An Optical Megaflare on EV Lac

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Abstract

We present a U-filter light curve of a very intensive flare on EV Lac, observed at 1 s time resolution with a 2 m telescope at BNAO. The monitoring lasted for 7.4 hours (UT 16:40-UT 24:04) on 01 November 1991, and EV Lac was affected by flaring throughout this time. The data have been corrected for atmospheric extinction and the presence of an optical companion in the photometer diaphragm.

A ΔU=7.2 magnitude flare maximum ($L_{f,U} = 4.6 \cdot 10^{31}$ ergs s^{-1}) represents an increase of 735 times the flux of the quiescent star. This is twice as large as a flare reported by Roizman and Shevchenko (1982, Sov. Astron. Lett. **8,** 85-86) and is 88% of the bolometric luminosity of EV Lac. The eruptive phase of the rise took 72 seconds, and the flare returned to half its maximum value in $t_{0.5}$ = 39 seconds. The classically peak-shaped flare went into a slow decay phase after about 20 minutes. Several secondary flares were superposed on the > 5 hours decay. The U-filter flare energy released during the major peak was $7.23 \cdot 10^{33}$ ergs. It accounts for 93% of the energy released during the entire flare event ($E_U = 7.8 \cdot 10^{33}$ ergs).

The flare occurred close to maximum brightness of the 4.4 days rotational modulation of EV Lac, which had a V-amplitude 0.06 mag in 1991.

Introduction

The frequency distributions of stellar flares make giant eruptions on dMe stars into rarely observed events. They have been detected in dedicated, time consuming photometric programs (e.g. Roizman and Shevchenko 1982), and a few have occasionally occurred during multi-instrument campaigns to study several spectral regions of flare radiation (Hawley and Pettersen 1991, Kowalski et al. 2010). Most efforts of this kind have produced data on medium and small flares. The question “How large can a flare be on a given star?” is still open to guesswork. We present the light curve of a serendipitous megaflare on EV Lac.

Observations

An unsophisticated one-channel photoelectric photometer with an uncooled, blue sensitive photomultiplier and a laptop recording system was mounted on the 2 m reflector at BNAO during a four-night run in November 1991. The observations presented here were obtained with a time resolution of 1 s through a U-filter. Differential photometry of variable and comparison stars was obtained in UBV by manually rotating a filter wheel. We used a 1 mm diaphragm during such observations. During U-filter monitoring of EV Lac a larger diaphragm of 4 mm was used to obtain uninterrupted time series of reasonable length before re-centering of the star was required. The brightness thus recorded was the sum of EV Lac and its nearby companion star (separation 5”). Differential photometry on two separate nights showed that EV Lac and the companion star were equally bright in the U-filter outside of flares, which allows a simple correction for the presence of the companion star in the data discussed later. We used observations of the companion and two comparison stars to determine atmospheric extinction as a function of air mass, and corrected the monitoring data of EV Lac for that effect.

The U-filter monitoring of EV Lac on 1 November 1991 began at UT 16:39:37 and lasted for 7.2 hours. The time series is shown in Fig. 1, with the brightness shown on logarithmic (upper panel) and linear (lower panel) scales. In the latter, we have truncated the bright phase of the megaflare. The intensity scale is in counts per second after correcting for sky background, atmospheric extinction, and the presence of the companion star. Minimum intensity occurs about 5000 seconds after start, at a count rate of 2150 $\pm$ 112 cps. Within the observational scatter of $\sigma_U = \pm 0.05$ this compares well with the quiescent level of EV Lac two nights later. For reference, we consider this the quiescent brightness level of EV Lac, although we cannot exclude that it could be set lower.

The time series in Fig. 1 begins with the slow decay of a previous flare for 5000 seconds. The brightness then increases linearly from the quiescent level to 2350 cps during $\sim$ 27 minutes, when the initial flare rise is noted (3σ rise at 6650 s after start), Fig. 2. Two small preflares superposed on a steady brightness increase takes place during the next 4.5 minutes (to reach 5000 cps), after which several acceleration phases brings the flare light to maximum 7002 seconds after start. The total rise phase thus lasts 352 s = 5.87 min, but the eruptive rise is done in 72 seconds.

30 minutes after the megaflare maximum, the count rate has again fallen to <10000 cps. During the flare decay there are several secondary flares. Those occurring during the late decay are seen in Fig. 1, which also shows that EV Lac never returned to quiescence during the 5.5 hours after flare maximum.

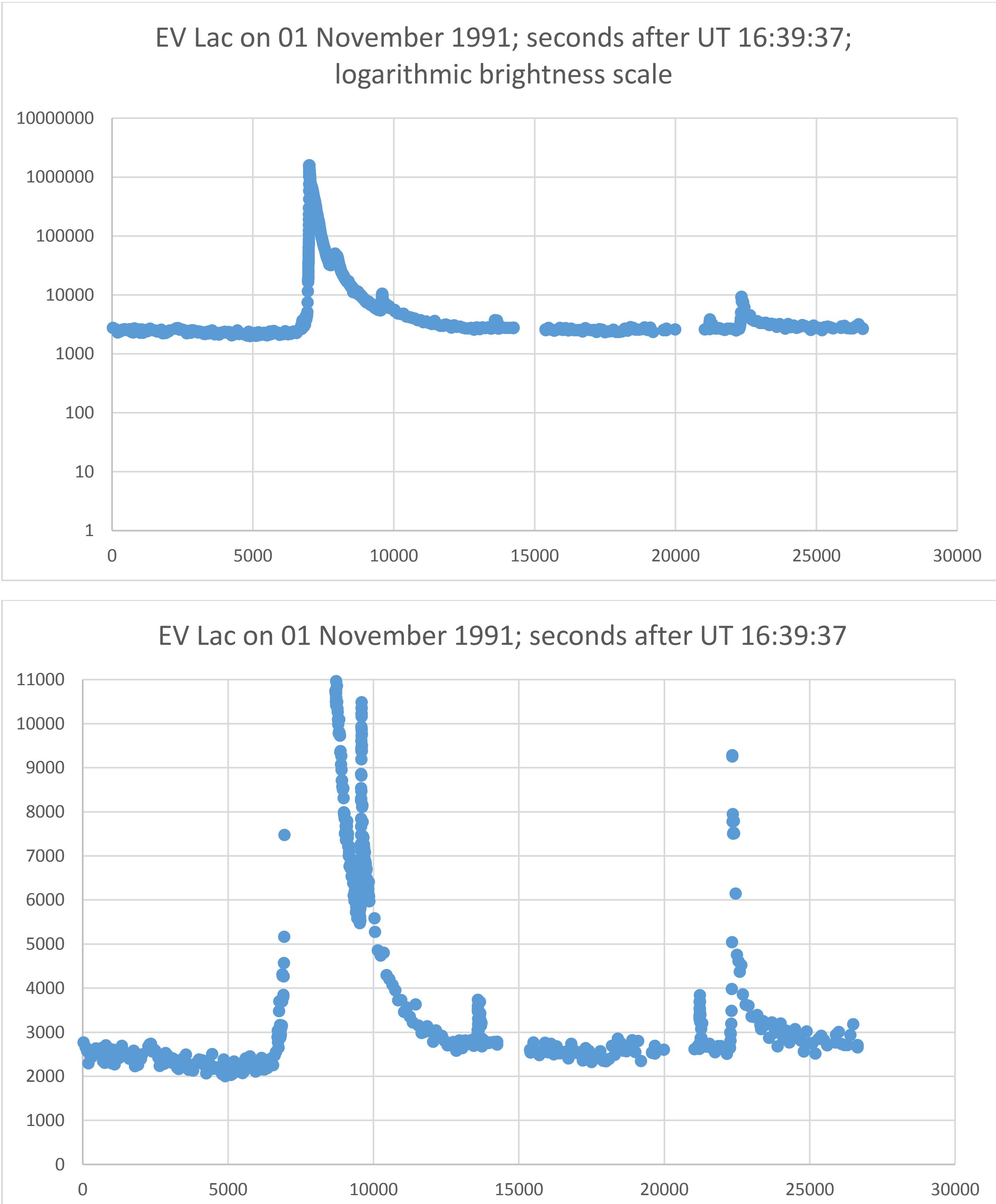


Figure 1. The U-filter time series of EV Lac for 7.2 hours on 01 November 1991. The upper panel has a logarithmic brightness scale. The lower panel has a linear brightness scale which truncates the megaflare.

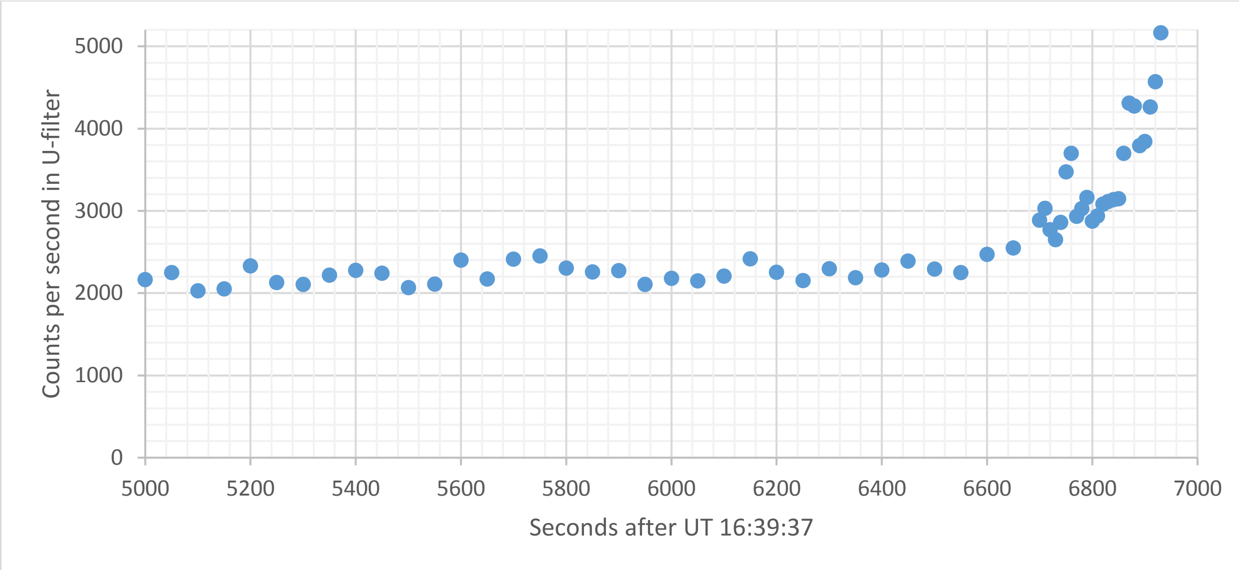


Figure 2. Slow brightness increase for 27 minutes until flare rise is evident (>3σ) at 6650 seconds after start.

The megaflare

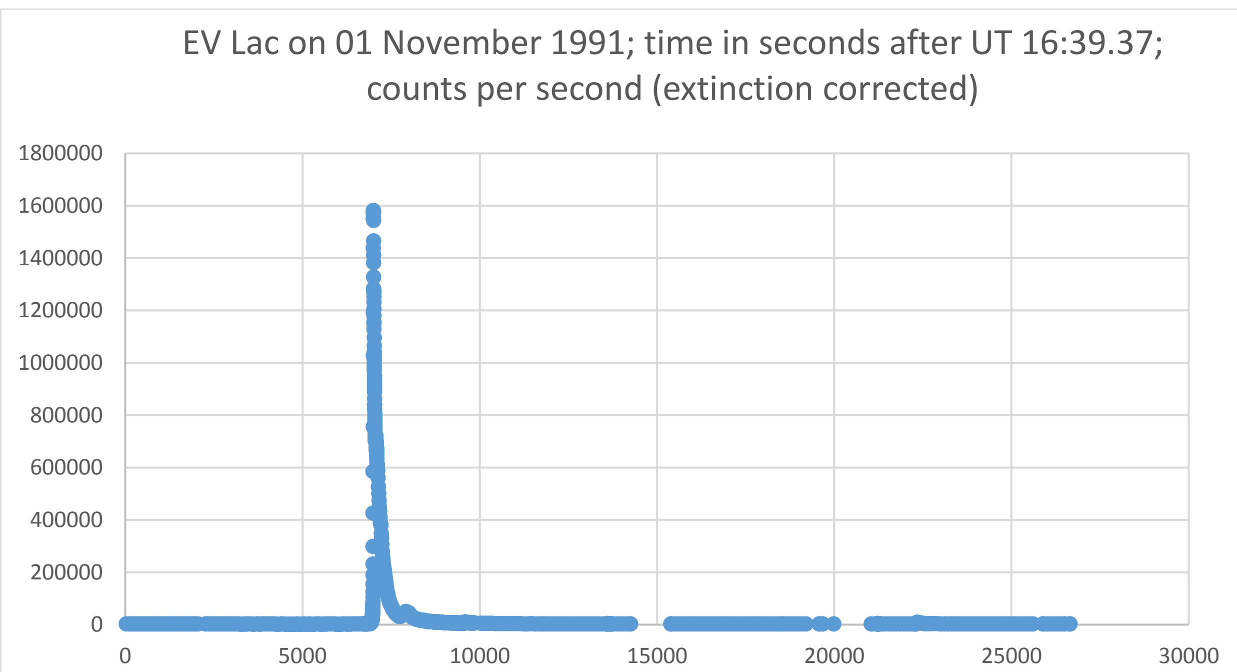


Figure 3. The U-filter time series, including the megaflare.

The first 3σ detection of flare rise at 6650 seconds after start is followed by a steady increase for 4.5 minutes, to 5000 cps. The brightness increase then accelerates by increasing the count rate by almost 5% every second for about 50 seconds. The count rate has then reached 51449 cps at 6980 seconds after start. During the next 5 seconds the acceleration increases to 11%, and then to 21% for 5 seconds. At 6990 seconds after start the count rate is 231369 cps. The final rise phase of the flare is 7 seconds at an acceleration of 30% to count rate 1435051 cps at 6997 seconds after start. The acceleration then flattens out, a double peak is produced, and the maximum occurs at 7002 seconds with a count rate of 1581577 cps (Fig. 4). The flare then radiates at 735 times the level of the quiescent star. The quiescent U-filter luminosity of EV Lac is $L_U = 6.25 \cdot 10^{28}$ ergs s^{-1}, so at flare maximum $L_U^{max} = 4.6 \cdot 10^{31}$ ergs s^{-1}. This is 88% of the bolometric luminosity of the quiescent star. During the eruptive rise phase the brightness increase per second repeatedly exceeded the output of the quiescent star by a factor of 100.

Figure 4 shows that a rapid decay follows; $t_{0.5} = 38.5$ s. This implies that the flare luminosity is reduced by $2.3 \cdot 10^{31}$ ergs s^{-1} in 38.5 seconds, i.e. $-dL_U/dt = 5.96 \cdot 10^{29}$ ergs s^{-2}. The flare decay enters a pause for 4 seconds at 7010 s due to a secondary flare and then continues with a different slope. The initial decay after maximum (7003-7009) produces a loss rate of $–dL_U/dt = 1.43 \cdot 10^{30}$ ergs s^{-2}. During the second decay (7013-7041) the loss rate is $–dL_U/dt = 5.05 \cdot 10^{29}$ ergs s^{-2}.

In addition to the double peaked maximum there are several small secondary peaks throughout the flare decay. Medium sized flares occured during the late decay phases.

The major part of the megaflare lasts about 44 minutes (Fig. 5). The numerical integral under this part of the light curve was estimated to 115643 seconds, i.e. $E_U = 7.23 \cdot 10^{33}$ erg. The remaining part of the entire time series, including all other flares and the continued slow decay of the megaflare, adds up to $0.56 \cdot 10^{33}$ ergs s^{-2}. The $\Delta U = 7.2$ magnitude flare thus accounts for > 93% of flare light recorded that night.

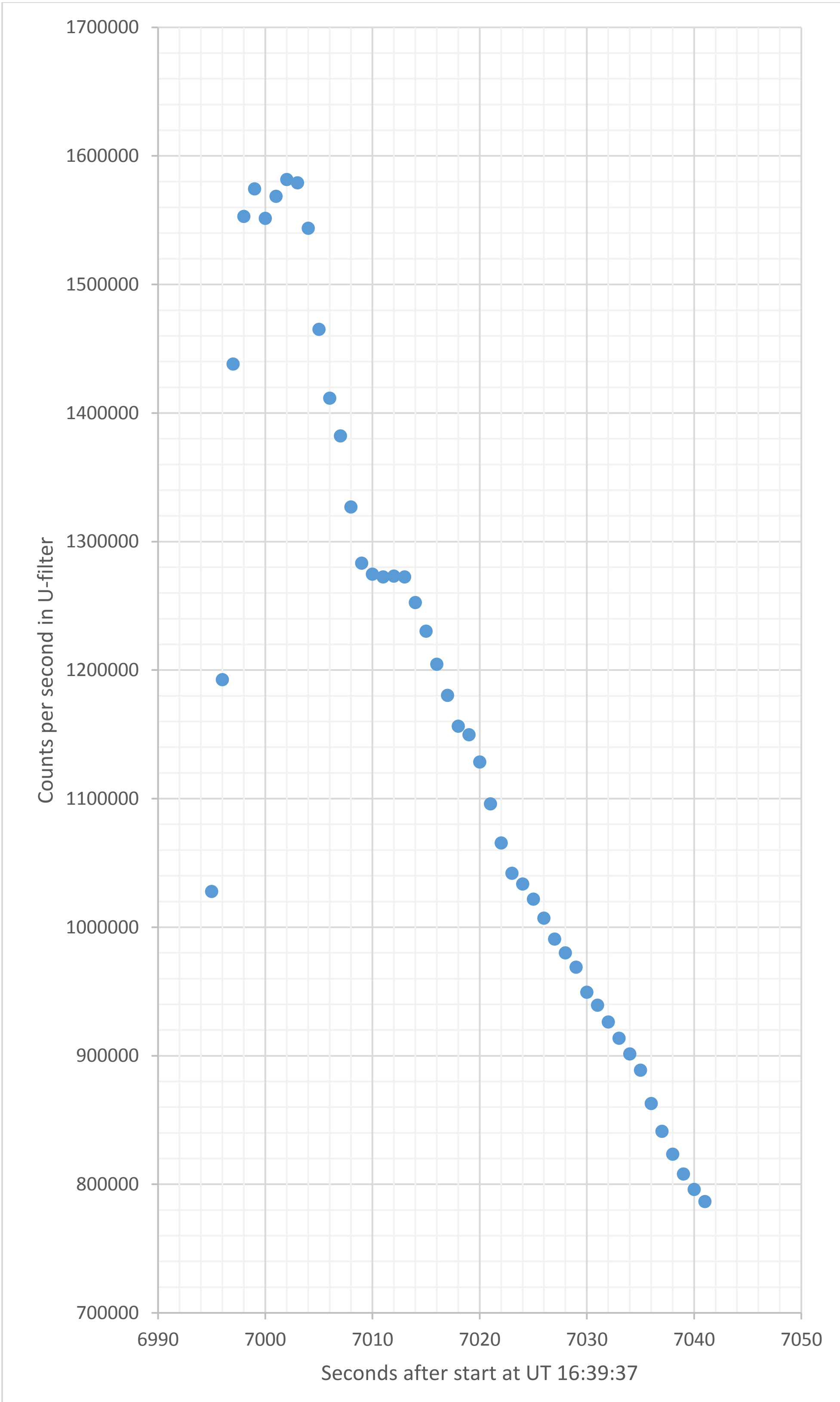
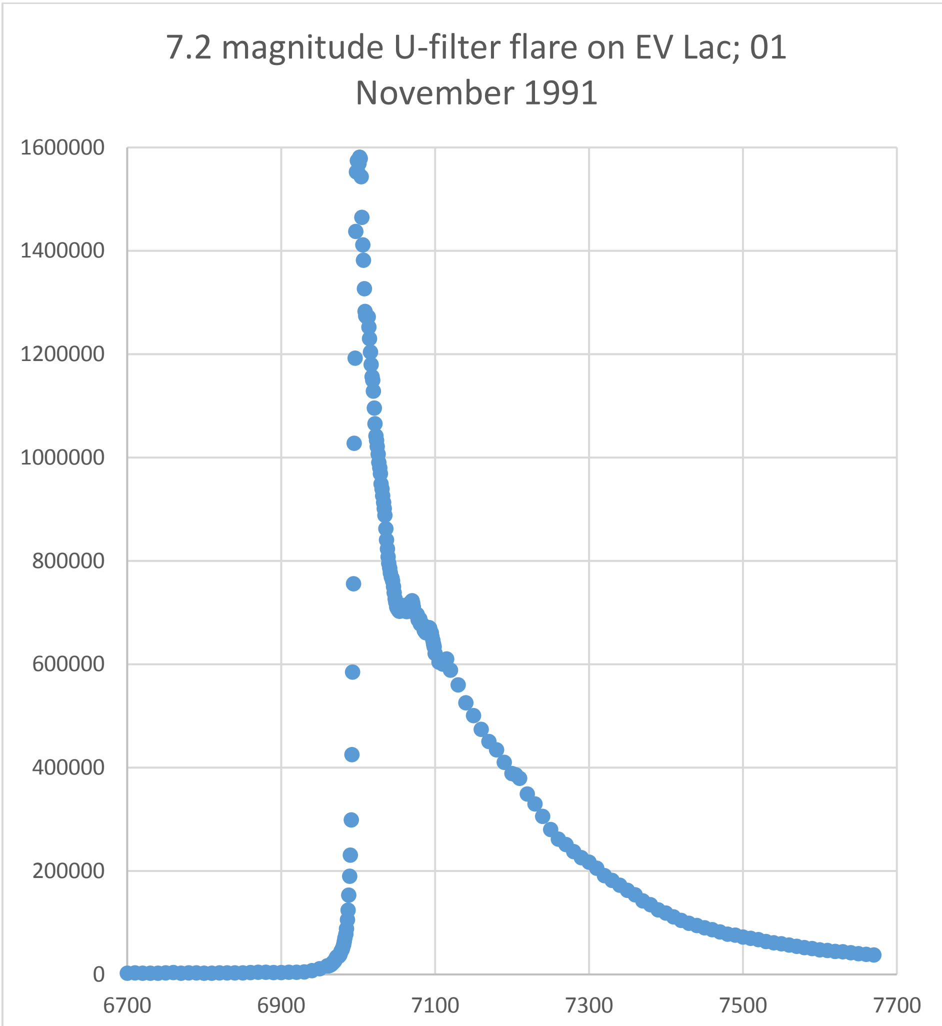


Figure 4. Flare maximum and the upper half of the light curve.



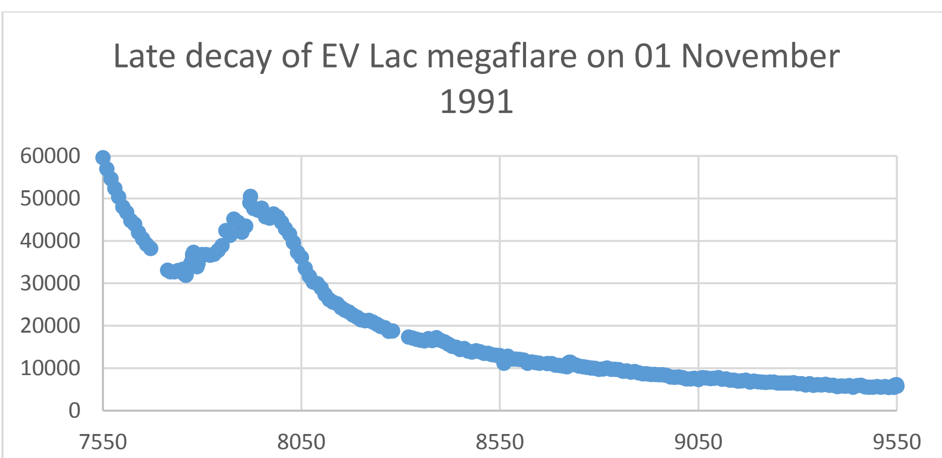


Figure 5. The major part of the megaflare. Upper panel: The first 12 minutes. Lower panel: The next 32 minutes.

Discussion

Gershberg and Shakhovskaya (1973) demonstrated a relationship between the flare luminosity at maximum (L_U^{max} in ergs s^{-1}) and the decay rate immediately after maximum ($-dL_U/dt$ in ergs s^{-2}) for a number of flare stars. A revised version for U-filter data by Shakhovskaya (1989) is reproduced in Figure 6.

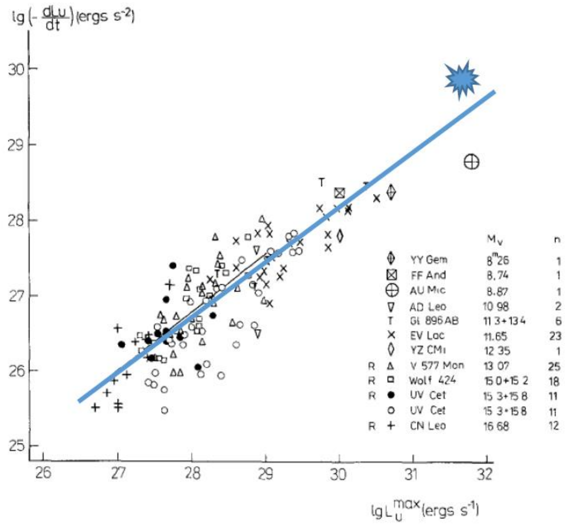


Figure 6. The empirical relationship between flare luminosity at maximum and the initial decay rate after maximum, from Shakhovskaya (1989). The blue marker is the EV Lac megaflare. The blue line is the relationship expected for black body radiation near flare maximum.

The initial decay rate for the EV Lac megaflare (see above) is log ($-dL_U/dt$) = 30.16 ergs s^{-2}. At log $L_U^{max} \geqq$ 31.66 ergs s^{-1} this extends the relationship to higher energies.

Also inserted into Fig. 6 is a line with slope 0.75, to be expected if flare light at maximum is dominated by black body radiation. Several investigators have noted that the color indices of the flare light itself around maximum suggest black body temperatures of $\sim 10^4$ K (Kowalski et al. 2013 and references therein). If that holds, then $L \propto T^4$. By differentiation $dL/dt \propto 4\ T^3 \cdot dT/dt = 4\ dT/dt \cdot L^{3/4}$. So for none (or moderate) temperature changes near maximum, Shakovskaya's relationship should hold a slope of 0.75.

Conclusions

The U-filter light curve of a very large flare on EV Lac is presented. The classical shape and rapid decay phase limits the emitted flare energy to $E_U = 7.8 \cdot 10^{33}$ ergs. At maximum this 7.2 magnitude flare emits a record U-filter flux of $L_U^{max} = 4.6 \cdot 10^{31}$ ergs s^{-1}. At these extreme values the flare extends and supports the empirical relationship of Gershberg and Shakhovskaya (1973), which holds for flare light being dominated by black body radiation near flare maximum.

References

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