Revista Mexicana de Astronomía y Astrofísica, **33**, 107–115 (1997)

SOME STATISTICAL PROPERTIES OF SHORT FLARES OF FLARE STARS

H. M. Tovmassian, E. Recillas, and O. Cardona

Instituto Nacional de Astrofísica, Optica y Electrónica
Tonantzintla, Pue., México

and

V. P. Zalinian

Byurakan Astrophysical Observatory
National Academy of Sciences, Armenia

Received 1997 February 18; accepted 1997 June 9

RESUMEN

Se han detectado algunas ráfagas de las estrellas EV Lac y V 577 Mon con observaciones de muy alta resolución temporal, llevadas al cabo con el telescopio de 40-cm de Byurakan, el telescopio 1-m del Observatorio Astronómico Nacional ubicado en Tonantzintla y el telescopio de 2.1-m del INAOE en Cananea, Sonora. Alrededor de la mitad de las ráfagas detectadas son del tipo de punta afilada con una duración menor que 1 seg. Se muestra que las ráfagas afiladas ocurren preferentemente después de una ráfaga normal de larga duración y sus colores son sistemáticamente más azules que las ráfagas principales precedentes.

ABSTRACT

Several flares were detected in the flare stars EV Lac and V 577 Mon in high time resolution observations carried out with the 40-cm telescope at Byurakan, the 1-m telescope of the OAN in Tonantzintla, and the 2.1-m telescope of the INAOE in Cananea. About half of the detected flares are of the spiky type with a total duration less than 1 sec. It is shown that the spiky flares which occur mostly after normal, longer lasting flares are systematically bluer than the preceding main flares.

Key words: **STARS – FLARE**

1. INTRODUCTION

Flare stars are intriguing objects. It was shown by Ambartsumian (1969) that almost all faint stars in the young stellar cluster Pleiades are flare stars. Hence, he concluded that the phenomenon of flare activity is inevitable in the early phases of the evolution of stars. Therefore, the detailed study of the flare event is very important for the understanding of the processes of stellar formation and evolution.

In recent years much attention has been payed to the similarities between solar and stellar flares (Haisch 1989; Haisch, Strong, & Rodono 1991). However, the energies released during solar flares reach at most $10^{31} - 10^{32}$ erg, while stellar flares can have enormous energies of up to 3×10^{36} erg (Gershberg 1989). Such huge energies sometimes are released during very short time intervals, less than a few tenths of a second. These short, spiky type flares were discovered by observations of flare stars with the *UB* two-channel fast photometer at Byurakan Astrophysical Observatory (Zalinian & Tovmassian 1987, 1988). In this paper, we present the results of recent observations made with the same two-channel fast photometer, and discuss some statistical properties of the short flares.

2. OBSERVATIONS AND RESULTS

The observations were made with the 40-cm telescope at Byurakan Astrophysical Observatory during 1994–1996, with the 1-m telescope of the Observatorio Astronómico Nacional (OAN) in Tonantzintla in November and December 1996, and with the 2.1-telescope of the INAOE in Cananea in December 1996 and January 1997. The two-channel (U and B) fast photometer of the Byurakan Observatory (Zalinian & Tovmassian 1989) was used in all observations, but the mode of the observations was different. The first observations were made using a 0.1 s integration time (Zalinian & Tovmassian 1987; Tovmassian & Zalinian 1988). The output signal was recorded only when the value of the current count in U exceeded the mean value of the preceding hundred counts by 5 σ. The latter value was continuously counted during the observation. Hence, only very sharply rising, short flares were recorded. Normal, slowly rising flares were not detected.

In the present observations, made at Byurakan Observatory, the monitoring was also made with an integration time of 0.1 s, but in this case the counts integrated during 10 s were recorded, until the count in U, integrated in 0.1 s, exceeded the mean value of the preceding hundred counts by 5σ. The signal in both channels (U and B) was then recorded with an integration time of 0.1 s. One hundred counts before and after a short flare were also recorded with 0.1 s integration. The mode of recording was adopted because of the limited memory of the computer. Hence, the normal flares with relatively slow increase in brightness were recorded in this mode with 10 s integration, while the sharply rising spiky flares were recorded with 0.1 integration.

Twelve flares in EV Lac were detected during 25 hours of monitoring. In México the flare stars EV Lac, V 577 Mon and YZ CMi were observed. EV Lac (only the flaring component of the double star) was observed 12.43 hours with the OAN-Tonantzintla 1-m telescope, and 3.2 hours with the INAOE 2.1-m telescope. V 577 Mon was observed 3.25 hours with the 1-m telescope, and 3 hours 15 min with the 2.1-m telescope. YZ CMi was observed 0.75 hours with the 2.1-m telescope. The observations were made with integration times of 0.5 s, 0.1 s and 0.05 s depending on the size of the telescope in use, and the observing conditions (night sky brightness, brightness of the Moon). In these observations all of the information was been recorded. Nine flares in EV Lac, and five flares in V 577 Mon were detected. No flares were detected from YZ CMi during 45 min of monitoring.

The light curves of the detected flares are shown in Figures 1–18. The results are presented in Tables 1 and 2 (EV Lac), and 3 (V 577 Mon). Table 1 refers to the Byurakan observations, when both components of the double star EV Lac were observed simultaneously. Table 2 refers to the México observations of EV Lac, when only the flaring component of the double was observed. In the consecutive columns of these tables the following information is given: the date of observation; UT at the maximum of the flare; the designation of separate peaks observed during one

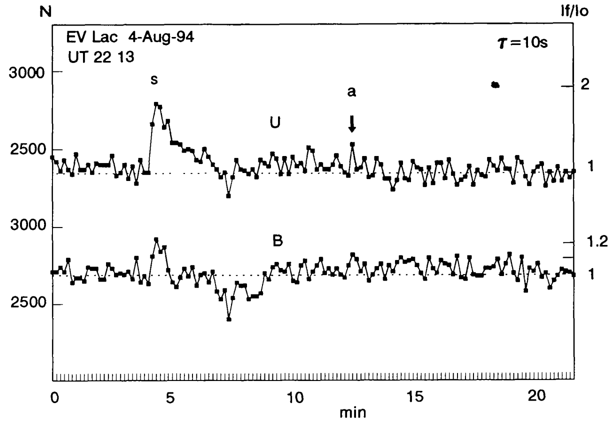

Fig. 1a. The brightness curves of the detected flares.

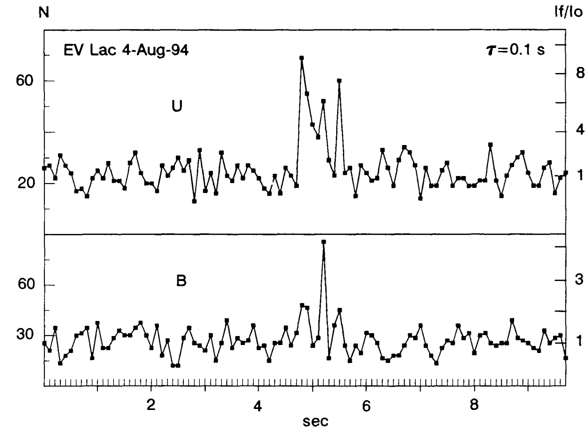

Fig. 1b. Same as Figure 1a.

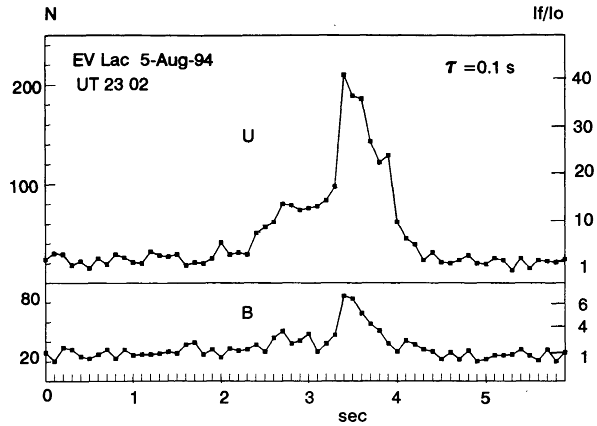

Fig. 2. Same as Figure 1a.

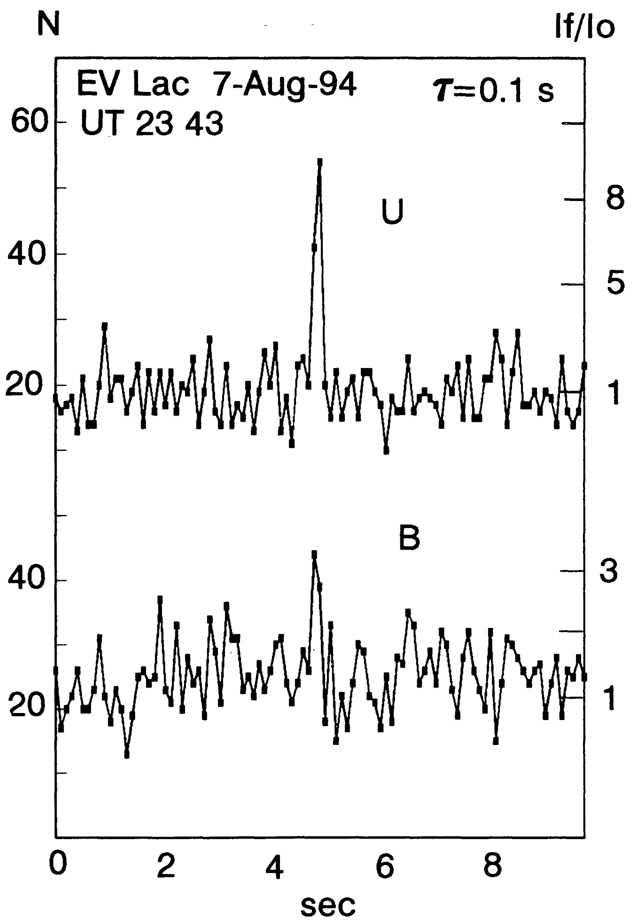

Fig. 3. Same as Figure 1a.

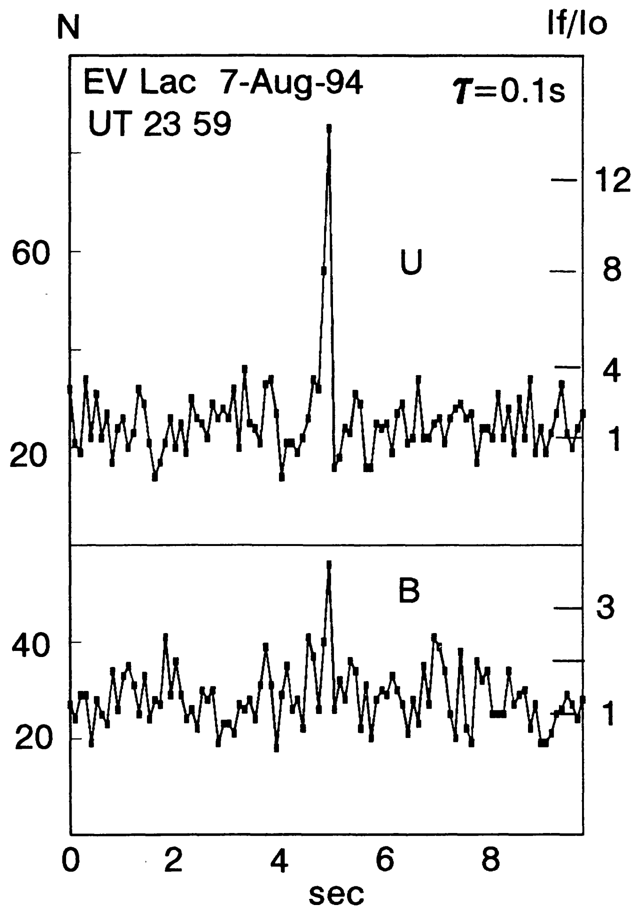

Fig. 4. Same as Figure 1a.

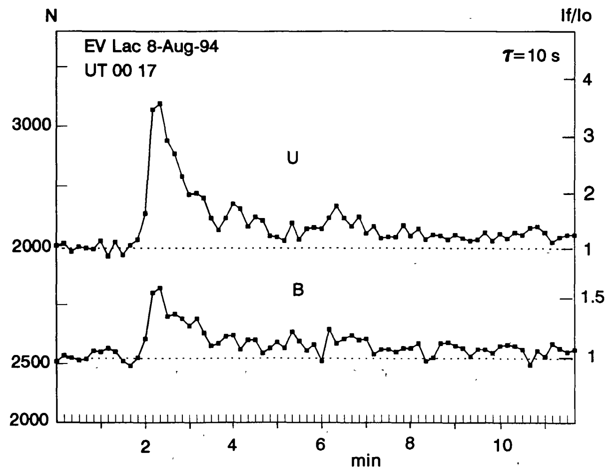

Fig. 5. Same as Figure 1a.

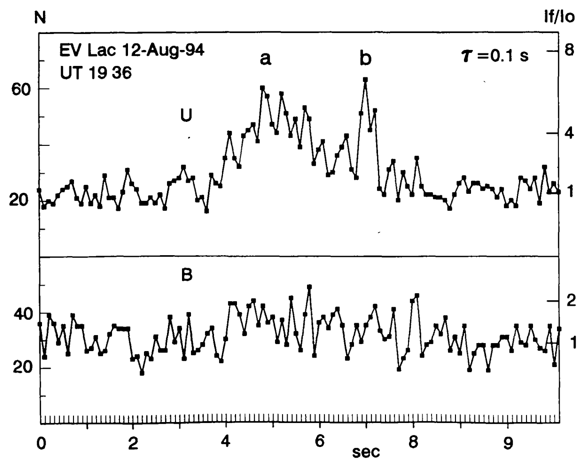

Fig. 6. Same as Figure 1a.

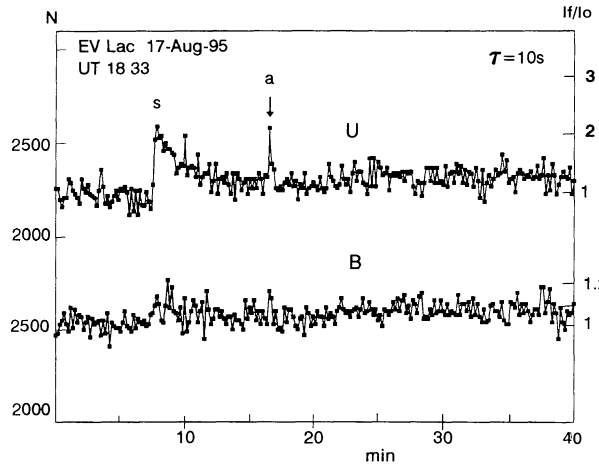

Fig. 7a. Same as Figure 1a.

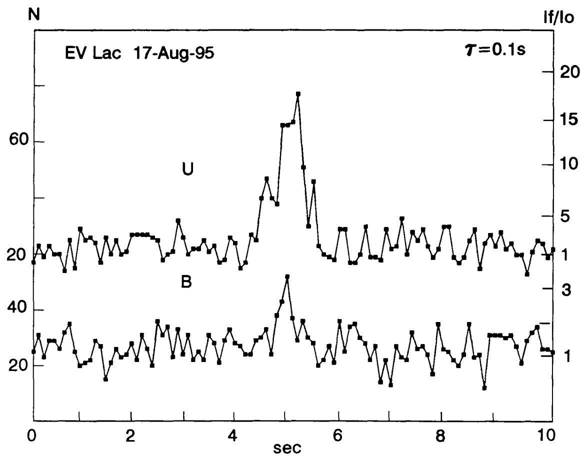

Fig. 7b. Same as Figure 1a.

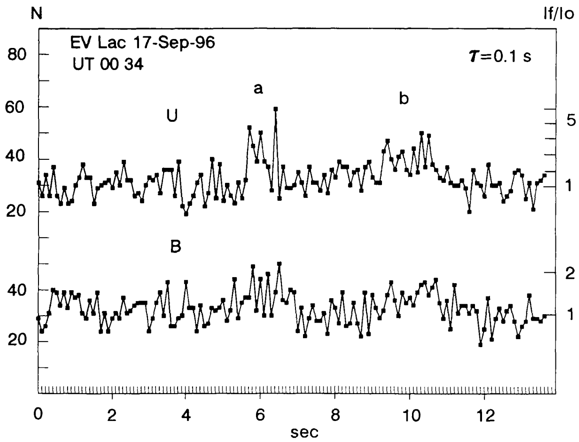

Fig. 8. Same as Figure 1a.

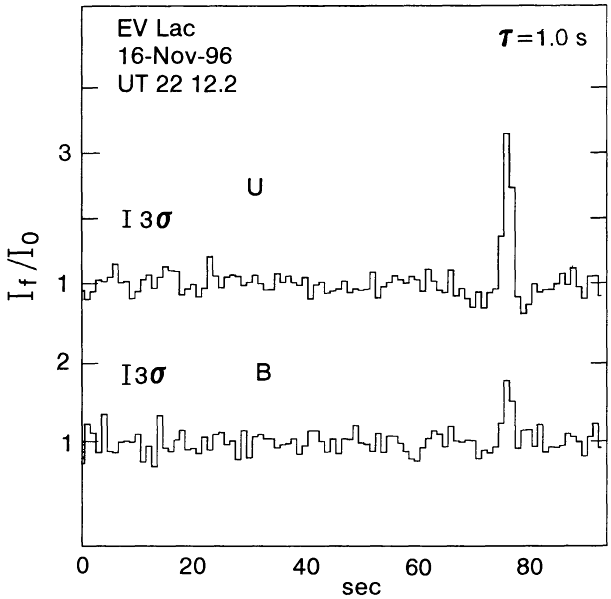

Fig. 9. Same as Figure 1a.

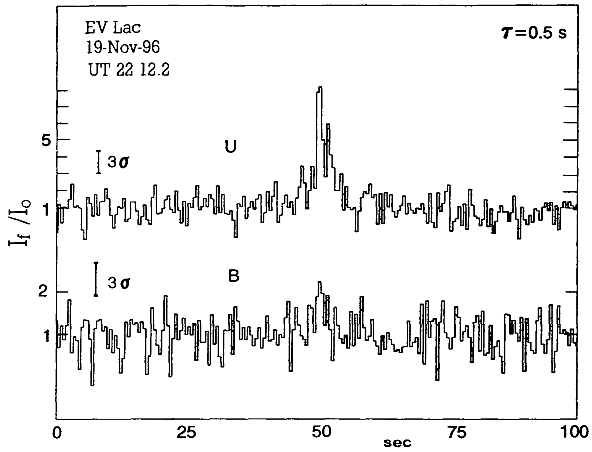

Fig. 10. Same as Figure 1a.

flare; ΔU; ΔB; the color $(U-B)$s of the star at the maximum of flare; the intrinsic color $(U-B)$f of the flare itself, the rising time of the flare t_r, and the full duration of the flare.

The last two columns of the Tables 2 and 3 list the integration time of observation, and the telescope with which the observations were made.

In deducing the parameters of the flares detected at Byurakan, where both components of EV Lac were observed, we adopted the following photometric data for EV Lac AB: $V=10.05$, $B-V=1.37$, $U-B$

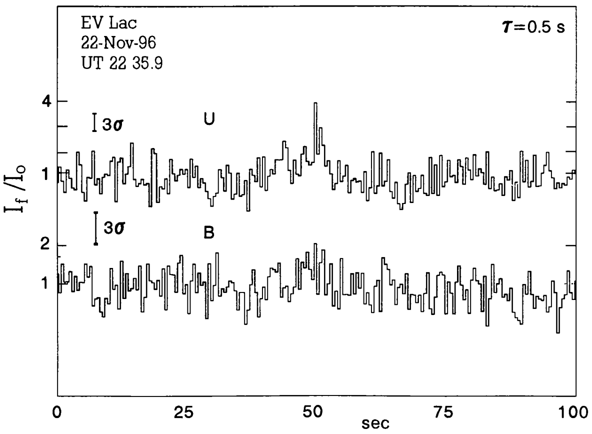

Fig. 11. Same as Figure 1a.

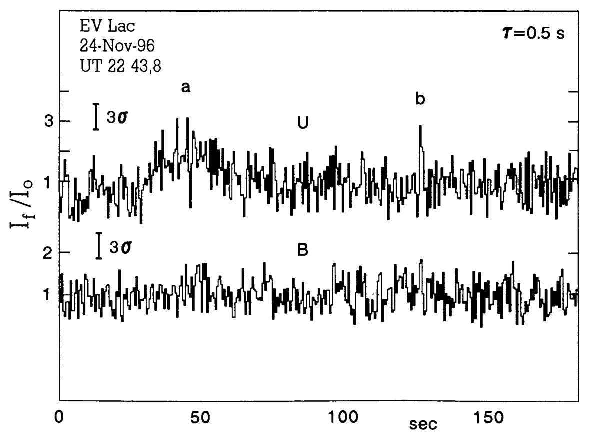

Fig. 12. Same as Figure 1a.

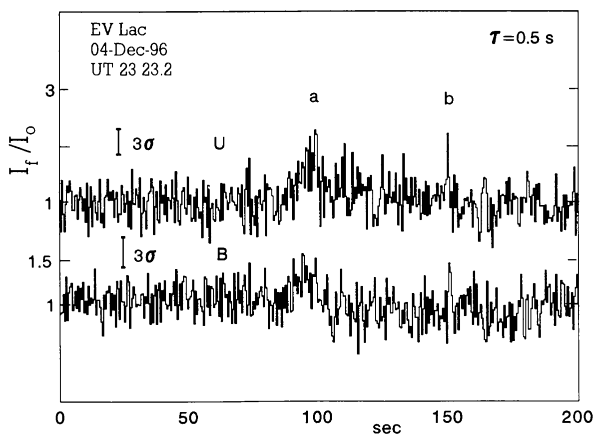

Fig. 13. Same as Figure 1a.

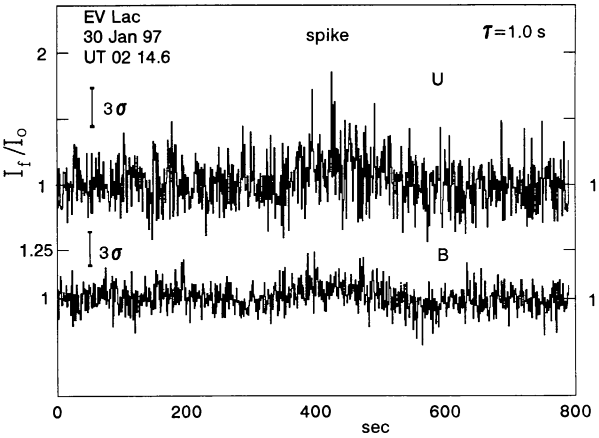

Fig. 14. Same as Figure 1a.

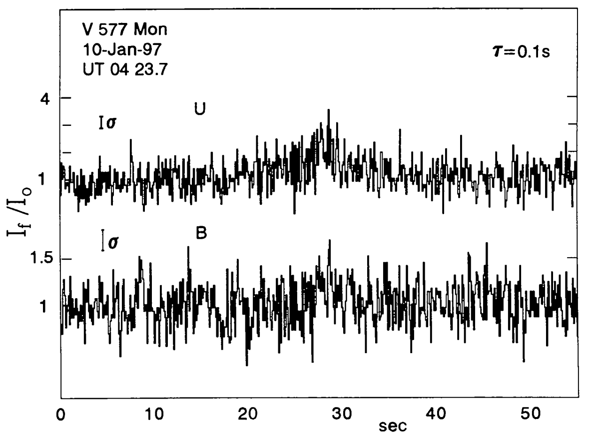

Fig. 15. Same as Figure 1a.

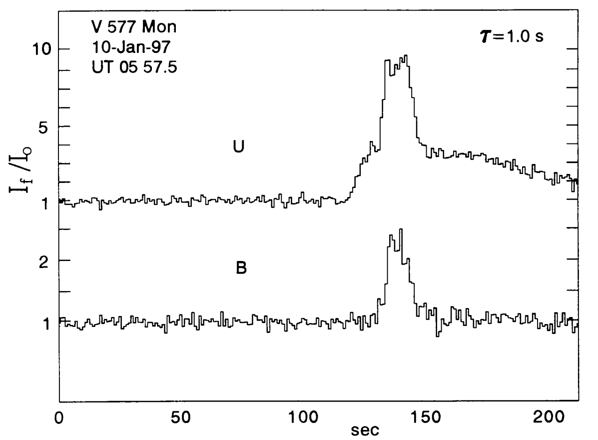

Fig. 16a. Same as Figure 1a.

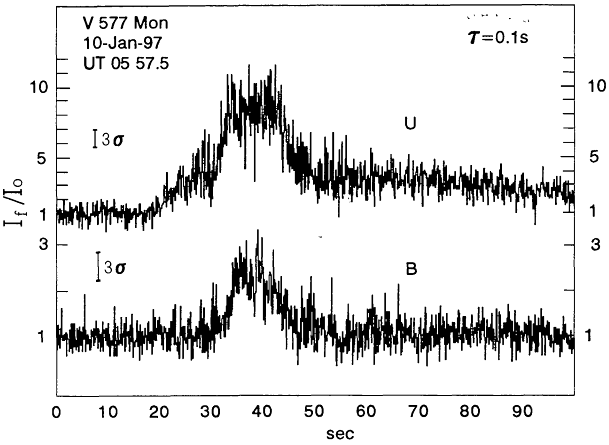

Fig. 16b. Same as Figure 1a.

= 0.75 (Moffet 1974). For the México observations, where only the flared component of EV Lac was observed, we adopted the values V = 10.26, $B - V$ = 1.55 and $U - B$ = 0.98 (Alekseev & Gershberg 1995). For V 577 Mon, we adopted the values U = 14.0 and B = 12.8 (Shvartsman et al. 1988).

The amplitudes and colors of the flares were calculated using the smoothed median light curves of the flares. The colors were not calculated in the few cases when the rise in the brightness was not observed in B.

The observational data described above allowed us to deduce the following properties of the detected flares:

1. *The spiky flares and the fine structure of flares.* Among the detected flares, the short, spiky type flares with a total duration of about 1 s or less were very remarkable. Such spiky flares were also detected in previous observations with the two-channel fast photometer (Tovmassian & Zalinian 1988; Zalinian & Tovmassian 1997). In the light curves presented by Shvartsman et al. (1988), there are also some very short spikes similar to the flares detected by us. However, they stated that they did not detect flares with durations less than 2–3 s. We suggest that Shvartsman et al. assumed that such spikes, registered at only one waveband, were only noise, and for this reason they were not considered real flares. The situation is different for simultaneous observations in two wavebands. A chance coincidence of two noise spikes on two independent records in U and B, with values of counts exceeding 5 σ, may take place once in 3 × 10^4 hours. Yet we registered about a dozen such coincidences during only a few hours of obser-

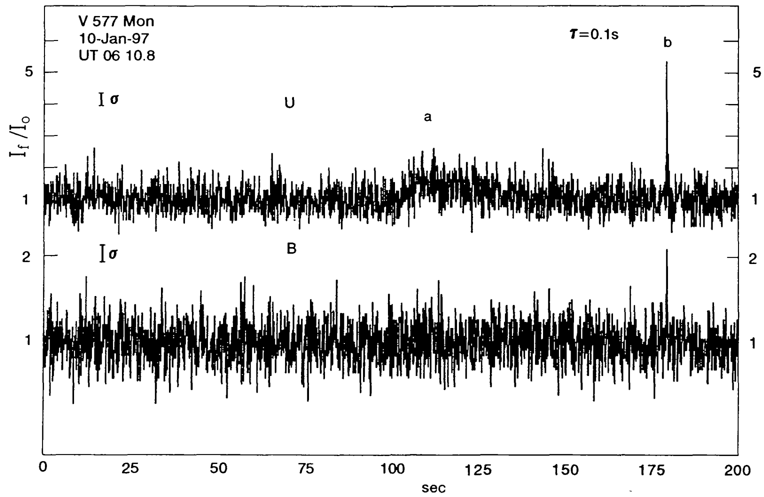

Fig. 17. Same as Figure 1a.

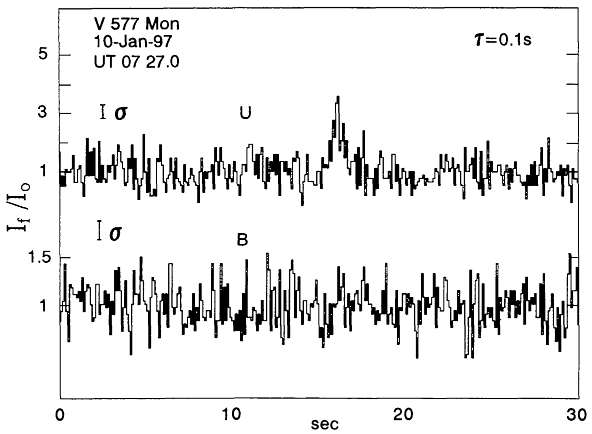

Fig. 18. Same as Figure 1a.

TABLE 1

FLARES OF EV LAC DETECTED BY OBSERVATIONS WITH THE 40-CM TELESCOPE

Date	UTmax h	UTmax m	Peaks	ΔU	ΔB	$(U-B)_s$	$(U-B)_f$	t_r sec	Duration
4 Aug. 94	22	13	s	0.64	0.24	0.29	−0.52	20	3.5 m
			a	2.2	1.1	−0.35	−0.68	0.1	0.4 s
5 Aug. 94	23	02	...	4.0	1.9	−1.35	−1.53	0.2[a]	2.0 s
7 Aug. 94	23	43	...	2.2	1.2	−0.25	−0.53	0.2	0.3 s
7 Aug. 94	23	59	...	2.7	1.2	−0.75	−1.09	0.2	0.3 s
8 Aug. 94	00	17	s	1.32	0.44	−0.13	−0.94	30	6.5 m
12 Aug. 94	19	36	a	1.8	0.5	−0.55	−1.40	0.8	2.4 s
			b	2.0	0.5	−0.75	−1.64	0.2	0.5 s
17 Aug. 95	18	33	s	0.79	0.35	0.31	−0.37	20	10.0 m
			a	2.9	1.2	−0.95	−1.31	0.8	1.2 s
17 Sep. 96	00	34	a	1.7	0.7	−0.25	−0.80	0.1	0.8 s
			b	1.2	0.4	−0.05	−0.89	0.2	0.2 s

[a] The fast rising part.

TABLE 2

FLARES OF EV LAC DETECTED BY OBSERVATIONS WITH THE 1-M AND 2.1-M TELESCOPES

Date	UTmax h	UTmax m	Peaks	ΔU	ΔB	$(U-B)_s$	$(U-B)_f$	t_r sec	Duration sec	τ sec	Tel. m
16 Nov. 96	22	12.2	...	1.3	0.6	0.28	−0.26	2.0	4.0	0.5	1.0
19 Nov. 96	22	24.0	...	2.2	0.7	−0.52	−1.17	1.5	4.0	0.5	1.0
22 Nov. 96	22	35.9	...	1.5	0.8	0.28	−0.11	0.5	2.5	0.5	1.0
24 Nov. 96	22	43.8	a	0.8	0.4	0.58	0.01	13.0	44.0	0.5	1.0
			b	1.2	0.6	0.38	−0.11	0.5	1.5	...	...
04 Dec. 96	23	23.2	a	0.8	0.4	0.58	0.01	12.0	45.0	0.5	1.0
			b	0.9	0.3	0.38	−0.54	0.5	1.0	...	...
30 Jan. 97	02	14.6	slow	0.4	0.08	0.66	...	41[a]	150.0	0.5	2.1
			spike	0.7	0.08	0.36	...	<1.0	<1.0[a]	...	...

[a] Not certain.

TABLE 3

FLARES OF V 577 MON DETECTED BY OBSERVATIONS WITH THE 2.1-M TELESCOPE

Date	UTmax h	UTmax m	Peaks	ΔU	ΔB	$(U-B)_s$	$(U-B)_f$	t_r sec	Duration sec	τ sec
10 Jan. 97	04	23.7	...	1.1	0.4	0.5	−0.29	1.7	4.0	0.1
10 Jan. 97	05	57.5	...	2.5	0.9	−0.4	−0.91	5.0[a]	30.0	0.1
10 Jan. 97	06	10.8	a	0.6	0.0	0.6	...	8.0	40.0	0.1
	06	12.0	b	1.8	0.8	0.2	−0.28	0.1	0.3	0.1
10 Jan. 97	07	27.0	...	1.2	0.0	0.0	...	0.5	1.5	0.1

[a] The small preflare (Fig. 16) is not considered.

vations. Thus, we conclude that the observed spikes were real flares.

Observations made with small integration time reveal the fine structure of the flares. Let us consider, for example, the flare of V 577 Mon which was observed on 10 January 1997. Its light curve, recorded with 1 s integration time, is presented in Fig. 16*a*. The same light curve recorded with 0.1 s integration time (as it was observed) is shown in Fig. 16*b*. A definite structure is seen in the latter figure. Flares of V 577 Mon are known to be long lasting (Shvartsman et al. 1988). In the case of the considered flare, the brightness of the star, after the relatively fast decline, remained slightly enhanced for about half an hour. In about 13 minutes after the main flare, a second smaller flare occurred at UT 06 10.8, which was followed by the short spiky flare of 0.3 s duration, shown in Fig. 17.

In Figures 1*a* and 7*a* the short flares of EV Lac observed on 4 August 1994 and 17 August 1995, and integrated in 10 s, are shown. The same flares recorded with 0.1 s integration are shown in Figs. 1*b* and 7*b*. The existence of fine structure is evident in these flares.

Variation of the intensity as considered above, is seen in a time scale of 0.1 s. This means that some flares may consist of a few shorter flares.

In some cases the rise of the flare was registered in just 0.1 s. Since this is the time resolution of our observations, it means that the real rising time of these flares may be even less.

2. *The occurrence of spiky flares.* Spiky flares of duration less than 1 s occur mostly after a normal flare. Indeed spiky flares of EV Lac observed on 4 August 1994 (Fig. 1), on 12 August 1994 (Fig. 6), 17 August 1995 (Fig 7*a*), 24 November 1996 (Fig. 12), 4 December 1996 (Fig. 13), and of the V 577 Mon on 10 January 1997 (Fig. 17) occurred almost immediately after the longer-lasting flares. Another spiky flare occurred immediately after the short flare of August 4 1994 (Fig 1*b*). A similar event happened on 17 September 1996 (Fig. 8).

3. *The colors of flares.* The ΔU, $U-B$ diagram for the flares of EV Lac and of V 577 Mon observed in Tonantzintla and Cananea are shown in Fig. 19. The flares become bluer with the increase of the maximum intensity of the flare in U. This trend was noticed earlier (Tovmassian & Zalinian 1988). In Fig. 20, an identical diagram is shown for the flares of EV Lac detected at the Byurakan Observatory. Crosses in Fig. 20 correspond to observations with 0.1 s integration time. Circles refer to the same observational data integrated over 10 s. The number of circles is less than the number of crosses because some of the flares are blended with nearby ones due to the integration in 10 s. Fig. 20 shows that the flares recorded with larger integration time are displaced from those recorded with smaller integration time, so that colors of flares become redder. Therefore, the flares are intrinsically bluer, and somewhat redder colors are deduced if longer integration time is used.

The intrinsic $U-B$ colors of all flares are, with one exception, negative (see Tables 1 to 3). The $U-B$

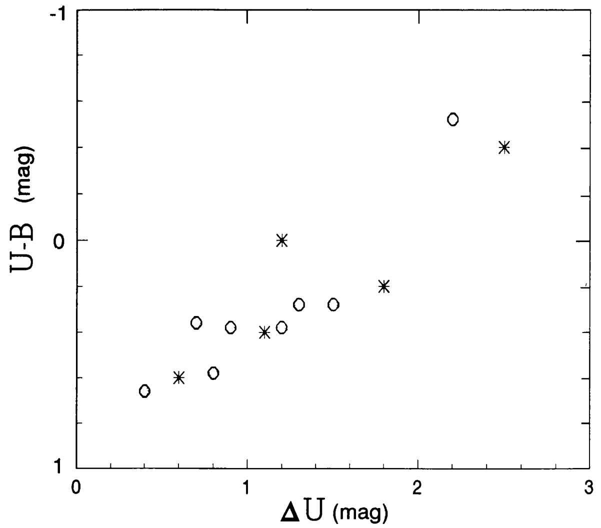

Fig. 19. ΔU, $U-B$ diagram of the flares of EV Lac and V 577 Mon detected by observations with the 1-m and 2.1-m telescopes.

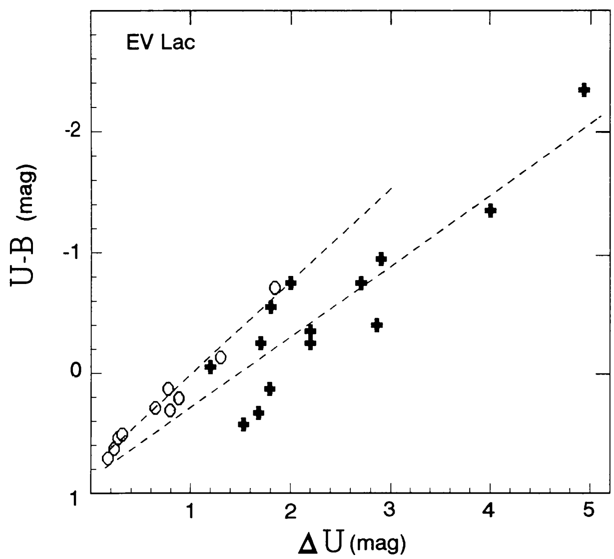

Fig. 20. ΔU, $U-B$ diagram of flares detected by observations of EV Lac with the 40-cm Byurakan telescope. The values of ΔU and $U-B$ are calculated on the records obtained with 0.1 s (crosses) and 10 s (circles) integration times respectively.

values of only two flares of EV Lac, from 24 November and 4 December 1996, are slightly above zero.

The comparison of the colors of the main, long lasting flares with those of the subsequent spiky flares (Tables 1 to 3) shows that the latter are systematically bluer than the former. Short flares in general are slightly bluer. The mean value of $U-B$ color of 16 flares with duration less than 4 s is -0.79 ± 0.52, while that of the 6 flares with durations larger than 20 s is -0.45 ± 0.42.

3. DISCUSSION

The simultaneous observations of the flare stars with integration time of 0.1 s in U and B revealed the existence of very short spiky flares of a total duration of a few tenths of a second. Moreover, some flares consisted of a few fast components. Spiky flares often occur after normal, longer-lasting flares. This finding suggests that the shock caused by the main flare rarefied the stellar atmosphere, and the release of energy of the subsequent flares takes place much faster. The bluer color of the follow-up spiky flares may then be explained by a smaller dilution of high energy emission of the flare agent in the media rarefied by a previous flare.

The occurrence of very short spiky flares puts certain constraints on the theories of flares. Indeed, in the case of some spiky flares, the brightness of the star increases by nearly one hundred times in about 0.2 s (Tovmassian & Zalinian 1988), or as little as 0.1 s. If one assumes that the outer boundary of the flare area expands in the stellar atmosphere with a velocity of 5000 km s^{-1}, then during 0.1 s the diameter of this area will reach at most about 1000 km. On the other hand, the diameters of dwarf flare stars are of the order of 5×10^5 km (Bopp, Gehrz, & Hackwell 1974). Hence, to explain the observed fast increase of the stellar brightness, we have to assume that the surface brightness of the area of the flare (the spot) is at least 10^7 times larger than that of the photosphere of the star. Otherwise, we have to assume the flare acts as an expansion of a cloud of relativistic electrons in a vacuum or in a very rarefied medium. The problem could be solved by invoking Ambartsumian's (1954) hypothetical super dense matter and its explosions in the upper layers of the stellar atmosphere.

The authors are grateful to the Instituto de Astronomía of the UNAM for using their facilities at the 1-m telescope in Tonantzintla. This work has been partially supported by the CONACYT research grant No. 0009P-E. We acknowledge the anonymous referee for careful reading of the manuscript and valuable comments.

REFERENCES

Alekseev, Yu., Gershberg, R. E. 1995, Afz, 39, 67
Ambartsumian, V. A. 1954, Contr. Byurakan Obs., 13, 3
__________. 1969, in Stars, Nebulae, Galaxies, ed. L. V. Mirzoyan, (Armenia: Acad. Sci., Armenian SSR)
Bopp, B. W., Gehrz, R. D., & Hackwell, J. A. 1974, PASP, 86, 939
Gershberg, R. E. 1989, Mem.Soc.Astron.Ital., 60, 263
Haisch, B. 1989, in IAU Colloquium 104, Solar and Stellar Flares, ed. B. Haisch & M. Rodono (Dordrecht: Kluwer)
Haisch, B., Strong, K. T., & Rodono, M. 1991, ARA&A, 29, 275
Moffet T. J. 1974, ApJS, 29, 1
Shvartsman, V. F., Beskin, G. M., Gershberg, P. E., Neizvestni, S. I., Plakhotenkova, V .L., & Pustilnik, L. A. 1988, Izv. Crimean AO, 79, 71
Tovmassian, H. M., & Zalinian, V. P. 1988, Afz, 28, 131
Zalinian, V. P., & Tovmassian, H. M. 1987, IBVS No. 2992
__________. 1989, Contr. Byurakan Obs., 61, 142

Octavio Cardona, Elsa Recillas, and Hrant M. Tovmassian: Instituto Nacional de Astrofísica, Óptica y Electrónica, Apartado Postal 51 y 216, 72000 Puebla, Pue., México (elsare@inaoep.mx, hrant@inaoep.mx).
V. P. Zalinian: Byurakan Astrophysical Observatory (BAO), Academy of Science of Armenia, Byurakan, 378433 Armenia.