UV–B and B-band Optical Flare Search in AR Lacertae, II Pegasi, and UX Arietis Star Systems

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Abstract A high-cadence search was conducted on the known RS CVn-type flare stars AR Lac, II Peg, and UX Ari. Two optical flares were observed in the B-band on AR Lac at 5 milliseconds (ms) resolution for a rate of 0.04 fl/hr. Flare energy of the two B-band fast-flares ranged from 0.55 to 16.7 × 10^{33} ergs. The UV–B and B-band search of II Peg for 44.5 hours at 5 and 10 ms resolution and UV–B band search of UX Ari for 25.6 hours at 10 ms resolution detected no flare activity.

1. Introduction

A flare survey was conducted on the known RS CVn-type flare stars AR Lac, II Peg, and UX Ari. This star class contains detached binaries with the more massive primary star being a G-K giant or sub-giant and the secondary a G to M spectral class sub-giant or dwarf (Berdyugina 2005). With orbital periods typically in the 1 to 14 day range, their rapid rotation and close proximity makes them “stellar dynamos,” magnetically active and energetic emitters with many showing chromospheric activity, X-ray and microwave emissions, and strong X-ray, radio, and optical flares (Christian *et al.* 1996). The three stars studied were selected for their known optical flaring in the UV and B bands.

The three stars were observed from 2012-08-15 through 2012-12-28 with a total of 117.6 hours of data collection time. The objective was to collect photometric data at a minimum of 100 Hz (10 ms sampling period) for high resolution capture of the flare rise profiles, detection of possible oscillations during the flare sequences (Mathioudakis *et al.* 2003) and gathering of additional flare rate data on the star systems. The optical system was a 43-cm corrected Dall-Kirkham telescope, a high-speed silicon photomultiplier (SPM), and a data acquisition system capable of sub-millisecond data collection times.

The unique component of the optical train is the Silicon Photomultiplier, a significant divergence from standard photometric detectors. The SPM is not a conventional CCD detector, but rather a non-imaging detector with characteristics comparable to a vacuum photomultiplier (PMT). The SPM advantages versus a PMT are higher quantum efficiency over a wider spectral range, insensitivity to optical overload, very small size, low voltage, and wide bandwidth (greater than 10MHz). The SensL SPM module used (SensL 2013) has a peak photon detection efficiency (PDE) of 23%, a 1-mm square active detection area, and 848 20-μ microcells. Higher PDEs are available with the larger microcells having greater active area fill ratios (Vander Haagen 2012). Unlike conventional CCD detectors, the SPM is insensitive to gamma-ray/particle impacts as confirmed by personal email communications with the SensL engineering organization. This eliminates the difficulty in separating high-energy impacts from photons in a non-imaging detector.

The device's 1-mm square active area is composed of an array of 848 microcells, each a silicon avalanche diode operated in the Geiger mode. The diodes are all connected electrically in parallel. When a photon strikes a single microcell with more energy than the band gap of the detector material it is absorbed, exciting a valence band electron into the conduction band. This electron is accelerated into the avalanche zone under a very high electric field and causes impact ionization. That electron in addition to the first accelerates and produces a chain reaction or "avalanche" multiplication. One photon producing one electron is multiplied through this process by $\sim 10^6$. However, the microcell is now acting as a conductor or producing a Geiger discharge. To stop the conduction process a resistor is placed in series with each of the microcell diodes such that the voltage drop during discharge is large enough to drop the junction below the breakdown voltage and reset the device. With this device, one captured photon produces one short current burst with duration of 20 to 60 ns. However, because the cell is operated at a reverse voltage well above its breakdown there is a level of spontaneous breakdown within the device causing dark counts. For a single microcell this level is 20 to 500 counts per second, depending on the active area size, junction temperature, and bias level. For the SPM used, with its 848 parallel cells, the dark count rate is approximately 20KHz at its operating temperature of –30° C.

In application the incoming light is slightly defocused to allow more than half of the microcell array to be illuminated by the incoming field. This allows an incoming stream of photons to be spread out and impinge on one of several hundred or more cells. After a cell is impacted and is in its Geiger discharge mode it takes approximately 50 ns to complete the discharge and reset. A second simultaneous photon impact on a discharging cell will not be detected. The device's linearity in photometric applications confirms multiple impacts on a single cell are not an issue.

To effectively trigger the data acquisition system for pulse counting the output of the SPM is amplified to standard logic level voltages with 0–0.8 volt for low state and 2+ volts for high state. This necessitates a 10 MHz bandwidth pulse amplifier for the narrow SPM current pulses with an amplifier voltage gain of approximately 1,000. An impedance-matching line driver takes the signal and drives a length of 50-ohm coax for connection to the data acquisition system. The data acquisition system is a PC-mounted card with bandwidth capability to 100,000 photon counts per second and integration from sub-milliseconds to seconds, data collection triggering on count rate or event, and integrated software for real time data storage and review of events.

2. Flare search

Initial review of the data showed two categories of flares: five very short duration events among the three stars and two additional longer duration flares on AR Lac only. The five very short duration flares ranged in duration from 30 to 85 ms with peaks 0.29–0.51 mag. above the mean and were analyzed by Vander Haagen (2013). This document focuses on the flare search results and on the two longer duration flares and their parameters.

2.1. AR Lac search results

AR Lac is the brightest known totally eclipsing RS CVn binary system with a period of 1.98 days and near equal mass K0 IV+G4 IV subgiants, separated surface-to-surface by just under the diameter of the cooler larger primary (Ayres *et al.* 2005). This system has been a popular target for observers at all wavelengths (Christian *et al.* 1996). AR Lac has had flaring reported from the X-ray to the optical region (Kovari and Pagano 2000), making it a prime choice for this study.

AR Lac was observed in the B band for 47.5 hours, or 171 ksec. Photometric sampling was at 200 s/sec (5 ms sampling period). Two flares were detected and are summarized in Table 1. Given in this table are each flare's rise time (t_r, mean to peak), decay time (t_d, peak to mean at the end of decay), the flare equivalent duration (P_b), total energy (E_b), flare magnitude above the mean (b-mag), ratio t_d / t_r, and flare type.

Classification of the flares used a process described in Dal and Evren (2012) whereby a t_d / t_r ratio less than 3.5 is designated a slow flare and above 3.5 a fast flare. This classification separates those flares generating a sudden release of energy in the impulsive phase, or non-thermal process, from the longer duration thermal events. Dal and Evren conclude that the ratio defines the region between which the non-thermal and thermal events dominate the energy emitting process. Table 1, t_d / t_r data, defines flares 1 and 2 as fast flares. The flare profiles are contained in Figures 1 and 2.

The flare energy is calculated using equations (1) and (2):

$$E_b = 4\pi d^2 10^{-0.4 m_b} \Pi_b P_b \tag{1}$$

$$where\ P_b = \int [(I_f - I_o) / I_o]\, dt \tag{2}$$

For AR Lac $d = 1.32 \times 10^{20}$ cm (van Leeuwen 2007), $m_b = 6.89$, $\Pi_u = 2.32 \times 10^{-6}$ erg cm^{-2} s^{-1} (Bessell 1979). The term Π_b is estimated for the B band by $E_u \simeq 1.20\, E_b$ (Mathioudakis *et al.* 1992). Equation (2) was numerically integrated in EXCEL using the actual photometric data. The parameters for each flare are contained in Table 1. Referring to Figure 2, it is instructive to note that the initial impulse phase of flare 2 contains approximately 5.6% of the total energy in 1% of the total flare time.

The rate of flare activity was 0.04 fl/hour. Table 2 summarizes the literature showing the difficulty in comparing these results with past surveys. Two of the surveys reported at least one flare in the UV but there is insufficient data to calculate the rates. The third survey was focused on spectroscopy, Chandra HEG in UV, but did report flare rate data at 0.07 fl/hour.

A FFT analysis was run on flare 2 data for possible oscillation detection. Mathioudakis *et al.* (2003) identified intensity variations in II Peg after the impulsive phase. These intensity variations in a much longer flare were analyzed using FFT and Wavelet analysis and found to have a high confidence period of 220 s. The FFT analysis of AR Lac showed no evidence of oscillations.

There is concern that the flares are not real but rather a gamma-ray impact(s) or an instrumental or a reduction issue. This concern is heightened by the considerably shorter event duration than typical of RS CVn type flares, particularly flare 1. As noted previously the SPM does not response to gamma-ray impacts. The data were further reviewed for instrumental and reduction issues and the S/N were also confirmed at 18 or greater for these events. A literature review does reveal observations of short duration RS CVn flares. Mathioudakis *et al.* (1992) describes an II Peg flare with $(t_r + t_d) \sim 245$ sec. Byrne *et al.* (1998) also describes an II Peg flare with duration of 59 seconds. Both of these are comparable to flare 2 described in Table 1. No short duration references were found for AR Lac. The brief description of five very short duration flares from the same study is described in section 2 of this paper. Their intensity profile is significantly different and 2 to 3^+ orders shorter in duration. Additional observations are needed to verify these and the flare 1 results.

2.2. II Peg and UX Ari search results

Two similar RS CVn type stars, II Peg and UX Ari, were studied, having demonstrated optical flaring activity (Henry and Newsom 1996). II Peg is a 6.72-day single-line spectroscopic binary system with spectral type K2 IV-V star and an as yet unseen M-dwarf companion (Gu and Tan 2003). This system has been widely studied with reported flares from X-ray through optical wavelengths (Mathioudakis *et al.* 1992). UX Ari is a less studied 6.4 day double-line spectroscopic binary system with G5 V and K0 IV components and optical UBV flaring reported by Henry and Newsom (1996).

II Peg had a varied sampling plan; 15.6 hours in B band at 200 s/sec, 14.6 hours in B band at 100 s/sec, and 14.3 hours in UV–B band at 100 s/sec for a total of 44.5 hours. Photometric measurements at 200 s/sec and 100 s/sec resulted in sampling periods of 5 ms and 10 ms, respectively. UV–B-band observations used an Edmund 500 nm short pass filter. When combined with the response of the SPM the resultant band pass was approximately 380 to 500 nm. This gave some added sensitivity to any UV flare component. The UX Ari search was conducted for 25.6 hours in the UV–B band at 100 s/sec.

No flares were detected in either system over the sampling period. Table 2 summarizes the current search and historical rate data. II Peg has a range of reported rates from 0.225 fl/hour to 0. As noted in the cited references the system seems to vary widely in activity from a highly energetic period (Byrne *et al.* 1994) to a quiet state.

Definitive flare rate data on UX Ari were limited to Henry and Newsom (1996), where a single flare just after maximum resulted in a flare rate of 0.034 fl/hr. Data from the Advanced Satellite for Cosmology and Astrophysics (ASCA) and the Extreme Ultraviolet Explorer (EUVE) campaigns were analyzed by Gudel *et al.* (1999) where UV flares were detected. However, no flare rates were calculated or could be accurately inferred from the information.

3. Discussion

Inspection of the AR Lac flare rise time data indicates under-sampling at 200 s/sec with the true profile not characterized. Figure 3 shows the rise time portion of flare 1 in 5 ms intervals. With the actual flare rise time unknown, it is important to understand what sampling options are needed and possible to better characterize the flare waveform. Equation (3) describes the relationship between the measurement system's bandwidth (BW) and the rise time (t_r) of a signal under study:

$$\mathrm{BW} = \frac{0.35}{t_r} \tag{3}$$

To avoid signal aliasing, the sampling rate f_s must exceed the Nyquist Rate f_n, thereby equation (4):

$$f_s > f_n \text{ where } f_n = 2\,\mathrm{BW} \text{ (minimum)} \tag{4}$$

Assume the actual flare rise time is 2 ms; the equivalent minimum system BW requirement would be 175 Hz, necessitating a sampling rate of 350 s/sec. With the limited light from the optical system an additional search at 500 s/sec in the B band should be possible. With the shorter sampling duration the S/N would degrade from approximately 18 to 12 and provide adequate BW for t_r as short as 1.5 ms. Sampling at 1,000 s/sec using the UV–B filter should also result in S/N above 10. Either sampling rate would improve the rise profile resolution under energetic impulse conditions.

The lack of flare detection on either II Peg or UX Ari was disappointing but typical of the results from other studies. Note again the large variability in

Table 2 on the searches (Mathioudakis *et al.* 1992), (Henry and Newsom 1996), and (Byrne *et al.* 1994). There is clear evidence of long-term variability in the level of optical flaring. While two of the searches were in the UV band, where flare energy is at least 1.2 times greater than B band (Mathioudakis et al. 1992) the S/N should be sufficient for all but low level flares, such as < 0.05 mag. This limitation is exacerbated by both the telescope aperture and more importantly by the lack of a second SPM monitoring a reference star for optical transmission correction. Fast occurring transmission variations can mask low level flares and make positive discrimination of these events difficult. A two-sensor system has been designed but has not been constructed due to its complexity and difficulty in alignment.

This study provided the highest reported sampling rates found for study of these three stars. An additional search, at the higher sampling rates, is planned to further refine the rise time profiles. In addition, further observations may serendipitously discover other short duration flares to verify these results.

4. Acknowledgements

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Table 1. AR Lac flare characteristics in the B-band.

Date	*Flare*	t_r *(sec)*	t_d *(sec)*	P_b *(sec)*	E_b *(10^{33} ergs)*	*Flare (b-mag)*	t_d/t_r	*Flare Type*
Aug 23, 2012	1	0.010	2.55	0.62	0.55	0.51	255	fast
Aug 23, 2012	2	0.015	203.1	18.8	16.7	0.49	13540	fast

Table 2. Flare rate comparison between current flare search and historical data.

Star System	*Search Time (hours)*	*Search Flare Rate (fl/hour)*	*Historical Rates (fl/hour)*
AR Lac	47.5	0.04 B-band	X[a]
			X[b]
			0.07[c]
II Peg	44.5	0	0.17[d]
			0.225[e]
			0[f]
			X[g]
UX Ari	25.6	0	0.034[e]
			X[h]

a) (Christian et al. 1996), EUVE study, rate not reported. b) (Kovari and Pagano 2000), UV flares, rate not reported. c) (Huenemoerder, Canizares, and Tibbetts 2003), Chandra HEG in UV. d) (Mathioudakis et al. 1992), UV- band. e) (Henry and Newsom 1996), UBV search. f) (Byrne et al. 1994), UV–Band. g) (Byrne et al. 1998), UV–Band, 1-large flare, rate not reported. h) (Gudel et al. 1999), ASCA and EUVE data, UV flares, rate not reported.

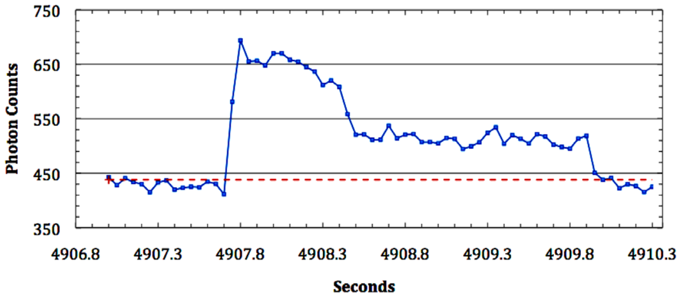

Figure 1. Flare 1, August 23, 2012, 4:21 UTC, resampled at 50 ms, orbital phase 0.26 (Kreiner 2004).

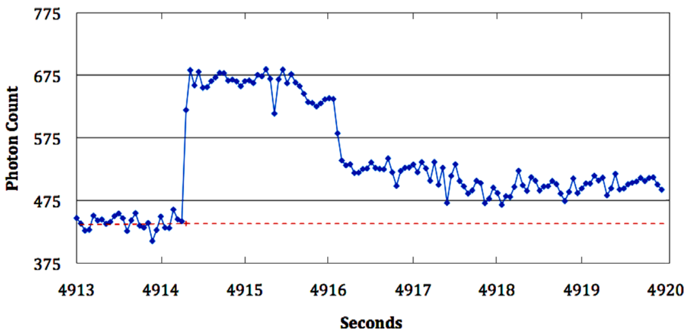

Figure 2. Flare 2, August 23, 2012, 4:21 UTC, early impulse portion only, resampled at 50 ms, orbital phase 0.26.

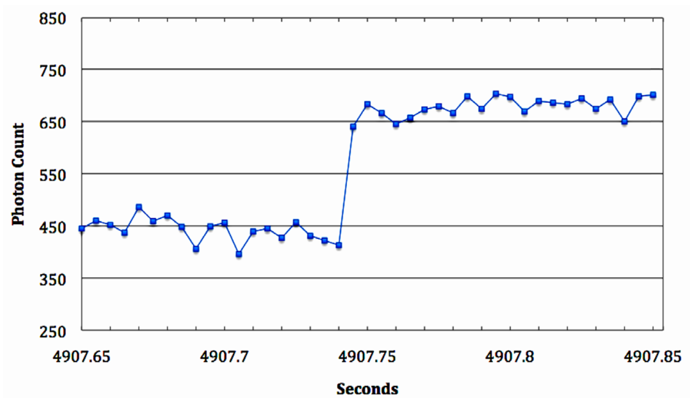

Figure 3. Flare 1, August 23, 2012, 4:21 UTC, original photometric data sampled at 200 s/sec (5 ms sampling period), noting under-sampling of signal during the impulsive rise time portion.