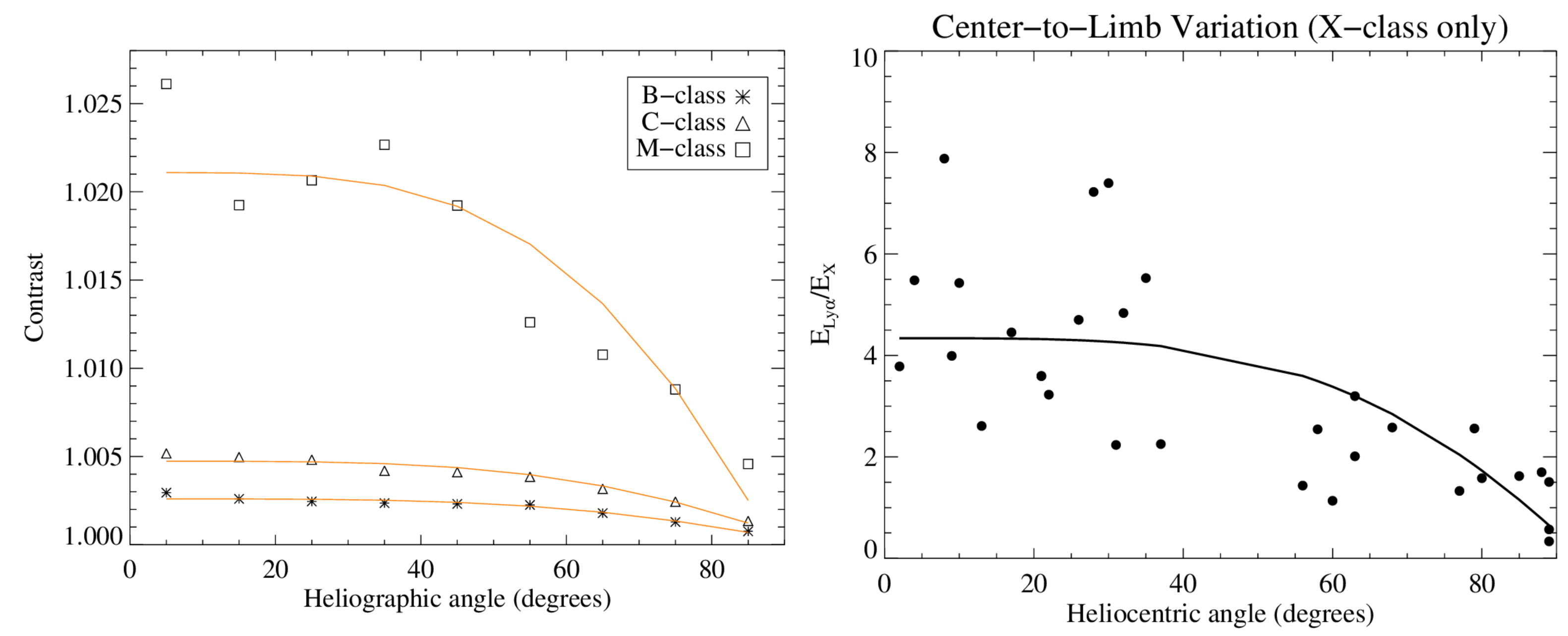

Figure 5: Left: All B, C, and M class flares were binned in 10 degree intervals from disk center, and then averaged based on their peak X-ray time. In all cases the relative contrast diminished for flares that occurred closer to the limb. Right: Same plot for X-class flares, although the total Lyα energy was normalised to the X-ray energy for each individual event. The curves in each panel are given by $R=R_C(k+2(1-k)(\mu-\mu^2/2))$, where k in the limb variation relative to disk center and $\mu = \cos(\theta)$.

Lyα Flare viewed from Earth and Mars

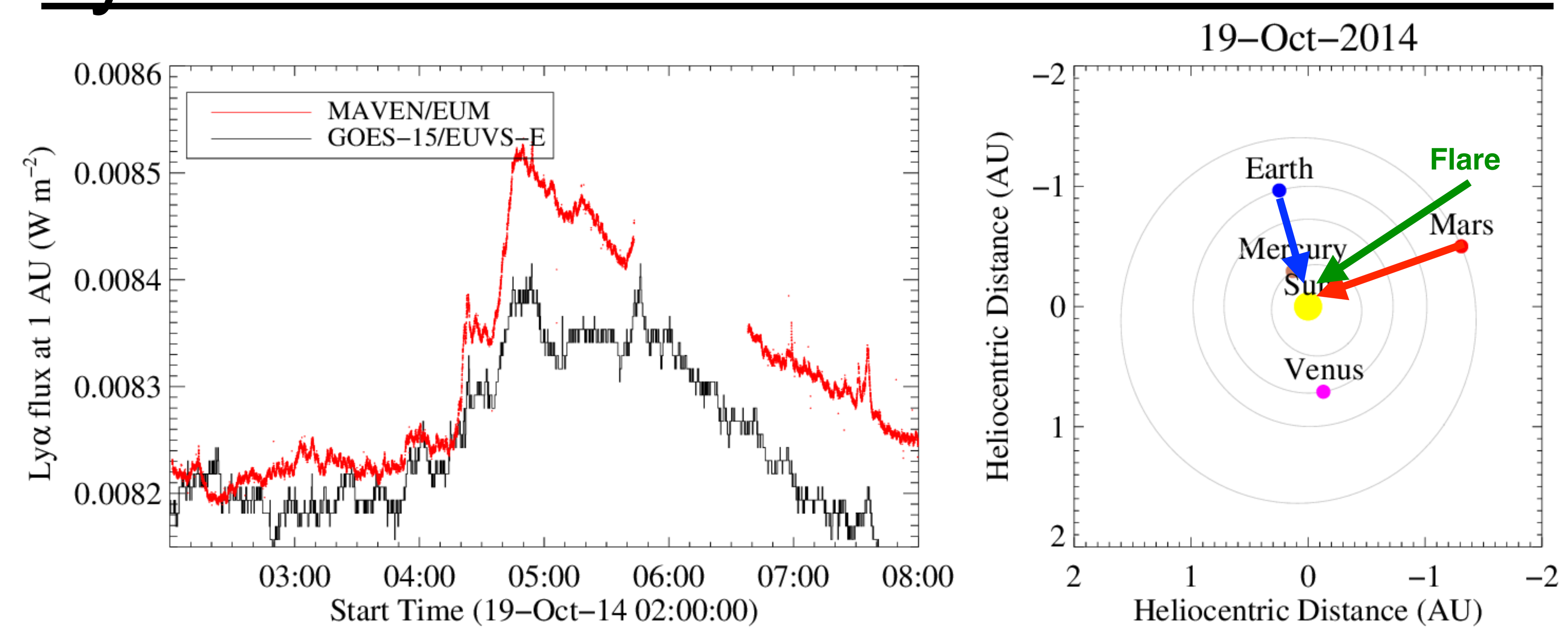

Figure 6: An X-class flare that occurred on 19 October 2014 was located on the eastern solar limb as viewed from Earth, but was close to disk center as viewed from Mars. Left: time profiles of the Lyα power as measured by GOES/EUVS (black curve) and MAVEN/EUM (red curve). After correcting for the Earth/Mars-Sun distances and light travel times Lyα was ~45% weaker as viewed from Earth due to the center-to-limb variation. Right: Top-down view of the inner solar system on 19 October 2014.

Conclusions

- A statistical study of solar flares observed in Lyα emission is presented.
- Increases of <10% were observed in M- and X-class flares, with a maximum of 30% (left panel of Figure 2). Comparable to AR evolution but on much shorter timescales. Energy radiated in Lyα is 1-100 times that of X-rays (1-8Å; right panel of Figure 2).
- While B- and C-class flares are not readily detectable in disk-integrated observations, a superposed-epoch analysis revealed flare enhancements of <1% (Figure 3).
- Impulsive Lyα emission - not X-rays - was found to induce currents in the E-layer of the ionosphere for an X-class flare. X-rays correlated more with a D-layer response after accounting for "sluggishness" (Figure 4).
- Center-to-limb variation is significant for all flare classes (Figure 5) as confirmed by stereoscopic GOES and MAVEN observations (Figure 6). Due to either opacity effects and/or foreshortening of the flare ribbons.

References and Acknowledgements

1. Milligan, R. O., Hudson, H. S., Hannah, I. G., Chamberlin, P. C., & Hayes, L. A. (2020) *Lyman-alpha Variability During Solar Flares Over Solar Cycle 24 Using GOES-15/EUVS-E. Space Weather*, Vol 18, Issue 7, Art. 02331
2. Milligan, R. O. (2020) *Solar Spectral Irradiance Variability Due To Solar Flares Observed in Lyman-alpha Emission.* Solar Physics, *In preparation*

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