Chapter 6

A LONG DURATION FLARE FROM EVOLVED RS CVn TYPE ECLIPSING BINARY SZ Psc

In this chapter, we investigate a very long duration flaring event observed from Swift satellite from an RS CVn type eclipsing binary star SZ Psc. The system consists of a spotted, chromospherically active K1 subgiant and a much less luminous, inactive F8 star (Kharchenko et al., 2007), with an orbital period of about 3.9657 days (Eaton & Henry, 2007). The K1 subgiant is the more massive component and is filling 80–90% of its Roche lobe. The light variations in optical waveband on SZ Psc was found by several researcheres, such as Jakate et al. (1976), Catalano et al. (1978), Tumer & Kurutac (1979), Eaton et al. (1982), Tunca (1984), Antonopoulou et al. (1995), Lanza et al. (2001). The spot model was applied by Eaton & Hall (1979) to explain a distortion wave in optical light curves. Lanza et al. (2001) has studied Long-term starspot evolution, activity cycle and orbital period variation of SZ Psc. Whereas Kang et al. (2003) have studied chromospheric activity by analysing photometric data and have given light-curve/spot solutions. Doyle et al. (1994) observed flaring activity on SZ Psc in Ultraviolet waveband. They also found variation in Mg II strength, possibly phase dependent, and an apparent eclipse of a plage in Mg II. MAXI/GSC detection of a possible flare from SZ Psc was reported by Negoro et al. (2011).
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Figure 6.1: Swift BAT (top panel), XRT (middle panel), UVOT (bottom panel) observations show flare FSZ and the post-flare PFSZ.

6.1 X-ray light curves

Fig. 6.1 shows the X-ray light curves of SZ Psc obtained in 14–150 keV, 0.3–10 keV and five UVOT bands. The flare FSZ triggered Swift’s BAT on 2015 January 15 UT 09:08:42 (=T0₃) as an Automatic Target trigger on board (reported by D’Elia et al., 2015; Drake et al., 2015). SZ Psc entered in the BAT FOV around 100 s before the trigger interval. SZ Psc was also within the BAT FOV in the earlier orbits before ~ 12 ks from the T0₃. The BAT light curve shows variability during and after the trigger interval. The count rate initially appears to fall from an earlier peak, followed by an increase up to a count rate of ~0.0084 counts s⁻¹.
The Swift XRT started to observe the flare FSZ from T0$_3+380.5$ s in WT mode, while the XRT count rate was $\sim 82.5$ counts s$^{-1}$. The XRT count rate increased to $\sim 100$ counts s$^{-1}$ by the end of the initial observation at T0$_3 + 2.2$ ks, and then over the next 8 hours declined rapidly, dropping to $\sim 30$ counts s$^{-1}$ at T0$_3 + 30$ ks. After a gap of $\sim 16$ ks, the XRT observations for the period T0$_3 + 58$ ks to T0$_3 + 92$ ks shows much slower decay of the flare during which the count rate was decreased from $\sim 7$ counts s$^{-1}$ to 3 counts s$^{-1}$. After $\sim 109$ ks of these observations, the soft X-ray flux of SZ Psc was decreased to 1.3 counts s$^{-1}$. The Swift returned to the field of view of SZ Psc after 5.67 days (or 0.49 Ms) from the trigger, where the XRT count rate dropped to a value of $\sim 0.5$ counts s$^{-1}$. This region is marked as “PFSZ” in Fig. 6.1.

The Swift UVOT observations of the flare peak and early decay phases of SZ Psc were saturated by all three UV filters. However, the early rise phase was detected without saturation by the optical $u$, $b$ and $v$ filters, as shown in the lower panel of Fig. 6.1. This shows that, flare peaks earlier in the $u$ band, then in the $b$ and $v$ band. This phenomenon is similar to the “Neupert Effect”. Only in the $uvm2$ filter, the light curve is not saturated during the flare decay, and the light curve seems to follow the similar variation in the XRT energy band.
The duration for the flare FSZ is derived to be >70 ks, which is among the longest duration flares observed on SZ Psc, thus far. The flare duration is also very much larger than that of the flares derived in other BY Dra and RS CVn binaries (Pandey & Singh, 2008, 2012). The e-folding rise times ($\tau_r$) and decay times ($\tau_d$) of the flare FSZ in XRT band are derived using the equation 4.1 and found to be $12.5\pm0.4$ and $19.9\pm0.1$ ks, respectively. Both of these values are comparable or more than those of the observed flares in other G-K dwarfs, RS CVn binaries, and dMe stars (e.g. Osten & Brown, 1999; Pandey & Singh, 2008, 2012; Schmitt, 1994). Due to insufficient statistics for BAT data, and incompleteness of the flare in all the UV filters due to saturation or faintness, we could not derive the rise and decay time in other energy bands. Since SZ Psc is an eclipsing binary, we have also investigated if the flare is affected by the eclipse or not. We have phase folded the XRT light curve with a period of 3.96 days and according to the revised ephemeris from Eaton & Henry (2007). We have overplotted the X-ray light curve on the optical V and B band light curve derived by Kang et al. (2003), and shown Fig. 6.2. It is evident from the figure that the flare was observed out of eclipse from binary phase 0.18 to 0.4. The later phase of the flare was partially eclipsed. The post flaring region was very close to the secondary eclipse at binary phase 0.55 showing that the primary component of SZ Psc is relatively strong X-ray emitter.

6.2 X-ray Spectral Analysis

Both the BAT and XRT spectra during the flaring event were extract adopting the methods as given in Chapter 2. The detailed analysis of BAT spectra could not be done due to poor count statistics. Therefore, only XRT spectra were analysed to study the this long duration flare.

6.2.1 Post-Flare spectra

The spectra of post-flare phase were fitted single (1-T), double (2-T), and triple (3-T) temperature APEC model. The global abundances ($Z$) and interstellar HI column density ($N_H$) were left as free parameters. None of the plasma models (1-T, 2-T, or 3-T) were formally acceptable with solar photospheric abundances as large values of $\chi^2$ were obtained. Only a 3-T plasma model with the sub-solar abundances was found to be acceptable with a reduced $\chi^2$ value of 1.01 for 36 DOF. This shows that post-flare coronae of SZ Psc were well represented by three temperatures plasma. In
Figure 6.3: The time-resolved XRT spectra obtained in 0.3–10 keV. The black circle shows the spectra of the PFSZ phase. The rest spectra corresponds to the different parts of the flare rise and decay and the time-bins are as given in Table 6.1.

Our analysis, $N_H$ was a free parameter and the value was found to be less than the total galactic HI column density (Dickey & Lockman, 1990) towards the direction of SZ Psc. The three temperatures from the best-fit 3-T models were derived to be $0.027^{+0.009}_{-0.060}$, $0.66^{+0.09}_{-0.06}$, and $7^{+12}_{-2}$ keV, respectively. The corresponding ratios of the emission measures were $EM_2/EM_1 = 2 \times 10^{-4}$ and $EM_3/EM_2 = 0.39$. The X-ray luminosity in 0.3–10.0 keV band during the post-flare region was derived to be $1.2^{+0.1}_{-0.1} \times 10^{29}$ erg s$^{-1}$. The value of the luminosity is comparable or larger than the quiescent X-ray luminosities observed on other RS CVn stars (Pandey & Singh, 2012).

### 6.2.2 Flare spectra: Time-Resolved Spectroscopy

We have performed a detailed time-resolved analysis in order to investigate the evolution of spectral parameters during the flare FSZ in the soft X-rays. The flare was divided into twenty four time bins, so that each time bin contains sufficient and similar number of counts. The length of the time bins is variable, ranging from 210–
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Figure 6.4: Evolution of XRT spectral parameters of SZ Psc during the flare. From top to bottom: (a) the X-ray luminosities are derived in 0.3–10 keV, (b) plasma temperature, (c) EM, and (d) abundance are shown. All the vertical bars show 68% confidence interval, whereas horizontal bar shows the time interval for which the spectra were obtained.

10960 s. Larger time bins also contain large data gaps due to the earth occultation of satellite which also shows the decrement in the total counts. Table 6.1 gives the time intervals for which the X-ray spectra were accumulated and spectra for those time interval are shown in Fig. 6.3. In order to study the flare emission, we have performed 1-T, 2-T, and 3-T spectral fit of the data using the apec model. A 1-T model gives the best-fit with the reduced $\chi^2$ values as given in Table 6.1. Initially, in the spectral fitting $N_H$ was a free parameter and found to be constant within a $\sigma$ level of the quiescent state value. Therefore, it was fixed at a value of quiescent state in the next stage of spectral fitting. The time evolution of derived spectral
the flaring loop. Parameters of the flare FSZ is shown in Fig. 6.4 and are given in Table 6.1. The value is of the similar order to those of the superflares detected on CC Eri (Karmakar et al., 2017), EV Lac (≈150 MK and ≈142 MK; Favata et al., 2000; Osten et al., 2010), II Peg (≈300 MK; Osten et al., 2007), and AB Dor (≈114 MK; Maggio et al., 2000).

![Image](image-url)

**Table 6.1: XRT time-resolved spectral parameters during the flare from S Z Psc**

<table>
<thead>
<tr>
<th>Parts</th>
<th>Time Interval (s)</th>
<th>kT (keV)</th>
<th>EM (10^{54} cm^{-3})</th>
<th>L_k [0.3–10] (10^{33} erg s^{-1})</th>
<th>Z (Z⊙)</th>
<th>(\chi^2) (DOF)</th>
</tr>
</thead>
</table>
| P01     | T0₁+380.5 : T0₁+710.5 | 17.6±0.8 | 2.89±0.06               | 4.35±0.05                         | 0.69±0.14 | 0.033 (52)
| P02     | T0₁+710.5 : T0₂+1030.5 | 16.8±0.8 | 2.34±0.05               | 4.52±0.05                         | 0.72±0.15 | 0.032 (52)
| P03     | T0₁+1030.5 : T0₁+1339.5 | 14.2±0.8 | 2.44±0.05               | 4.55±0.04                         | 0.56±0.12 | 0.032 (52)
| P04     | T0₁+1339.5 : T0₁+1650.5 | 15.6±0.8 | 2.53±0.05               | 4.63±0.04                         | 0.40±0.12 | 0.032 (52)
| P05     | T0₁+1650.5 : T0₂+1950.5 | 14.9±0.8 | 2.47±0.05               | 4.74±0.05                         | 0.68±0.13 | 0.032 (52)
| P06     | T0₂+1950.5 : T0₂+2220.5 | 15.0±0.8 | 2.49±0.05               | 4.79±0.05                         | 0.69±0.14 | 0.032 (52)
| P07     | T0₂+2220.5 : T0₂+2800.5 | 15.7±0.8 | 2.46±0.04               | 4.59±0.04                         | 0.56±0.11 | 0.032 (52)
| P08     | T0₂+2800.5 : T0₂+3140.5 | 12.3±0.5 | 2.36±0.04               | 4.38±0.03                         | 0.48±0.08 | 0.032 (52)
| P09     | T0₂+3140.5 : T0₂+3610.5 | 12.7±0.5 | 2.36±0.04               | 4.31±0.03                         | 0.46±0.08 | 0.032 (52)
| P10     | T0₂+3610.5 : T0₂+3800.5 | 12.7±0.5 | 2.32±0.04               | 4.31±0.03                         | 0.45±0.08 | 0.032 (52)
| P11     | T0₂+3800.5 : T0₂+3900.5 | 15.0±0.8 | 2.11±0.03               | 4.09±0.03                         | 0.67±0.08 | 0.032 (52)
| P12     | T0₂+3900.5 : T0₂+4140.5 | 15.2±0.8 | 2.02±0.03               | 3.76±0.05                         | 0.48±0.11 | 0.032 (52)
| P13     | T0₂+4140.5 : T0₂+4700.5 | 15.2±0.8 | 1.92±0.04               | 3.66±0.05                         | 0.41±0.12 | 0.032 (52)
| P14     | T0₂+4700.5 : T0₂+5300.5 | 15.8±0.8 | 1.97±0.04               | 3.61±0.05                         | 0.44±0.11 | 0.032 (52)
| P15     | T0₂+5300.5 : T0₂+5840.5 | 12.8±0.8 | 1.89±0.04               | 3.49±0.04                         | 0.51±0.10 | 0.032 (52)
| P16     | T0₂+5840.5 : T0₂+6140.5 | 16.8±0.8 | 1.89±0.04               | 3.49±0.04                         | 0.51±0.10 | 0.032 (52)
| P17     | T0₂+6140.5 : T0₂+6759.5 | 13.7±0.5 | 0.75±0.01               | 1.27±0.01                         | 0.22±0.07 | 0.032 (52)
| P18     | T0₂+6759.5 : T0₂+7200.5 | 13.7±0.5 | 0.70±0.01               | 1.19±0.01                         | 0.36±0.07 | 0.032 (52)
| P19     | T0₂+7200.5 : T0₂+7399.5 | 13.7±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)
| P20     | T0₂+7399.5 : T0₂+7530.5 | 13.6±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)
| P21     | T0₂+7530.5 : T0₂+7805.5 | 13.6±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)
| P22     | T0₂+7805.5 : T0₂+8470.5 | 13.6±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)
| P23     | T0₂+8470.5 : T0₂+9000.5 | 13.6±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)
| P24     | T0₂+9000.5 : T0₂+9500.5 | 13.6±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)
| P25     | T0₂+9500.5 : T0₂+10000.5 | 13.6±0.5 | 0.68±0.01               | 1.15±0.02                         | 0.24±0.07 | 0.032 (52)

**Notes:** All the errors shown in this table are in 68% confidence interval.

parameters of the flare FSZ is shown in Fig. 6.4 and are given in Table 6.1. The abundances, temperature, and corresponding emission measure were found to vary during the flare FSZ. The peak values of abundances were derived to be 0.72±0.15 \(Z_\odot\) which was \(\sim 4\) times more than that at the end of the flare. This value is also more than that of the other RS CVn type binaries as observed by Pandey & Singh (2012), indicating a higher amount of evaporation of the chromospheric plasma into the flaring loop.

The temperature was peaked at a value of 17.6±1.3 keV for the flare FSZ, which was \(\sim 5.3\) times more to that derived for end phase of the flare. The derived value of maximum temperature for the flare FSZ is quite high from previously observed maximum flare temperature on other RS CVn type binaries (Pandey & Singh, 2012), but this value is of the similar order to those of the superflares detected on CC Eri (Karmakar et al., 2017), EV Lac (\(\sim 150\) MK and \(\sim 142\) MK; Favata et al., 2000; Osten et al., 2010), II Peg (\(\sim 300\) MK; Osten et al., 2007), and AB Dor (\(\sim 114\) MK; Maggio et al., 2000).
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The EM followed the flare light curves and peaked at a value of $2.53 \pm 0.05 \times 10^{54}$ cm$^{-3}$ for the flare FSZ, which was $\sim$59 times more than the minimum value observed at the end of the flare. However, this value is within the range of earlier observed EM on RS CVn type stars (Pandey & Singh, 2012). The peak X-ray luminosity in 0.3–10 keV energy band during the flare was derived to be $4.79 \pm 0.05 \times 10^{33}$ erg s$^{-1}$, which was $\sim$92 times more luminous than that of the post flare phase. This value of the luminosity is larger than the earlier observed normal flares on late-type dwarfs and RS CVn binaries (Pandey & Singh, 2008, 2012). This is also one order greater than that of the observed superflares (see Favata et al., 2000; Karmakar et al., 2017; Maggio et al., 2000; Osten et al., 2007, 2010). However, the luminosity is found to be comparable with the large flares generally observed in PMS stars (Getman et al., 2008b). From Fig. 6.1, it is evident that the metal abundance and luminosity both found to vary along the flare light curves and they peak after the temperature peak, which is consistent with the idea of the hydrodynamic model (as discussed in detail in Chapter 5). This indicates the coherent plasma evolution and the heating causes the evaporation of the chromospheric gas and increase the metal abundances in the flaring loop.

6.3 Loop length of the flaring event

The loop length of the flare FSZ was determined using the hydrodynamic model as described in section 1.3.4.4, where $T_{\text{max}}$ and $F(\zeta)$ are calibrated for spectral response of Swift XRT by Osten et al. (2010) and given in equations 5.2. As mentioned earlier, currently, for the stellar flares an evolution of density along the flare is not possible as one require time resolved high resolution X-ray spectra with good signal-to-noise ratio. Therefore, $\sqrt{EM}$ was chosen as a proxy of the density. Fig. 6.5 shows the path log $\sqrt{EM}$ versus log $T$ for the flare FSZ. A linear fit to the data provided the slope $\zeta$ of 0.741 $\pm$ 0.014, indicating the presence of sustained heating during the decay phase of the flare FSZ. The maximum temperature at loop-apex was derived from the observed temperature using equation 5.1. The $T_{\text{max}}$ was derived to be 567$\pm$48 MK. The loop length of the flare FSZ was derived to be 7.3$\pm$0.3$\times$10$^{11}$ cm. The derived loop length is found to be similar to that of the other RS CVn binaries (see Pandey & Singh, 2012). Assuming a semi-circular geometry, the flaring loop height ($L/\pi$) was estimated to be 2.9 times of the stellar radius ($R_*$) of the primary component of SZ Psc. The derived parameters of the flaring loop are given in Table 6.2. The loop lengths are usually more than the loop lengths derived for other G–K dwarfs.
6.4 Properties of coronal loop

The primary component of SZ PSc is more active; therefore, can be safely assumed that the flare had happened in the primary. The peak X-ray luminosity of flare FSZ was then found to be 69\% of bolometric luminosity ($L_{\text{bol}}$) of the primary, whereas the peak luminosity was found to be 58\% of $L_{\text{bol}}$ SZ Psc system. These values are larger than that of the earlier reported flares on RS CVn binaries (Pandey & Singh, 2012), however this is similar to that of the observed superflares (Favata et al., 2000; Karmakar et al., 2017; Maggio et al., 2000; Pan et al., 1997). The derived loop length of the flare FSZ was much smaller than the pressure scale height ($\geq 3.5 \times 10^{12}$ cm for primary); therefore, we can assume that the flaring loop to be not far from a steady state condition. We have applied the RTV scaling laws (Rosner et al., 1978) to determine the maximum pressure in the loop at the flare peak and
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Table 6.2: Post loop modeling parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Flare FSZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_R$</td>
<td>(ks)</td>
<td>$12.5 \pm 0.4$</td>
</tr>
<tr>
<td>$\tau_D$</td>
<td>(ks)</td>
<td>$19.9 \pm 0.1$</td>
</tr>
<tr>
<td>$L_{X,max}$</td>
<td>($10^{33}$ erg s$^{-1}$)</td>
<td>$4.79 \pm 0.05$</td>
</tr>
<tr>
<td>$\zeta$</td>
<td></td>
<td>$0.741 \pm 0.014$</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>(10$^8$ K)</td>
<td>$5.67 \pm 0.48$</td>
</tr>
<tr>
<td>$L$</td>
<td>(10$^{11}$ cm)</td>
<td>$7.3 \pm 0.3$</td>
</tr>
<tr>
<td>Loop-Height</td>
<td>(10$^{11}$ cm)</td>
<td>$2.4 \pm 0.1$</td>
</tr>
<tr>
<td>$p$</td>
<td>(10$^4$ dyn cm$^{-2}$)</td>
<td>$9.1 \pm 2.7$</td>
</tr>
<tr>
<td>$n_e$</td>
<td>(10$^{11}$ cm$^{-3}$)</td>
<td>$5.8 \pm 2.2$</td>
</tr>
<tr>
<td>$V_F$</td>
<td>($10^{30}$ cm$^3$)</td>
<td>$\sim 7.6$</td>
</tr>
<tr>
<td>$B$</td>
<td>(kG)</td>
<td>$1.51 \pm 0.23$</td>
</tr>
<tr>
<td>$E_H$</td>
<td>(erg s$^{-1}$ cm$^{-3}$)</td>
<td>$\sim 8$</td>
</tr>
<tr>
<td>$H$</td>
<td>($10^{31}$ erg s$^{-1}$)</td>
<td>$\sim 6.10$</td>
</tr>
<tr>
<td>$E_{X,tot}$</td>
<td>($10^{36}$ erg)</td>
<td>$&gt;1.98$</td>
</tr>
<tr>
<td>$B_{tot}$</td>
<td>(kG)</td>
<td>$&gt;2.98$</td>
</tr>
</tbody>
</table>

The symbols has similar meaning as Table 5.5 of Chapter 5.

found to be $\sim 9.1 \times 10^4$ dyne cm$^{-2}$ for the flare FSZ. We have derived the plasma density, the flaring volume, and the minimum magnetic field using equation 4.1.5. We have estimated the values of $n_e$, $V$ and $B$ for the flare FSZ as $5.8 \pm 2.2 \times 10^{11}$ cm$^{-3}$, $7.6 \times 10^{30}$ cm$^3$, and $\sim 1.5$ kG, respectively. Using the scaling laws of Rosner et al. (1978), we have also estimated the heating rate per unit volume at the peak of the flare as $\sim 8$ erg cm$^{-3}$ s$^{-1}$. The total heating rate ($\frac{dH}{dt} \sim \frac{dH}{dV} \times V$) at the peak of the flare was derived to be $\sim 6.1 \times 10^{31}$ erg s$^{-1}$, which was $\sim 1.4$ times more than the flare maximum X-ray luminosity. The heating rate during the flare FSZ was also found to be only $\sim 1\%$ of the bolometric luminosity of the SZ Psc system. If the heating mechanism is responsible, the present flare are essentially due to some form of dissipation of magnetic energy. Assuming the constant heating rate throughout the decay phase of the flare, the total energy radiated during the flare was derived to be $\sim 29$ s of bolometric energy output of the primary component of SZ Psc. This value is ten times larger than the normal flare on 47 Cas as discussed in Chapter 4, but less than both the superflares on CC Eri as discussed in Chapter 5. The magnetic field strength that would be required to accumulate the emitted energy and to keep the plasma confined in a stable magnetic loop configuration can be estimated under the assumptions that the energy release is indeed of magnetic origin. The total non-potential magnetic field $B_0$ involved in a flare energy release
within an active region of the star can be estimated using the equation 4.5. The value of $B_0$ was estimated to be $>2.98$ kG for flare FSZ assuming the loop geometry does not change during the flare. This value is less than or comparable to that of the superflares observed on CC Eri as discussed in Chapter 5, but much greater than that of the normal flare as discussed in Chapter 4. However, this values are much larger than the derived magnetic fields on other RS CVn stars (Pandey & Singh, 2012).

6.5 Conclusions

In the present multi-band study of RS CVn type eclipsing binary, we have found that the flaring event is out of the eclipse. However, most of the flare parameters derived in this work are found to be at or beyond the extremum values, which makes this event very interesting. The peak X-ray luminosity was derived to be $\sim 10^{33.6}$ erg s$^{-1}$ in 0.3–50 keV energy band, which are larger than any other flares previously observed on SZ Psc, and other RS CVn flares, thus far (to the best of our knowledge). The time-resolved spectral analysis during the flare shows the variation in the coronal temperature, EM, and abundances. Temperature shows earlier peak than EM and abundance. The peak elemental abundances are found to be $\sim 0.72 Z_\odot$, which is $\sim 4$ times than that of the minimum observed values at the end of the flare. The peak observed flare temperature was derived to be $\sim 204$ MK. Using the hydrodynamic loop modeling, we derive flaring loop lengths of $7.3 \pm 0.3 \times 10^{11}$ cm. The heating rate during the flare is found to be 1% of the bolometric luminosity of the SZ Psc system. The evolved RS CVn binary SZ Psc shows more magnetically active than the MS stars, discussed in earlier chapters, possibly due to their tidally locked binary nature and extended corona.