RESPONSE OF THE TOTAL ELECTRON CONTENT IN THE IONOSPHERE TO THE IMPULSIVE AND LATE PHASES OF X-CLASS SOLAR FLARES

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Solar flares cause enhanced ionisation in the illuminated part of the Earth's ionosphere, leading to an increase in total electron content (TEC). Nearly 50% of X-class solar flares exhibit a secondary peak in warm coronal lines, such as Fe XV and Fe XVI, called the "EUV late phase". This study presents an analysis of the ionospheric response to 14 X-class flares with pronounced late phases. For the first time, empirical relationships are derived between increases in TEC and solar flux enhancements during both the impulsive and late phases of the flares. Additionally, the influence of flare location on the ratio of ionospheric responses to the impulsive and late phases is demonstrated.

Ionospheric Response to a Disk and a Limb Solar Flare

Two solar flares with pronounced late phases were selected for the analysis: one located near the centre of the solar disk (X2.37, 23.10.2012), and the other near the solar limb (X2.14, 22.09.2011) (Figure 1).

The main emission of the impulsive phase, He II 30.4 nm, originates from the chromospheric footpoints of flare loops and is therefore weaker in limb flares. The main emission of the late phase, Fe XV 28.4 nm, is generated in coronal loops and is thus independent of the flare's location on the solar disk. As a result, in limb flares, the ratio of the ionospheric TEC response during the late phase to that during the impulsive phase is generally higher for limb flares than for disk flares.

Figure 2 shows the lightcurves for the disk and limb flares, while Figure 3 presents the measured ionospheric response during the different phases of these flares.

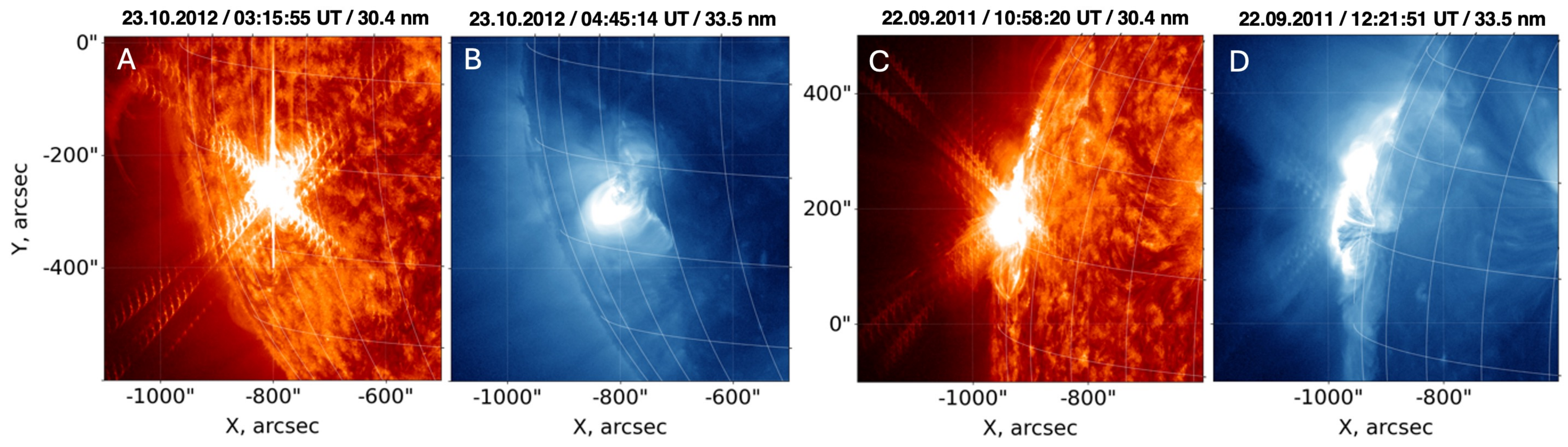

Figure 1. AIA images of He II 30.4 nm (a, c; impulsive phase) and Fe XVI 33.5 nm (b, d; late phase) emissions for the disk flare on 23.10.2012 (a, b) and the limb flare on 22.09.2011 (c, d).

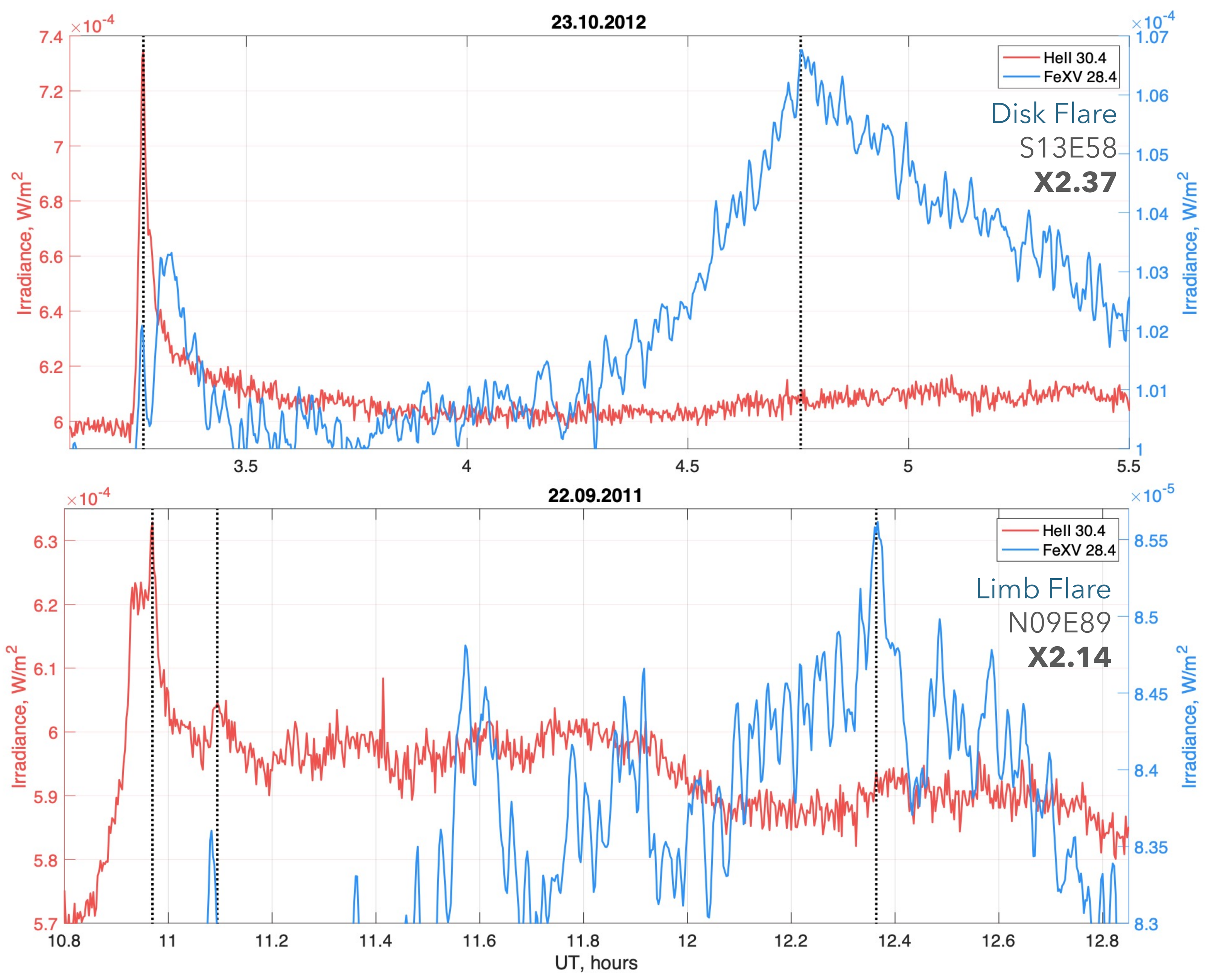

Figure 2. Solar flare lightcurves in He II 30.4 nm and Fe XV 28.4 nm emissions measured by EVE during disk flare on 23.10.2012 (top panel) and limb flare on 22.09. 2011 (bottom panel).

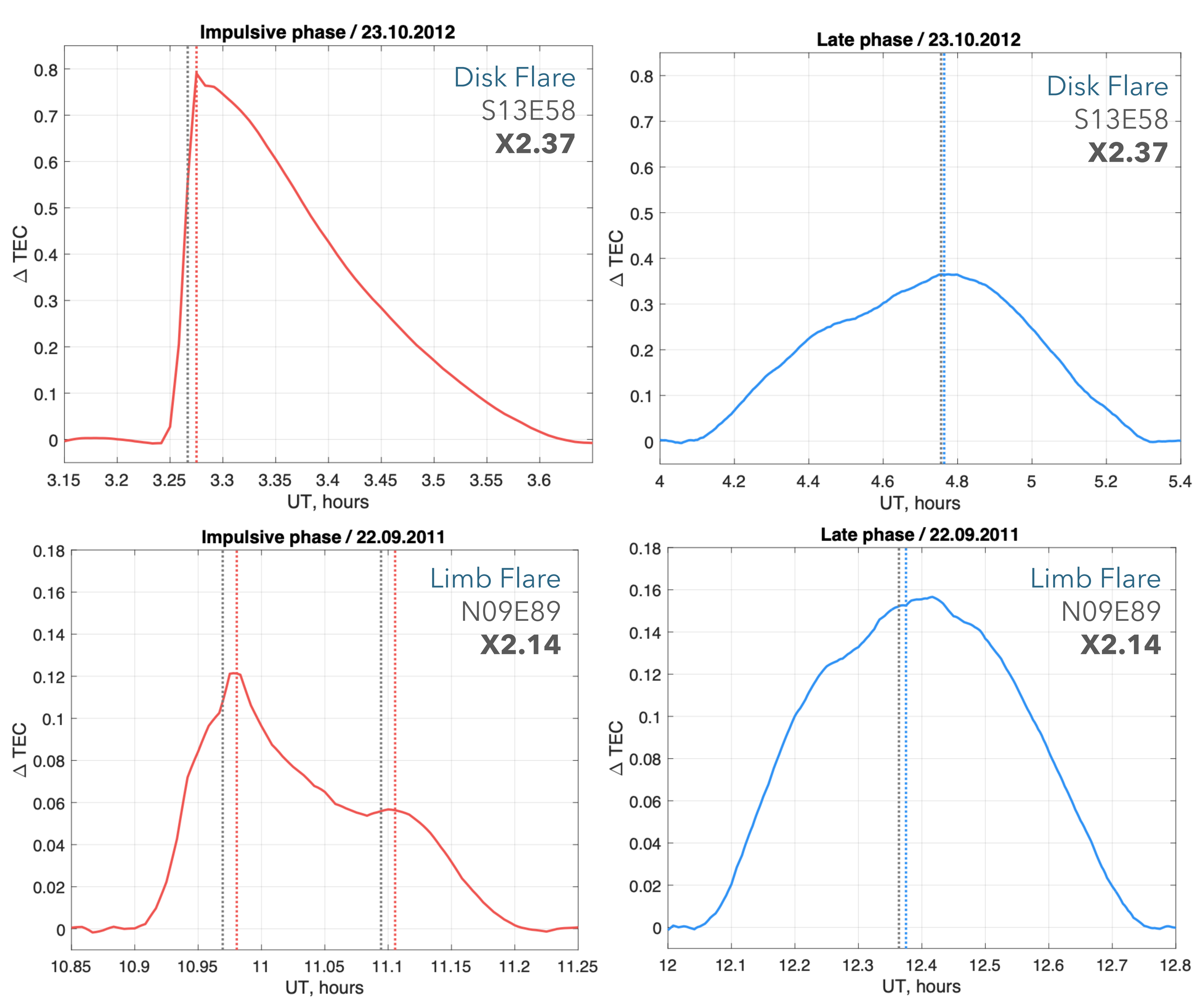

Figure 3. TEC increment during the impulsive (left panels) and late phases (right panels) of the disk flare on 23.10.2012 (top panels) and the limb flare on 22.09.2011 (bottom panels).

Centre-to-Limb Variations in EUV Emissions

Different emissions of the solar spectrum undergo varying levels of attenuation depending on the flare location on the solar disk. This variation is primarily due to the region in which the emission is generated.

Figure 4 shows the flux increase in the He II 30.4 nm (left) and Fe XV 28.4 nm (right) lines, normalised to $\Delta F_{X\text{-ray}}$, as measured by the EVE/SDO over several years. As we can see, the He II emission is optically thick and decreases with increasing heliocentric angle, whereas the Fe XV emission is optically thin and remains largely independent of the heliocentric angle.

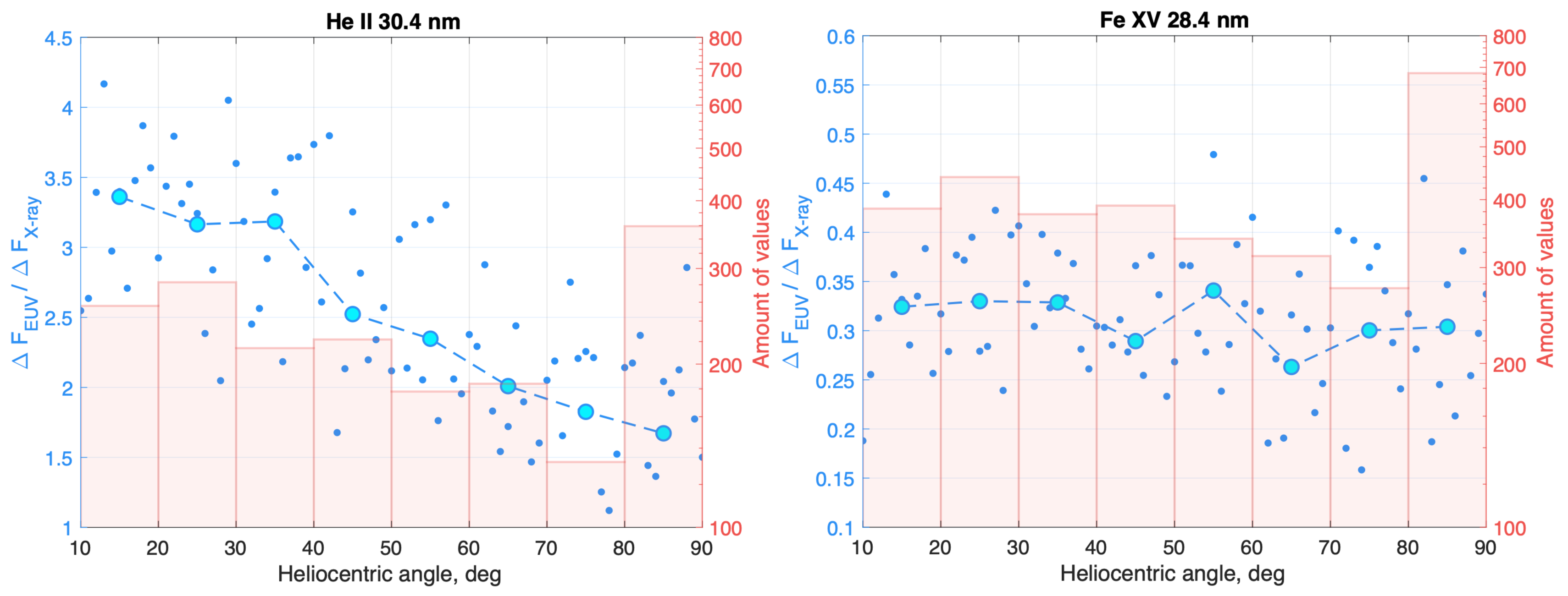

Figure 4. Flux increase in the 30.4 nm (left) and 28.4 nm (right) lines, normalised by flare class, as a function of heliocentric angle. The blue dots represent the average values for each degree of heliocentric angle; the cyan circles show the average values for 10-degree intervals.

Empirical Relationship Between TEC and EUV Irradiance

We analysed 14 X-class solar flares with pronounced late phases that occurred between 2011 and 2024. Figure 5 presents the increase in TEC during the impulsive and late phases of these flares as a function of the flux enhancements in the He II and Fe XV lines, respectively.

Both relationships are statistically significant and can be used to estimate TEC increases during different flare phases, provided that flux dynamics data for the corresponding solar emission lines are available.

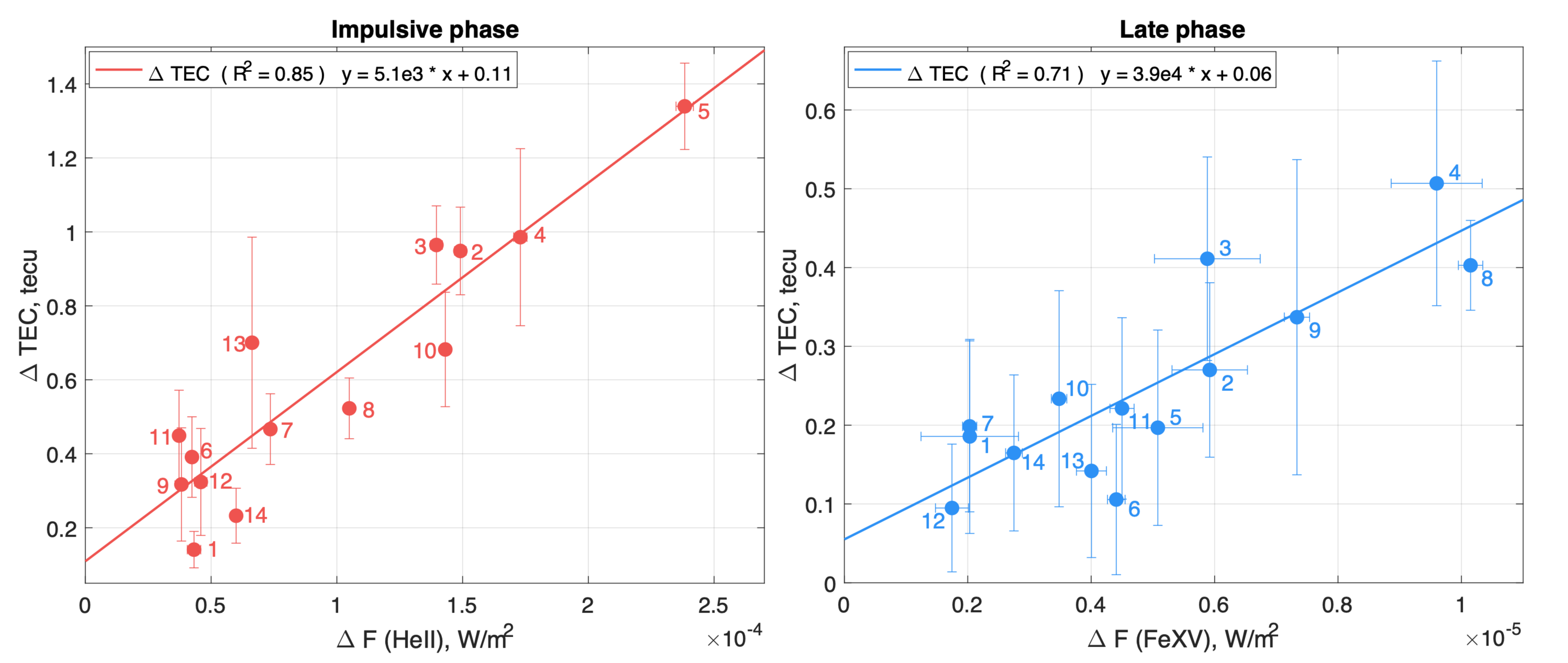

Figure 5. Dependence of ΔTEC on ΔF (He II) during the impulsive phase (left) and on ΔF (Fe XV) during the late phase (right).

Since Fe XV 28.4 nm and He II 30.4 nm characterise the late and impulsive phases, respectively, the ratio of TEC increase associated with these phases is expected to be higher for flares occurring near the solar limb.

Figure 6 demonstrates a correlation between a flare's location on the solar disk and its impact on variations in electron concentration in the ionosphere.

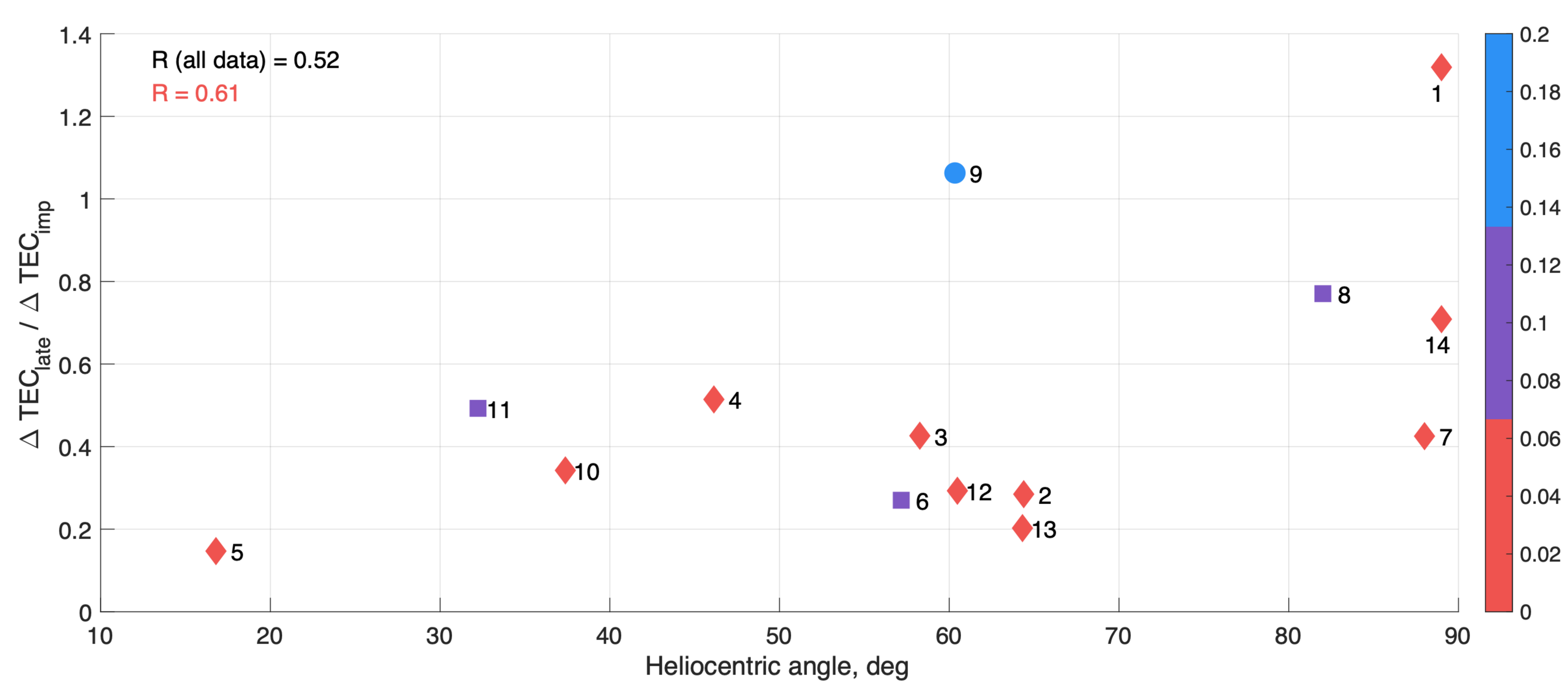

Figure 6. Dependence of the $\Delta TEC_{late}/\Delta TEC_{imp}$ on the heliocentric angle. The color indicates the ratio of fluxes ΔF (Fe XV) / ΔF (He II).

For more details see [Bekker, Milligan & Ryakhovsky, 2024, ApJ, 971, 188] and [Bekker, Milligan & Ryakhovsky, 2025, JGR, *in review*].

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