Supplementary Material

Impacts of extreme space weather events on September 6th, 2017 on ionosphere and primary cosmic rays

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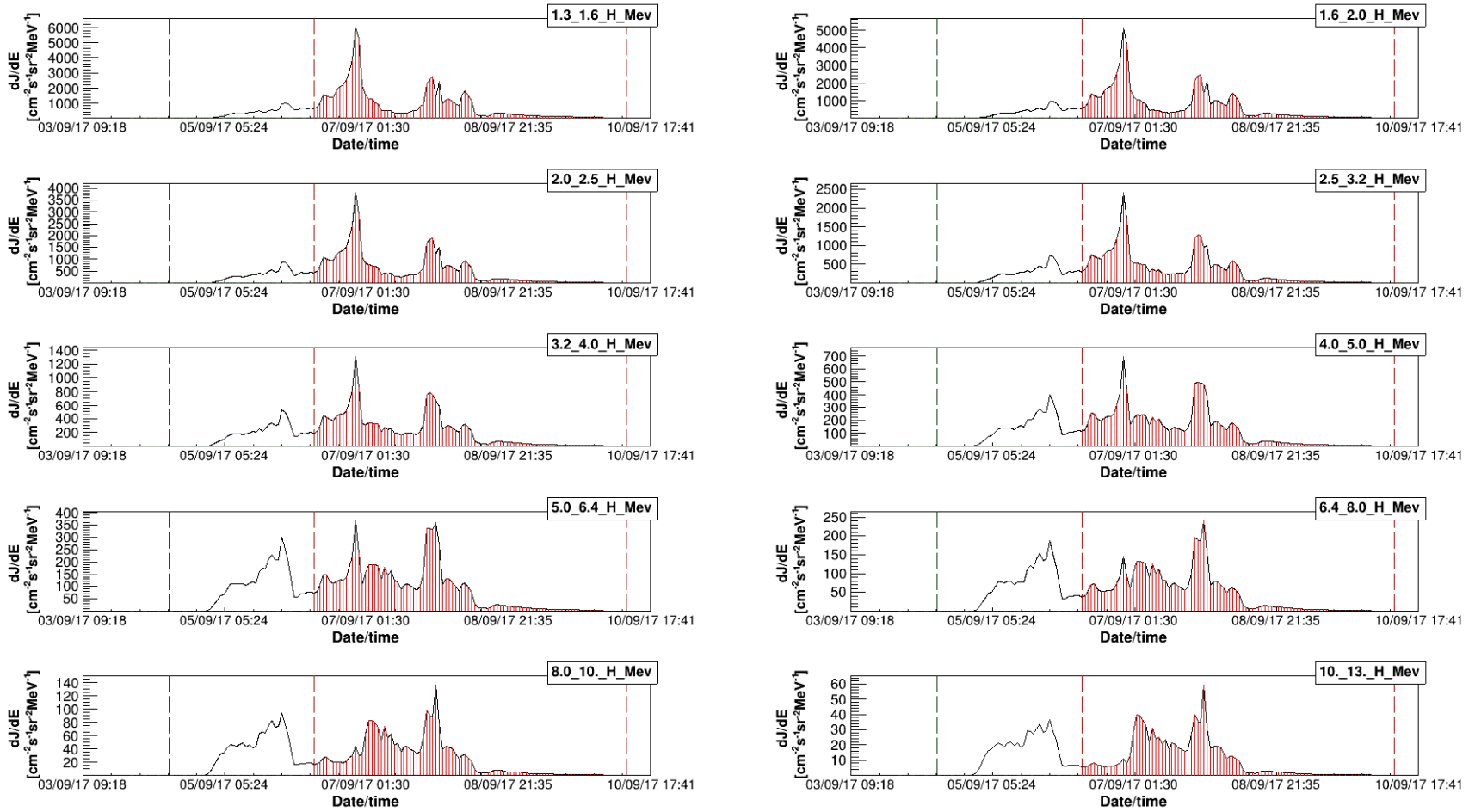


Figure S1. Differential SEP fluxes during extreme solar event in September 2017, measured by SOHO/ERNE energetic particle sensors LET (Low Energy Detector) proton channels. Red vertical dashed lines indicate the time for the start and the end of interval used to calculate the integral flux.

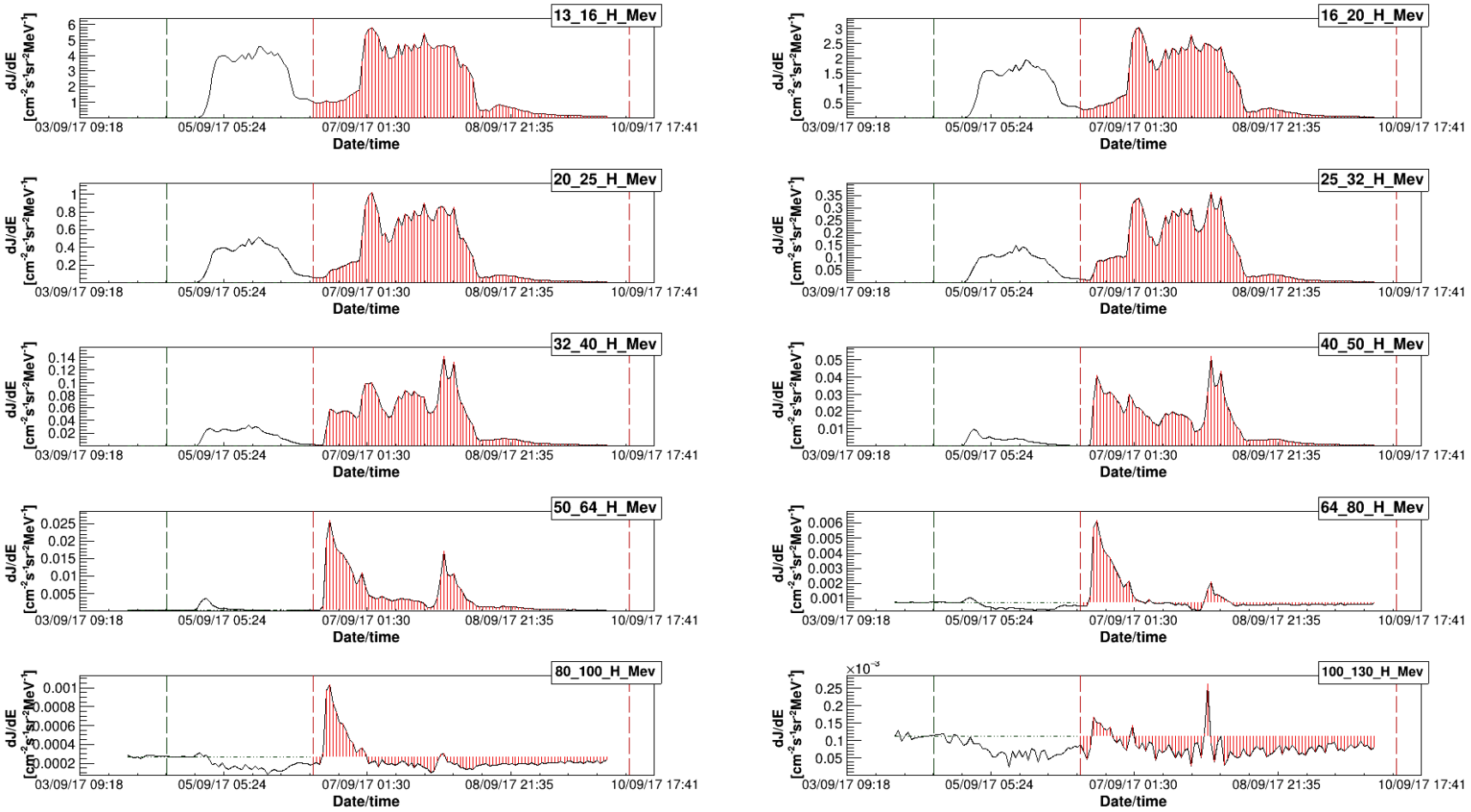


Figure S2. Differential SEP fluxes during extreme solar event in September 2017, measured by SOHO/ERNE energetic particle sensors HET (High Energy Detector) proton channels. Red vertical dashed lines indicate the time for the start and the end of interval used to calculate the integral flux.

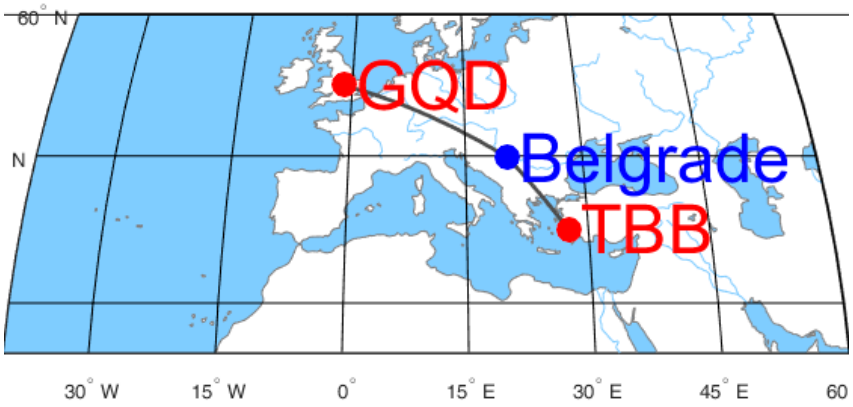


Figure S3. The geographic position of Belgrade (BEL) VLF receiver and the GQD transmitter (54.73° N, 2.88° W) Anthorn UK and TBB transmitter (37.43° N, 27.55° E) Bafa Turkey with GCP of sub-ionospheric propagating VLF signals.

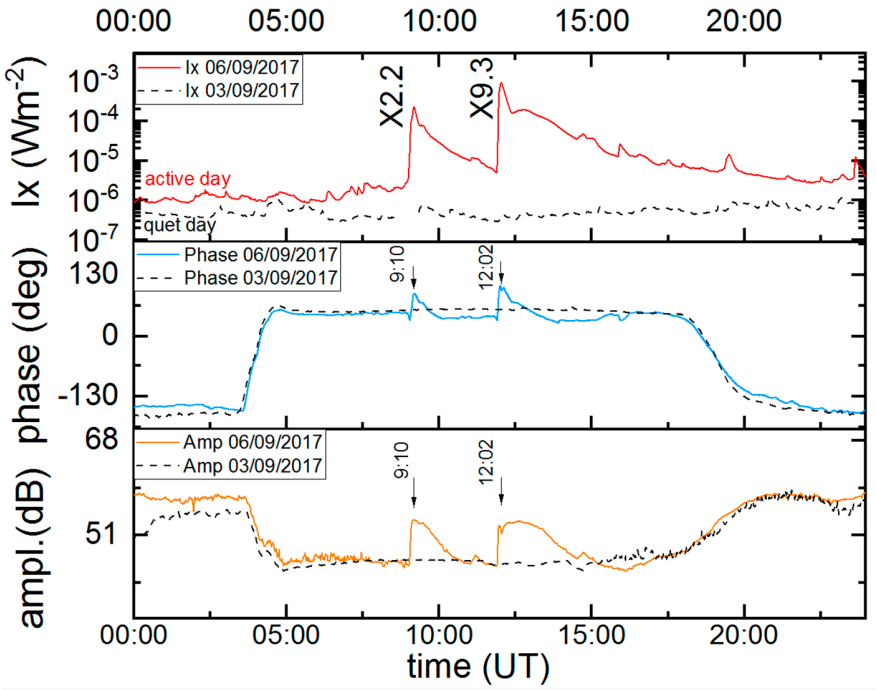
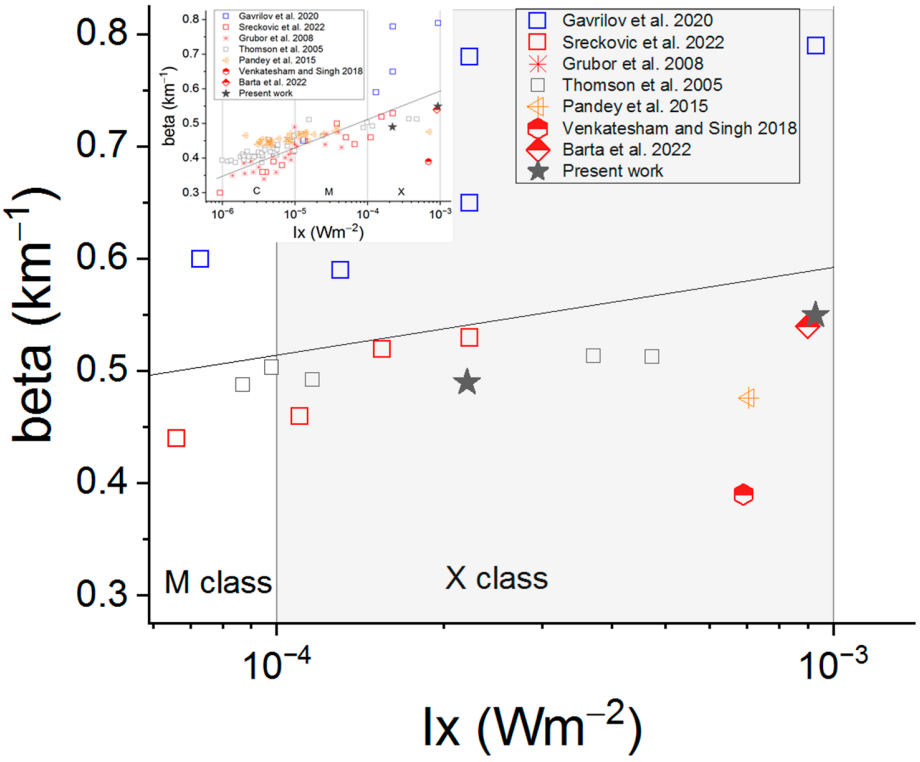
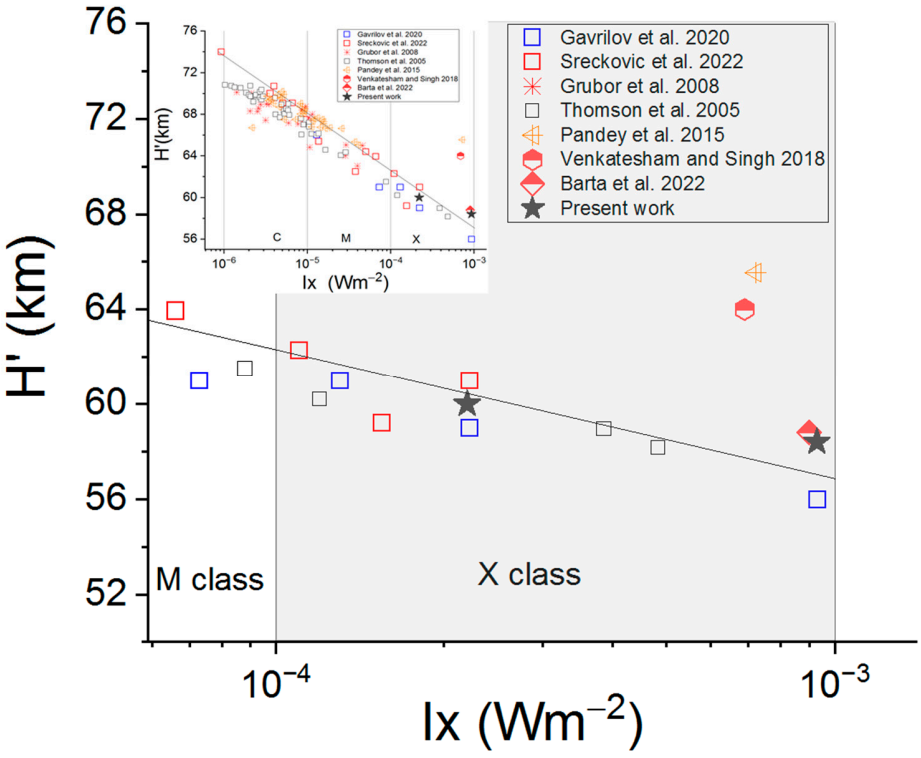


Figure S4. Simultaneous variations of X-ray flux (red), phase (blue) and amplitude (orange) of GQD/22.10 kHz signal versus universal time UT during occurrence of X2.2 and X9.3 class SFs of September 6th, 2017 (from upper to lower panel). Observed amplitude and phase perturbations on GQD radio signal, as well as quiet signal (dashed black), are measured at Belgrade station. Time variation of soft X-ray irradiance is measured by GOES-15 satellite.


Gavrilov et al. 2020
Sreckovic et al. 2022
Grubor et al. 2008
Thomson et al. 2005
Pandey et al. 2015
Venkatesham and Singh 2018
Barta et al. 2022
Present work
beta (km^{-1})
Ix (Wm^{-2})
M class
X class
C
M
X

(a)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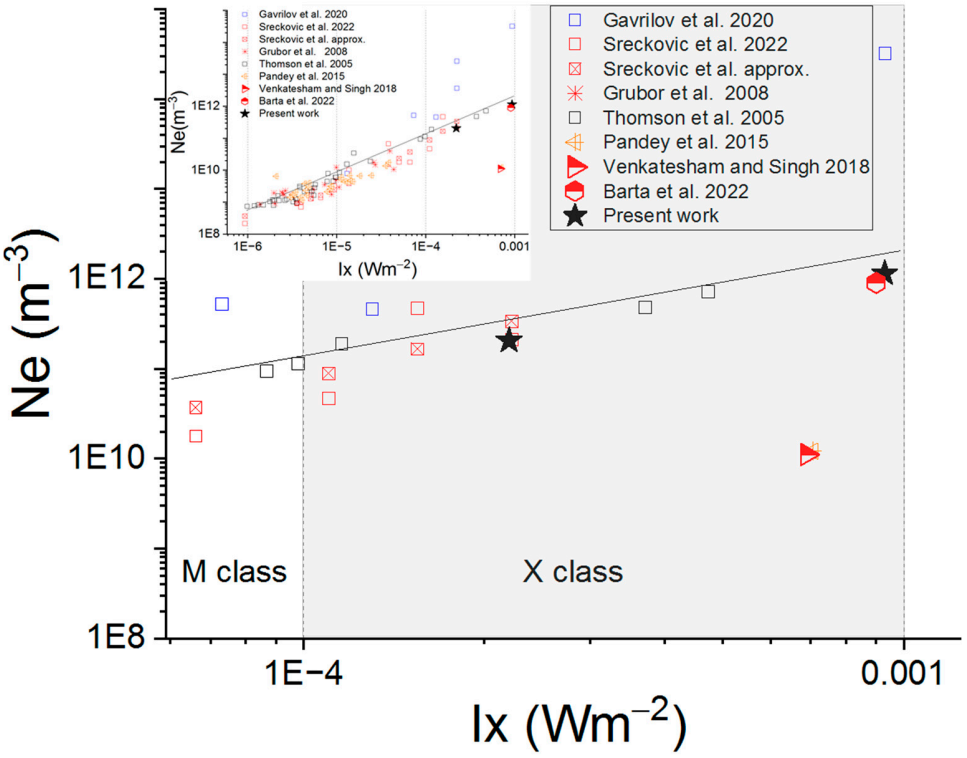
H' (km)
Ix (Wm^{-2})
M class
X class
C
M
X

(b)



(c)

Figure S5. Lower ionospheric response to SF events of different strength across X-class (shaded gray area), obtained indirect through modeling of VLF signals' propagation parameters: (a) sharpness β (km^{-1}) and (b) effective reflection height *H'* (km) and (c) estimated corresponding electron densities *Ne* (m^{-3}), in function of X-ray flux; results from our research are presented by black stars.

Our results (black stars) are compared to other studies including several major cases of strong SF events from period 2003-2011 with SF cases of class X28+–X6.9 (a-d) and with some other cases from period 2006-2017 covering range X1-X9.3 (e-i) and from period 1994-1998 in range X1-X5 (j):

a) X6.9 of August 9th, 2011 at 08:05UT - strongest SF of 24th solar cycle, associated with CME and SPE events; at low-latitude site [71,69]
b) X9 of December 5th, 2006 at 10:35UT – strongest SF in 2006 and eighth of 23rd solar cycle; at mid-latitude site (Belgrade VLF database) [7]
c) X28+ of November 4th, 2003 at 19:53UT – one of strongest solar flares ever recorded and strongest of 23rd solar cycle associated with CME and SPE events, from very active period October 20th-November 5th, 2003 including X10.1 of October 29th, 2003 at 20:49UT and X8.3 of November 2nd, 2003 at 17:25UT third and fourth in 2003 and sixth and ninth of 23rd solar cycle, both associated with CME; at mid-latitude site [72]
d) X7.1 of January 20th, 2005 at 07:01UT – second strongest SF in 2005 and tenth of 23rd solar cycle associated with CME and SPE events, from active period January 15th–22nd, 2005; at mid-latitude site (Belgrade VLF database) [73,74]

e) X1.1-X2.2 of June 10th and 11th, 2014 (CME?) & X17.2 of October 28th, 2003 (associated with CME and SPE events); at mid-latitude site (Belgrade VLF database) [5]
f) X1.3 of September 7th, 2017; at mid-latitude site (Belgrade VLF database) [8]
g) X1.3-X9.3 of June 10th, 2014 & September 6th–10th, 2017, with strongest two of them (both above X5) associated with CME; at mid-latitude site, but a bit northward from Belgrade [70]
h) X1.5 of December 14th, 2006 at 22:15UT; at low-latitude site [75]
i) X1-X3.2 in period May–December 2013, all associated with CME and one of the weaker ones associated with SPE; at low-latitude site [76]
j) X3-X5 in period 1994-1998, some associated with CME and SEP events; at mid latitude site [77]

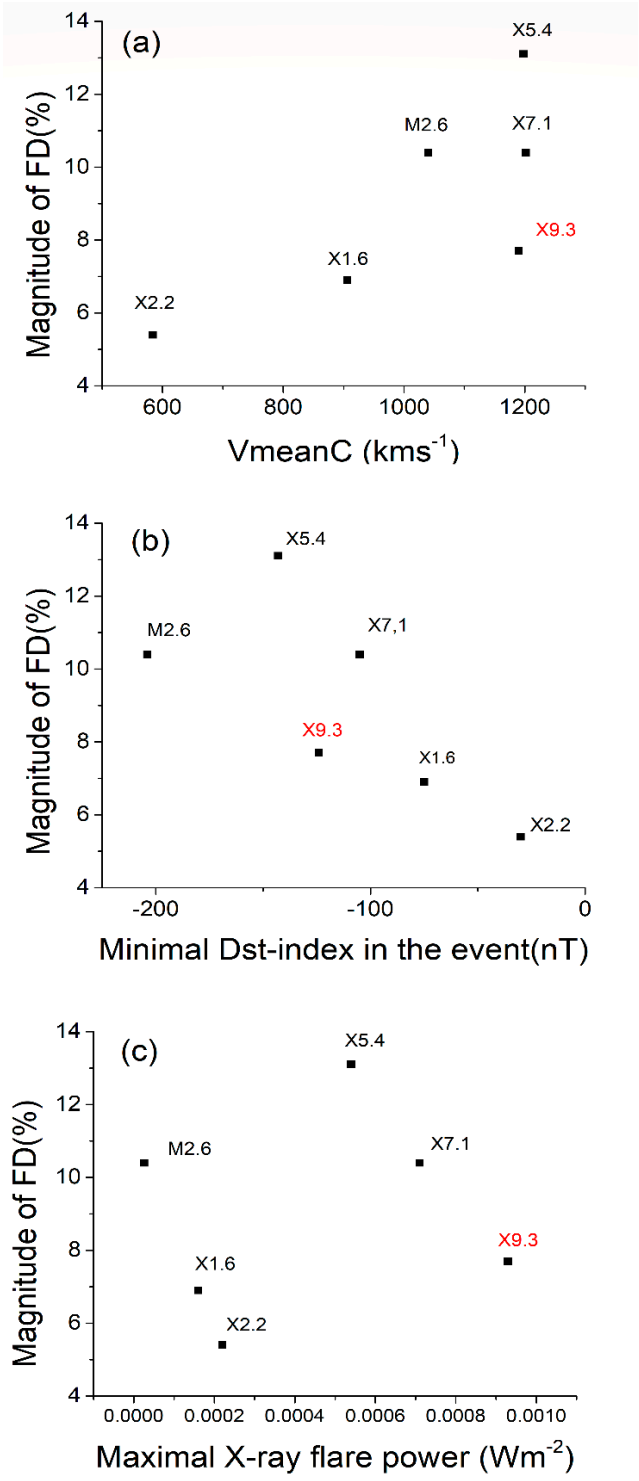


Figure S6. Magnitude of the FD versus the average CME velocity between the Sun and the Earth, calculated using the time of the beginning of the associated CME observations (a), Minimal Dst-index in the event (b), maximal X-ray flare power (c), with associated flare indicated in red.