Supplementary Material

1 21 JUNE 2015 AND 6 SEPTEMBER 2017 EVENTS - THE DETAILED DESCRIPTION

Here we provide a more detailed description of the two events examined in our study. More specifically, for each case we examine (i) the active region, (ii) the CME associated with flare, (iii) the propagation of the ICME and (iv) the resulting geoeffectiveness.

1.1 Case-1: the 21-22 June 2015 event

On 21 June 2015 two distinct flares of class M2.0 (*2015-06-21T01:02:00-FLR-001*) and M2.6 (*2015-06-21T02:06:00-FLR-001*) erupted from the same active region (AR 12371) located at the heliospheric position N13E23. This AR firstly appeared on the solar disk on 17 June 2015 as a β-type sunspot, i.e. a sunspot group that exhibits a simple division between positive and a negative polarities. In the successive days, the AR increased the complexity of its magnetic configuration and an irregular distribution appeared, merging its umbrae into a single penumbra (see **Supplementary Figure S1**). Because of its evolution pattern, on June 19, AR12371 was classified as $\beta\gamma\delta$. The AR maintained this configuration till 24 June 2015.

1.1.1 The Active Region

The increased complexity of the sunspot area indicates an enhancement in the amount of magnetic energy stored in the AR12371 magnetic configuration. In a solar flare, this energy can be converted into kinetic and thermal energy (Régnier and Priest, 2007). 48 hours before the event, eight C-class flares erupted and only three flares erupted on June 20. We listed the characteristics in the **Supplementary Materials**, see **Supplementary Table S1**. The lack of an intense class of flares indicates the low activity in the AR.

Supplementary Figure S2 shows the X-ray flux measured by the GOES-15 spacecraft in 0.5-4.0 Å channel (blue line) and in 1.0-8.0 Å channel (red line). There are two noticeable peaks, which indicate the occurrence of two separate flare events. The first M2.0 event started at 01:02 UT, reached its maximum at 01:42 UT and ended at 02:00 UT. On the other hand, the M2.6 event started at 02:06 UT, reached its maximum at 02:36 UT and ended at 03:02 UT. The Solar Dynamics Observatory (SDO, Pesnell et al., 2012) provides a visual representation of the event through a series of images captured from 01:26 to 03:11 UT (**Supplementary Figure S3**). This sequence clearly shows that the evolution between the two events occurred without interruption, suggesting a unique continuous event, as indicated in Piersanti et al. (2017). Also Joshi et al. (2018) investigated the AR during the first and second flares, identifying a two-step eruption process of a magnetic flux rope, that resulted in two consecutive flares. More in detail, the flux rope eruption proceeded in a distinct direction in the two phases.

Nevertheless, hereafter we indicate the event as unique instead of two distinguished events, as indicated in Piersanti et al. (2017).

1.1.2 The CME description

This event triggered the development of a CME flux rope, as highlighted by the post-eruptive arcades (Tripathi et al., 2004). Unfortunately, no data were acquired by both STEREO spacecraft (Kaiser et al., 2008) due to the lack of proper spacecraft communication (Temmer, 2021). Nonetheless, images of a

CME expansion through the heliosphere were retrieved by the SOHO/LASCO coronographs (Brueckner et al., 1995), whose fields-of-view (FoVs) span 2–6 $R_\odot$ (LASCO-C2) and 3.7–32 $R_\odot$ (LASCO-C3). The first detection of the CME structure was identified by LASCO-C2 at 02:36 UT. The upper panels of **Supplementary Figure S4** tracks the early evolution of the halo-CME. The expansion of the structure at distances higher than 6 $R_\odot$ is shown in the lower panels of Figure **Supplementary Figure S4**. The halo-CME can be observed moving towards the spacecraft within its FoV. Moreover, a shock-front is visible ahead of the CME. The resulting velocity measurements indicated $\bar{v} \sim 1400$ km s^{-1} and retrieved an acceleration $a \sim 21$ m s^{-2} at a height of 20 $R_\odot$. On the whole, during the early phase the halo-CME slightly accelerated ($a \sim 100$ m s^{-2}), whereas it decelerated ($a \sim -200$ m s^{-2}) during the successive expansion.

1.1.3 The ICME propagation

Solar wind parameters measured by the ACE spacecraft during the period 22–24 June 2015 are shown in left panel of Figure **Supplementary Figure S5**. The figure reports the solar wind proton density, the solar wind radial velocity and the components of the magnetic field strength B. It must be noted that the same AR 12371 produced two other CMEs in the earlier few days, on 2015-06-18 at 03:18 UT (CME1) and 2015-06-18 at 17:24 UT (CME2), respectively. The interplanetary (IP) shocks produced by the first two events crossed the ACE spacecraft on 2015-06-21 at ∼15:30 UT (shock-1) and on 2015-06-22 at ∼05:00 UT (shock-2).

The interplanetary coronal mass ejection (ICME) that occurred on 21 June 2015, produced an IP shock that arrived at Earth at 17:59 UT on 22 June 2015 (shock-3). The developed ICME magnetic sheath region and the magnetic cloud (MC) were visible. On one hand, the magnetic sheath region was characterised by enhanced plasma density (nearly 40 p cm^{-3}) and by magnetic field turbulence, which led to abrupt oscillations. On the other hand, the MC was located about 8 hours after the shock wave. Distinct features marked its passage both on the magnetic field (e.g. the coherent smooth oscillation of the magnetic field components or smooth increase of B_z) and plasma data. Then, the smooth speed decrease from the ICME front (∼750 km s^{-1}) to the back (∼600 km s^{-1}) suggests that the MC was expanding. Finally, it must be noted two dips in the magnetic field strength inside the magnetic cloud interpreted as a signature of heliospheric current sheet and the ICME, that led to two small flux ropes (FR1 and FR2) (Liu et al., 2015).

Note that, at the back of the MC a new IP shock (shock-4) was detected by ACE, at ∼ 12:57 UT on June 24. This CME was produced by a M6.5 flare that erupted on June 22 at 17:39 UT from the same AR.

Globally, the duration of the cloud was ∼ 44 hours. Thus, considering an average speed of ∼600 km s^{-1}, the cloud had a thickness of ∼ 0.64 AU.

1.1.4 Energetic Storm Particles

Energetic Storm Particles (ESPs) events, i.e. local increases of energetic charged particle intensities can be observed at IP shocks (Chiappetta et al., 2021, and references therein).

Right panel of **Supplementary Figure S5** depicts the proton flux measured by the Low Energy Magnetic Spectrometer-120 (LEMS-120), in the range 0.046 - 4.7 MeV, one of the telescopes of the Electron, Proton, and Alpha Monitor (EPAM, Gold et al., 1998) on ACE spacecraft.

ESPs observed around 06:00 UT on June 22, corresponding to the arrival of the IP shock-1 and shock-2, respectively. This event was limited to energies below 195 keV. Moreover the arrival of the shock-3 produced an enhancement in the proton intensities of ∼ 1 order of magnitude in all energy channels.

1.1.5 Geoeffectiveness

Some CMEs, like the one on June 22nd, can be considered more geoeffective according to their characteristics, such as the source location on the disk and the morphology. In fact, Gopalswamy et al. (2007) reported higher geoeffectiveness of events located at the center of the disk than at limb. Moreover, Gopalswamy (2009) documented that during the Solar Cycle 23 halo-CMEs caused the most intense geomagnetic storms.

The Case-1 event led to a major geomagnetic storm on 23 June 2015. To measure the intensity of this storm distinct indices can be used. Among them, the Dst index[1] gives information on how the ring current around Earth responds (in terms of strength) to solar wind. Similarly, the K_p index[2] measures the disturbances in the horizontal component of Earth's MF during a three-hour interval. **Supplementary Figure S6** reports the variation of Dst and K_p indices during 21-25 June 2015. Vertical dashed lines mark the arrival of each IP shock at the Earth. Note that in correspondence to the arrival of shock-1, the two indices give distinct results, i.e. the increase of K_p index occurs simultaneously with the increase of Dst index. Immediately after the arrival of shock-2, the Dst index started to decline reaching a minimum of -46 nT before the arrival of the major shock-3. It must be noted that the latter produced a first increase followed by a steeper decrease ($\Delta Dst \sim$ -150 nT). Immediately after the shock-3 we observe two abrupt changes of the Dst and K_p indices: the first one, at 21:00 UT Dst= -114 nT and K_p= 8+ evidences the intense storm regime; and the second one, nearly 12 hours later, evidences $\sim$ intense (Dst = -198 nT, 2 times more intense than the first one) and severe storm (K_p = 8-) regimes. The evolution of the geomagnetic storm suggests the presence of a double storm, associated with periods when the z-component of IMF was negative. Piersanti et al. (2017) attributed the first period to the arrival of the sheath region of the ICME whereas the second was associated with the initial magnetic cloud. Therefore, MR could occur enabling the plasma transport within the magnetosphere. Shortly after the second storm, the recovery phase started. On June 25, the Dst and K_p indices activity returned to their nominal values.

Consequently, a range of phenomena resulted from this geomagnetic storm, such as the erosion of the plasmasphere and its inward movement of up to approximately $\sim$ 2.5 $R_\odot$ (see Piersanti et al., 2017, for a description of magnetospheric, ionospheric and ground-based magnetic response).

1.2 Case-2: the 6-7 September 2017 event

On September 6, the AR 12673 produced two X-class flares. The first X2.2 flare erupted at $\sim$ 09:00 UT, whilst the second X9.3 flare started at 11:53 UT. However, only the latter flare was associated with a halo-CME. Due to its critical peak-intensity, the X9.3 flare is considered the largest event in solar cycle 24 (Yasyukevich et al., 2018; Mitra et al., 2018; Jiang et al., 2018).

1.2.1 The Active Region

Starting from September 4, the complexity of the active region increased as well as the number of flares erupted (see **Supplementary Table S2**). In the period September 4–10, AR 12673 produced 27 M-class and 4 X-class flares. This high flare productivity was related to the emergence of new bipolar regions that interacted with pre-existing ones. This interaction led the magnetic field to be highly sheared and, as a result, the magnetic energy to be accumulated (Yang et al., 2017). **Supplementary Figure S7** shows the magnetic configuration of AR 12673 on the day of the major eruption. Note that the sunspot region has a positive and negative polarity (i.e. $\beta - configuration$) with an irregular distribution (i.e.

[1] https://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html
[2] https://wdc.kugi.kyoto-u.ac.jp/kp/index.html#LIST

$\gamma - configuration$), which led its umbrae to be merged into a single penumbra (i.e. $\delta - configuration$). Thus, the AR 12673 has been classified as $\beta\gamma\delta$ on 6 September 2017. In the last decades, several works (e.g. Zirin and Liggett, 1987; Sammis et al., 2000; Takizawa and Kitai, 2015) have shown that ARs with such complexities produce powerful flares.

Notably, this major flare event was preceded by another X-class flare (X2.2) that erupted just three hours before, i.e. at 08:57 UT. For further details on the evolution of the magnetic configuration and description of X2.2 the reader can refer to Yang et al. (2017); Verma (2018) and Mitra et al. (2018), respectively.

According to Yang et al. (2017), the X9.3 flare was triggered by a filament that erupted owing to the *kink instability* (e.g., Hood and Priest, 1979; Török and Kliem, 2005; Rust and LaBonte, 2005). Based on continuum and UV images collected by SDO, Verma (2018) confirmed that the origin of increasing flare activity should be attributed to the collision between the newly emerging flux and the already existing regular, α-spot. Shortly after the eruption of the flux rope (at about 11:57 UT), two flare ribbons emerged on both sides of the PIL (Mitra et al., 2018), whose separation was extremely small compared to other impulsive X-class flares. In the successive minutes, the two ribbons gradually separated. Concurrently, during the gradual phase of the flare, a semicircular arc appeared in the northern part of the sigmoid. **Supplementary Figure S9** shows that by 12:11 UT plasma was erupting from this region. Finally, during the decay phase of the flare, the semicircular arc evolved into postflare loops.

1.2.2 The CME description

Due to the high flare productivity of the region, several CME events were produced. On September 4 a partial-halo CME (CME-1) was initially observed by SOHO/LASCO-C2 at 19:00 UT. Several factors (e.g. the eruption time and the direction of motion) suggested that it could be associated with a M1.7 class flare, that erupted at 18:46 UT. Nearly 100 minutes later (at 20:36 UT), a second CME (CME-2) associated to a M5.5 flare (S10W11) was detected. Since the CME-2 was faster (1 350 km s^{-1}) than CME-1 (710 km s^{-1}), they rapidly interacted and merged at 21:18 UT. On September 5, another two CMEs were produced by flares erupted from the same AR. However the first one was extremely faint and the second CME was not earthward directed. Another CME (CME-3) was associated with the major X9.3 class event. It was first detected by SOHO/LASCO-C2 as a halo-CME at 12:24 UT on 6 September 2017. The upper panels of **Supplementary Figure S10** tracks the early evolution of the CME-3. The expansion of the structure at distances higher than 6 $R_\odot$ is shown in the lower panels of **Supplementary Figure S10**. As one may notice, a shock-front is visible ahead of the CME-3.

A posterior analysis revealed the radial velocity of the CME-3, using LASCO ($\bar{v} \sim 1\,571$ km s^{-1}) and STEREO ($\bar{v} \sim 1\,100$ km s^{-1}) data.

1.2.3 The ICME propagation

The spacecraft located at the Lagrangian point L1 (e.g. ACE, WIND and DSCOVR) were the first to detect the arrival of the related interplanetary (IP) shocks. At 23:05 UT on 6 September 2017, the spacecraft encountered the IP shock (shock-1) produced by the merged CMEs (see left panel of **Supplementary Figure S11**). Shock-1 was followed by a prolonged sheath region, dominated by (i) enhanced plasma temperature, (ii) dynamic pressure and (iii) turbulent magnetic field components. The second IP shock (shock-2) associated with the fast halo CME-3 was detected on September 7 at 22:34 UT. Note that the shock-2 was immediately followed by a magnetic turbulent sheath region. The ICME shows some evidence of a rotation in field direction, but lacks some other characteristics of a magnetic cloud.

1.2.4 Energetic Storm Particles

Right panel of **Supplementary Figure S11** illustrates the temporal evolution of proton flux profile in the range 0.046 - 4.7 MeV, between 6 and 9 September 2017. The first vertical line denotes the onset times of the erupting X9.3 flare, whereas the second and the third lines indicate the occurrence of the ESP events triggered by the arrival of the interplanetary shock-1 and -2, respectively. On September 6, in correspondence to the arrival of the shock-1 an increase in the intensities of protons, mainly in low-energy channels, was observed at about 23:05 UT. On the contrary, an abrupt increase was observed in all eight channels, associated with the arrival of the shock-2.

1.2.5 Geoeffectivness

Supplementary Figure S12 shows the geomagnetic effect of the event in the period 6-9 September 2017. The upper panel presents the Dst index, whilst the lower panel shows the K_p index. The vertical dashed lines mark the arrival of shock-1 and shock-2 at Earth. Notably, during the arrival of shock-1, both indices give similar results, indicating a quiet period. Immediately after the arrival of shock-2, the Dst index started to gradually decline reaching a minimum of -122 nT at 03:00 UT on September 8. The decrease of Dst index occurred along with the increase of K_p index (K_p = 8). Note that the Dst index indicates a "slight" intense storm on September 6, while K_p indicates an intense storm. Moreover, a successive substorm was produced at about 14:00 UT later enough to be caused by magnetic reconnection in the magnetotail.

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