AstroSat observations of long-duration X-ray superflares on active M-dwarf binary EQ Peg

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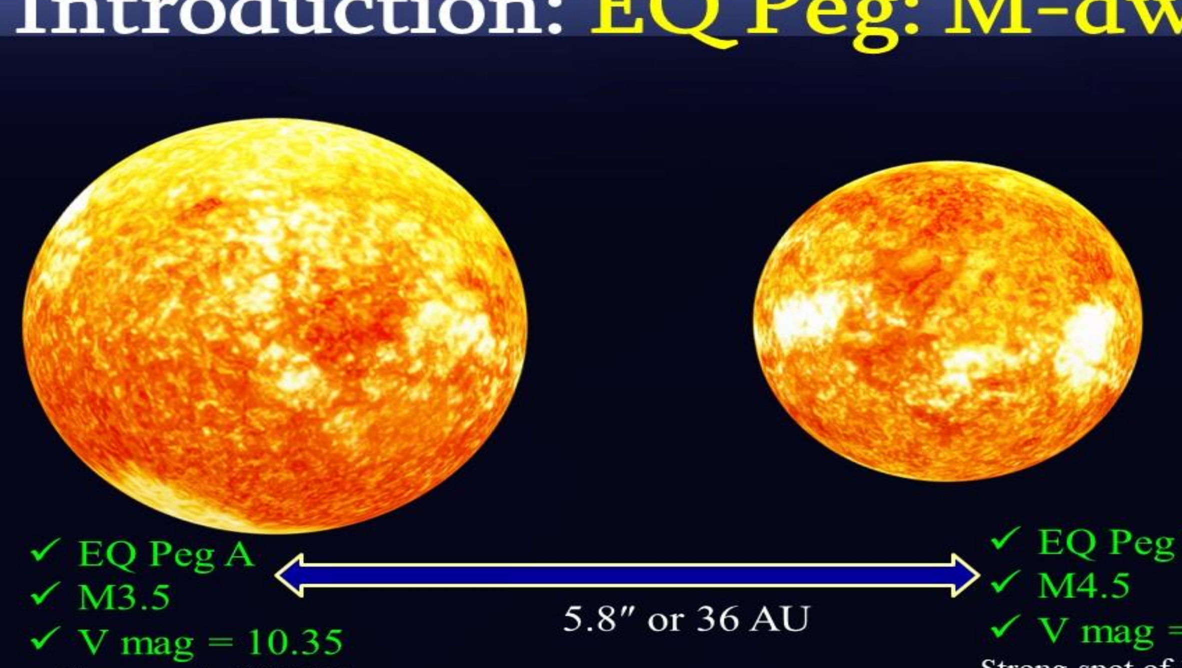
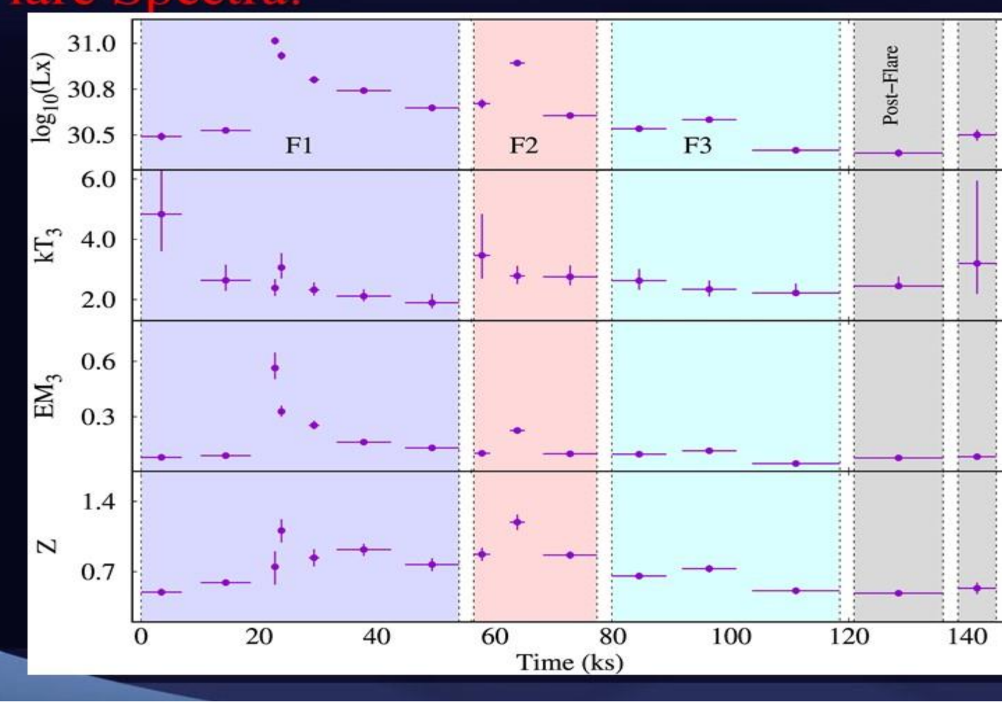
We present a comprehensive study of three large long-duration flares detected on an active M-dwarf binary EQ Peg using Soft X-Ray Telescope of the AstroSat observatory. The peak X-ray luminosities of the flares in the 0.3 -- 7 keV band are found to be within ~4-10 × 10^{30} erg s^{-1}. Spectral analysis indicates the presence of three temperature corona with the first two plasma temperatures remain constant during all the flares and the post-flare. The flare-temperature peaked at 56, 40, and 31 MK, which are 2.5, 1.8, and 1.4 times more than the minimum value, respectively. The peak emission measures are found to be 1.16 -- 5.64 × 10^{53} cm^{-3}, whereas the abundances peaked at 0.7 -- 1.2 times the solar abundances. Using quasi-static loop modeling, we derive loop-lengths for all the flares as 2.7 ± 1.4 × 10^{11}, 3.9 ± 1.5 × 10^{11}, and 6.4 ± 2.4 × 10^{11} cm, respectively. The estimated energies of all three flares are >10^{33-35} erg, putting them in a category of Superflare. All three superflares are also found to be the longest duration flares ever observed on EQ Peg.

Introduction: EQ Peg: M-dwarf binary

- ✓ Distance = 6.26 pc (Bailer-Jones et al. 2018).
- ✓ Age = 950 Myr (Parsamyan 1995).
- ✓ Period = 1.066 day (Norton et al. 2007).
- ✓ EQ Peg has a record of frequent and large flaring activities across the electromagnetic spectrum



Best-fit Spectral Parameters



Best-fitted with APEC 3-T model

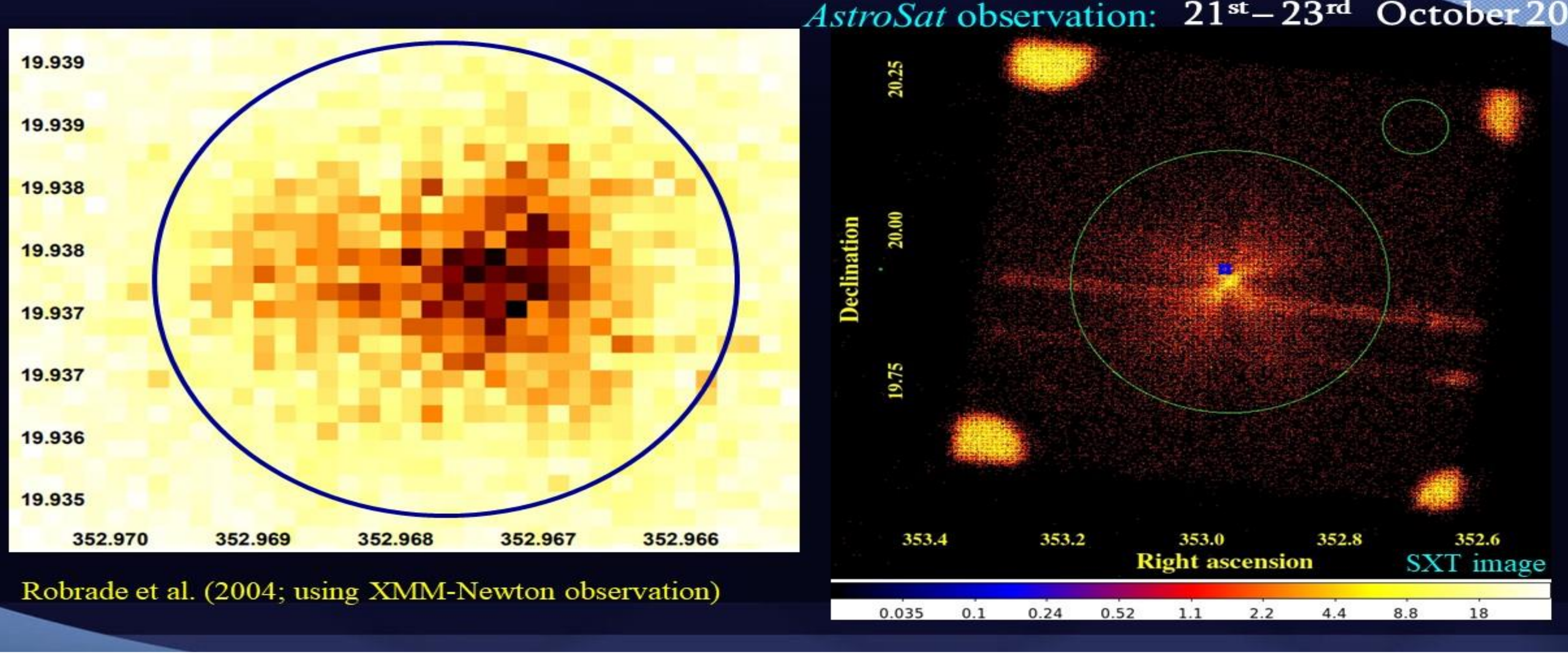
First two temperature components are fixed in the *Post-Flare* values.

- Flare F1:
  - Flare peak-temperature = 56 MK.
  - Peak Luminosity = 1.0 × 10^{31} erg s^{-1}
  - Peak Abundance = 1.1 * solar unit
  - Peak Emission Measure = 5.6 x 10^{53} cm^{-3}
- Flare F2:
  - Flare peak-temperature = 40 MK.
  - Peak Luminosity = 7.8 × 10^{30} erg s^{-1}
  - Peak Abundance = 1.2 * solar unit
  - Peak Emission Measure = 2.3 x 10^{53} cm^{-3}
- Flare F3:
  - Flare peak-temperature = 31 MK.
  - Peak Luminosity = 3.8 × 10^{30} erg s^{-1}
  - Peak Abundance = 0.7 * solar unit
  - Peak Emission Measure = 1.2 x 10^{53} cm^{-3}

All peak flare temperatures are ≥ 20 MK

EQ Peg: Two Components in X-ray

AstroSat observation: 21st – 23rd October 2019



Robrade et al. (2004; using XMM-Newton observation)

Quasi-static Loop Modeling

Flare Spectra:

Assuming the semi-circular loop with constant cross section;

$$L\ (cm) = R_\odot \left(\frac{\tau_{qs}}{10\ ks}\right)\left(\frac{kT(t_0)}{keV}\right)^{7/8}$$

$$n_e\ (cm^{-3}) = 4.4 \times 10^{10} \left(\frac{\tau_{qs}}{10\ ks}\right)^{-1}\left(\frac{kT(t_0)}{keV}\right)^{4/3}$$

$$a = 1.38 \left(\frac{\tau_{qs}}{10\ ks}\right)^{-1/2}\left(\frac{kT(t_0)}{keV}\right)^{-33/16}\left(\frac{EM(t_0)}{10^{54} cm^{-2}}\right)^{1/2}$$

- ✓ van den Oord & Mewe (1989)
- ✓ Tsuboi (2000)

Applicable only if Flare peak-temperature is ≥ 20 MK

$$T(t) = T(t_0)\left(1 + \frac{t - t_0}{3\tau_{qs,T}}\right)^{-8/7}$$

=> Quasi-static decay time $\tau_{qs,T}$

$$EM(t) = EM(t_0)\left(1 + \frac{t - t_0}{3\tau_{qs,EM}}\right)^{-26/7}$$

=> Quasi-static decay time $\tau_{qs,EM}$

$\tau_{qs,T} \approx \tau_{qs,EM} \approx \tau_{qs}$

Flare F1 => 9.1 ± 0.7 ks
Flare F2 => 21.7 ± 5.4 ks
Flare F3 => 47.1 ± 12.1 ks

The derived loop length for Flare F1, F2, and F3 are 2.7±1.4 × 10^{11}, 3.9±1.5 × 10^{11}, 6.4±2.4 × 10^{11} cm, respectively

Objective of this study

- **1. Using temporal and spectral analysis, understand the stellar atmosphere of EQ Peg.**
- **2. Estimate the coronal loop properties.**
- **3. Estimate the mass loss and velocity of the material during associated Coronal Mass Ejections.**

Coronal Mass Ejection associated to flare

- Drake et al. (2013) have estimated empirical relationship between solar flare X-ray energy and it's associated CME mass

$$M_{CME}\ (g) = \mu\ E_G^{\gamma}$$

where M_{CME} is the CME mass, μ is a constant of proportionality, and γ is the power law index, and E_G is the X-ray energy in GOES 1–8 Å band.

For magnetically active stars , Drake et al. (2013) estimated $\mu = 10^{-1.5 \mp 0.5}$ in cgs units and $\gamma = 0.59 \pm 0.02$.

- The kinetic energy ($E_{KE,CME}$) of the CME is given by following relation.

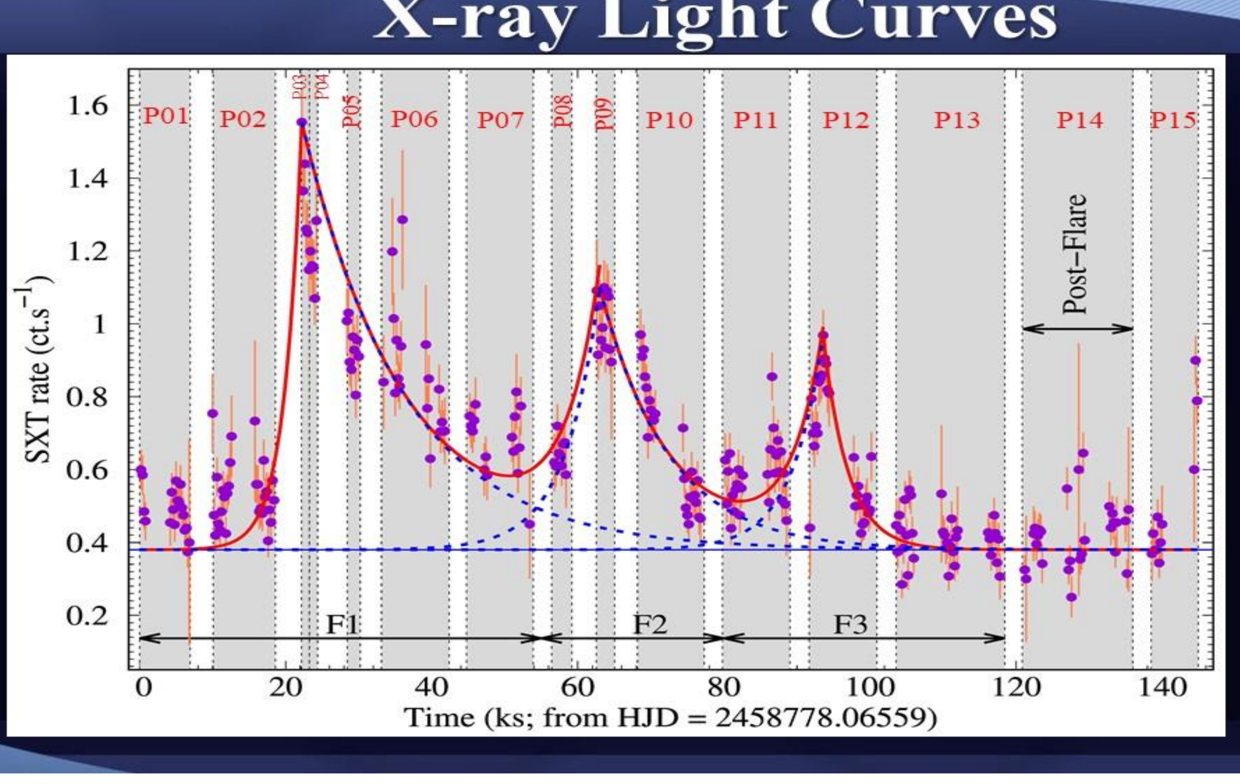
$$E_{KE,CME}\ (erg) = \frac{1}{2} M_{CME}\ v_{esc}^{2} = \frac{E_X}{\epsilon f_X}$$

where v_{esc} is the outward velocity of the CME, f_X is the fraction of the bolometric radiated flare energy appropriate for the waveband in which the flare energy E_X is being measured. The factor ϵ is a constant of proportionality.

Adopting values of f_X and ϵ from Osten & Wolk (2015) and Emslie et al. (2012) for late-type Main-sequence stars, For EQ Peg, We have estimated –

M_{CME} (10^{19} g)	$1.5^{+9.4}_{-1.3}$	$1.0^{+6.3}_{-0.9}$	$1.1^{+6.8}_{-0.9}$
v_{esc} (km s^{-1})	6486^{+10990}_{-4079}	5668^{+9523}_{-3553}	5818^{+9791}_{-3649}
$E_{KE,CME}$ (10^{36} erg)	3.16±0.02	1.64±0.01	1.86±0.01

X-ray Light Curves



21st – 23rd October 2019

3 X-ray Flares detected

Durations =>
Flare F1 = 14.4 hr,
Flare F2 = 5.6 hr,
Flare F3 = 11.1 hr

The e-folding rise-time = 0.7 – 1.3 hr

The e-folding decay-time = 0.9 – 3.8 hr

The derived Loop Parameters

Table Loop Parameters derived for flares F1, F2, and F3 of EQ Peg — Karmakar et al. (MNRAS, under review)

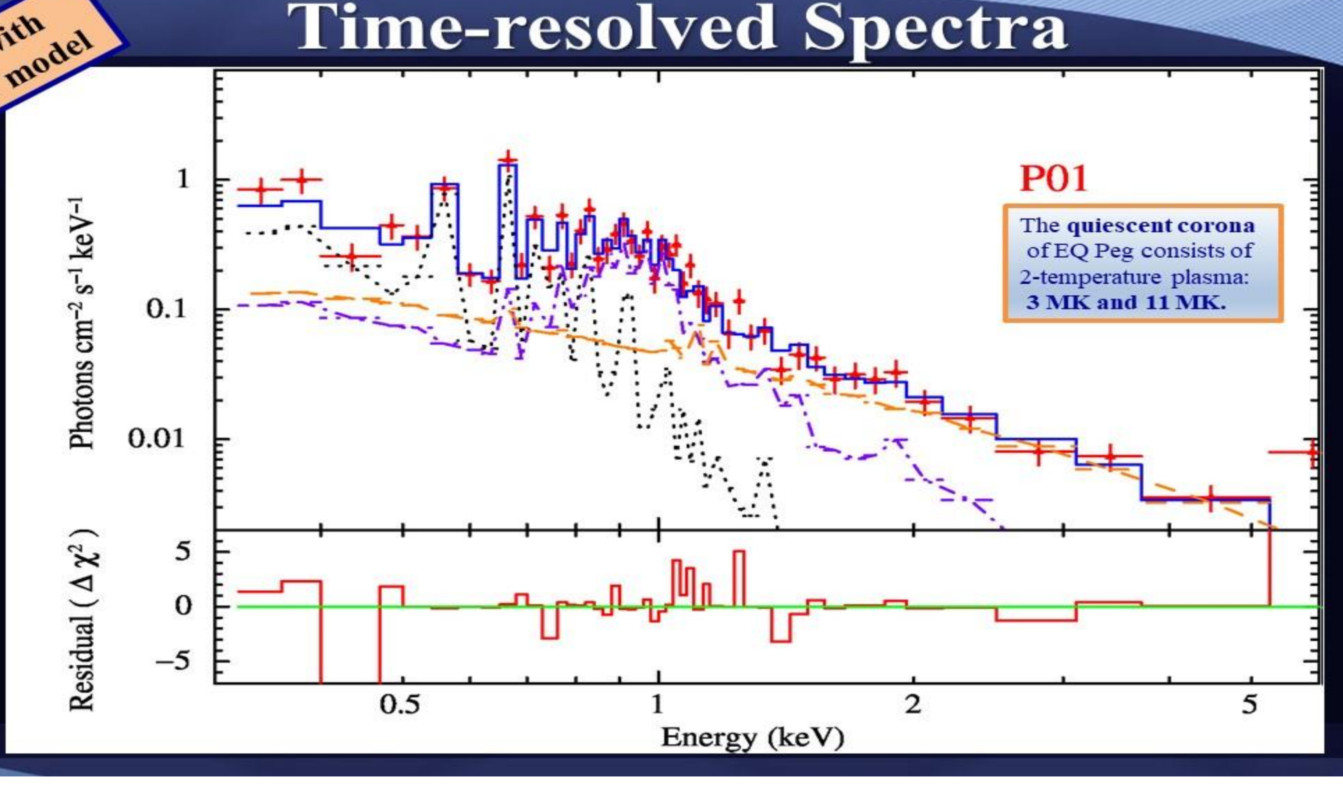
Sl.	Parameters	Flare F1	Flare F2	Flare F3
1	τ_r (ks)	2.358 ± 0.243	4.731 ± 0.776	4.332 ± 0.602
2	τ_d (ks)	13.832 ± 0.904	9.289 ± 0.734	3.422 ± 0.384
3	τ_{qs} (ks)	9.1 ± 0.7	21.7 ±5.4	47.1 ± 12.1
4	$L_{X,max}$ (10^{30} erg s^{-1})	10.318 ± 0.491	7.807 ± 0.324	3.832 ± 0.265
5	L (10^{11} cm)	2.7 ± 1.4	3.9 ± 1.5	6.4 ± 2.4
6	a	0.04±0.03	0.04±0.03	0.03±0.01
7	n_e (10^{11} cm^{-3})	3.6 ± 2.8	1.2 ± 0.7	0.41 ± 0.16
8	p (10^3 dyn cm^{-2})	~6	~1.4	~0.34
9	V (10^{30} cm^3)	~4	~15	~70
10	B (G)	130 – 630	100 – 180	70 – 116
11	HR_V (erg s^{-1} cm^{-3})	~0.7	~0.10	~0.013
12	HR (10^{30} erg s^{-1})	~3.0	~1.5	~0.93
13	E_X (10^{35} erg)	2.8 ± 0.2	1.5 ± 0.1	1.7 ± 0.1
14	E_H (10^{34} erg)	3.0 ± 1.2	2.1 ± 0.6	0.7 ± 0.1
15	M_{CME} (10^{19} g)	$1.5^{+9.4}_{-1.3}$	$1.0^{+6.3}_{-0.9}$	$1.1^{+6.8}_{-0.9}$
16	v_{esc} (km s^{-1})	6486^{+10990}_{-4079}	5668^{+9523}_{-3553}	5818^{+9791}_{-3649}
17	$E_{KE,CME}$ (10^{36} erg)	3.16±0.02	1.64±0.01	1.86±0.01
18	B_{tot} (G)	300 – 1100	140 – 380	77 – 135

Superflare

Note. 1, 2 – e-folding rise- and decay-time as derived from the light curve; **3** – quasi-static decay time as derived by fitting Equations 2 (see Section 4.1); **4** – X-ray Luminosity at the flare peak, estimated in 0.3 – 7 keV energy band; **5** – length of the flaring loops; **6** – loop aspect ratio i.e. diameter to length ratio of the loop; **7, 8** – Estimated maximum electron density and loop pressure at flare peak; **9** – loop volume of the flaring region. **10**– Minimum magnetic field. **11** – Heating rate per unit volume; **12** – Total Heating rate; **13** – X-ray energy estimated using trapezoidal integration of the derived X-ray luminosity. **14** – Estimated energy during flare due to heating of the stellar corona. **15** – Ejected coronal mass during the flaring events. **16** – Outward escape velocity of ejected coronal mass. **17** – Kinetic energy of the ejected coronal mass. **18** – Total magnetic field required to produce the flare.

Time-resolved Spectra

Best-fitted with APEC 3-T model



Take away

- Using Quasi-static loop modeling, the loop-length, peak density, peak pressure, and magnetic field of the three flares on EQ Peg are estimated within the range of 2.7–6.4 × 10^{11} cm, 0.4–3.6 × 10^{11} cm^{-3}, 0.3–6 × 10^{3} dyne cm^{-2}, and 77–1100 G, respectively.
- The total energy during the all three flares of EQ Peg are >$10^{33–35}$ erg, puts the flare in the category of Superflare.
- Our study indicates that all three flares are associated with the coronal mass ejections (CMEs), where ~1.0–1.5 × 10^{19} g of CME mass are found to be ejected upward with the CME velocity of ~5818–6486 km s^{-1}.

Thank You

CoolStars-20.5 -- virtually cool -- 2-4 March 2021

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