High-Cadence B-Band Search for Optical Flares on BY Dra

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Abstract The high-cadence search at 50 and 100 samples/sec of BY Dra revealed very short-duration B-band flares. A statistical criterion was used to isolate the short-duration optical flares from random photon events. Three flares, ranging in duration from 60 to 130 ms, with peaks 0.30–0.43 magnitude above the mean, were detected within the 80.2 hours of periodic monitoring from July 2012 through October 2015. This represents a flare rate of 0.04 flares/hour.

1. Introduction

BY Draconis is a main sequence archetype variable MK-type star whose low-level luminosity variability is due to its rotation coupled to chromospheric surface spots. Movement of these spots produce quasi-periodic variability closely related to its rotational period. Early studies conducted on BY Dra by Cristaldi and Rodono (1970) indicated that the star was also a flare star. Subsequent studies by Cristaldi and Rodono (1973) further supported flaring over a two-year monitoring window. The Cristaldi search was conducted using an S13 spectral response photomultiplier with an electronic equipment time constant of 1 second and recording chart rolling speed of 1 cm per minute, the objective being to capture conventional longer duration flares. While this archetype variable has been widely studied for its surface spots and resultant quasi-periodic variability, Zalinian and Tovmassian (1987) was the only high-cadence search found of BY Dra and recorded two short-duration flares.

The objective of this search was to conduct a high-cadence photometric study to capture conventional longer flares and also any solo or short-duration flares proceeding, during, or after the main outburst. Such data should improve the granularity of knowledge of an outburst event and potentially capture very fast solo events missed by conventional long integration photometry. Vander Haagen (2013) reported such events in RS CVn type star systems. This high-cadence search was conducted principally at sample rates of 50 and 100 samples/sec.

2. Optical system and data collection and analysis pipeline

The optical system consisted of a 43-cm corrected Dall-Kirkham scope, a high-speed silicon photomultiplier (SPM), and a data acquisition system capable of sub-millisecond data collection times. The SPM was chosen for this application because it has comparable sensitivity to a standard single channel vacuum photomultiplier, yet a more robust mechanical and electrical design with the disadvantage of higher dark counts (Vander Haagen 2012). The observations were conducted using an Edmund 500-nm short-pass filter to improve the overall transmission in the UV and blue. When combined with the response of the SPM, the resultant band pass was 380 to 500 nm giving approximately a 20 nm increase in the 3 db down point at the longer blue wavelengths versus a B-band filter. There was very minor UV response improvement due to the SPM's response at shorter wavelengths. This resulted in a non-standard photometric B-band pass.

The optical system is shown is Figure 1. The incoming beam is split approximately 80/4 with the reflected portion passing through the optical filter, an f-stop yielding a 57 arc-second field, and onto the SPM detector. A wide bandwidth pulse amplifier amplifies the SPM signal, producing a 2- to 3-volt pulse of approximately 50 ns for each converted photon. These photon pulses are sent to a PC-based data acquisition system where they are gated and counted based upon the collection rate. A 10 ms gate was used for most of the measurements, generating a 100 Hz data collection rate or 100 samples/second. The balance of the incoming beam passes straight through to a conventional CCD camera used for initial alignment, guiding, and measurement of both the guide star flux and background flux. Referring to Figure 2, the flux value counts from the target data stream along with GPS 1-second time stamps are recorded in the DAQ Log File by the data acquisition system (Vander Haagen and Owings 2014). The CCD Data and Control stream consists of reference and background flux values plus pixel counts for each guide star sample, typically every 5 seconds. These values are stored in the AG (auto-guider) Tracker Log file.

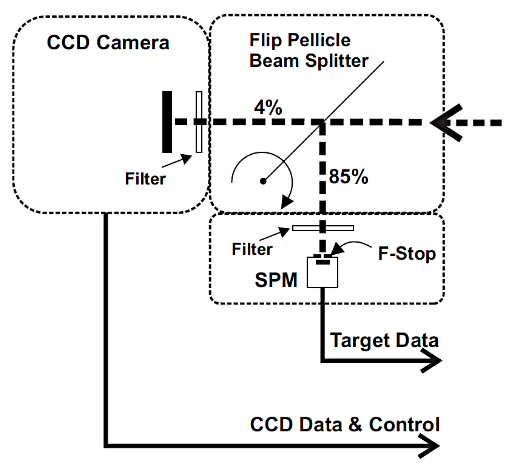

Figure 1. The optical train pictorial shows the pellicle beam splitter with both reflected and pass-through beams. The reflected beam passes through the narrow band filter, aperture, and onto the silicon photomultiplier (SPM). The pellicle can be flipped to allow 100% light transmission for initial target alignment using the CCD camera. The SPM is mounted on an X-Y stage for precise centering of detector to the centerline of the CCD camera. Guiding is provided with pellicle in position shown. The target SPM photon counts and data from the CCD camera are processed and stored as shown in data acquisition pipeline, Figure 2.

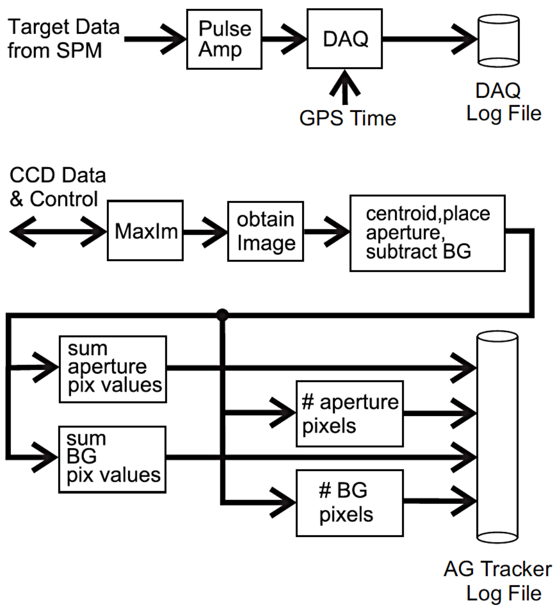

Figure 2. The data acquisition pipeline consists of two streams, the target photon counts and CCD camera image data. The low level SPM photon counts are amplified and counted by the data acquisition system (DAQ) for the period selected (ex. 10 ms) and the data written to the DAQ Log File. A GPS-synced time stamp is added every second to the appropriate data line. The DAQ Log is limited to 1 million data lines per file. The CCD data feed the camera control program that extracts the guide-star image, centroids the image, and extracts both flux and pixel counts for the guide star and background. This occurs at a rate determined by the guide star exposure, typically every five seconds. These data are written to the AG Tracker Log File.

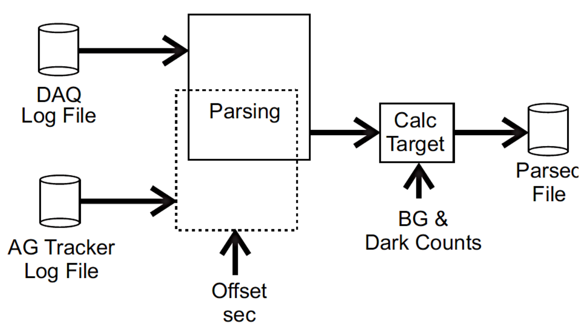

Figure 3. Upon completion of the data collection the DAQ and AG Tracker Log files are merged using a parsing operation. The lower resolution tracker file data are aligned with the DAQ target photon counts; the target counts are reduced using a quadrature calculation to remove the sky background and SPM dark counts thereby producing and integrated file of sample by sample target counts, reference star flux, and sky background all referenced to an accurate UT time stamp in seconds; for example, 5402 sec equals 1:30:02 UT with resolution to the sample period.

Upon completion of the night's search the DAQ Log File and the CCD's AG Tracker Log File are merged as shown in Figure 3. The large DAQ Log File with up to one million data samples is merged with the much slower occurring auto-guider, AG Tracker Log, reference data in a parsing process. Here, every target data point is matched to the time-appropriate Tracker data with the target counts corrected for the SPM dark counts and sky background in a quadrature calculation, and each sample GPS time stamped. This parsing operation results in an integrated file with all constituents ready for analysis, with each file containing up to one million sample lines each containing target, reference, and background data. Files of this size are too large for spreadsheet analysis but are easily analyzed using signal processing software such as SIGVIEW (SignalLab 2015). The files are reviewed and processed using a variety of filters, time domain transforms, and statistical tools.

3. Flare search

The study objective was capturing of high time resolution flaring activity connected with longer-duration conventional flares and short-duration solo flares. Very short flares of 10 to 100 ms duration have been observed unconnected with conventional flaring activity. These very short flares generally consisted of one or more points at 3σ or higher with a peak at 4–10σ. A 50 ms duration flare was reported for EV Lac in the U–B band by Zhilyaev and Romanjuk (1990) and simultaneous U and B-band flares on BY Dra (Zalinian and Tovmassian 1987). Vander Haagen (2013) also reported very short-duration flares on AR Lac, II Peg, and UX Ari of 30 to 85 ms duration with peaks 0.29–0.51 magnitude above the mean.

A criterion was developed to isolate these short-duration flares in very large sample sizes; flares must consist of a minimum of three consecutive data points, two at or above 3σ and one at or above 5σ. Since the minimum number of photons per gate was always 100 or more, normal distribution statistics were used to compute the standard deviation. Statistics were collected 600 seconds prior to the event where possible using digital signal processing software (SignalLab 2015). This process is similar in direction to that followed by flare searches (Byrne *et al.* 1994) and similar as described by Vander Haagen (2013). The probability of this sequence being a random event can be represented by Equation 1, where N is the number of integrations or samples taken during the observing interval and σ is for the positive events only.

$$\Pi_{3,3,5\sigma} = P_r(3\sigma)^2 5\sigma = (1.35 \times 10^{-3})^2 \times (2.9 \times 10^{-7})\, N = 5.2 \times 10^{-13}\, N \quad (1)$$

With N ranging from 1 to 2×10^6 samples during an observing interval the probability of the event sequence being random is appropriately small. This criterion was used for each of the data sets to isolate potential short-duration flares.

4. BY Dra data collection and analysis

Shown in Figure 4, the data collection was conducted over the period July 30, 2012, through October 8, 2015. The majority of the data (82%) were collected between June 2015 and October 2015. The total data collection time was 80.2 hours or 288.8 Ksec, with the first 23.8 Ksec at 200 samples/sec, which was considered oversampled. The next 87.3 Ksec was sampled at 50 samples/sec and after S/N and resolution review was increased to 100 samples/sec, 10 ms gating period, for the remaining 177.7 Ksec of the study. When combined with the response of the SPM the resultant band pass is approximately 380 to 500 nm. This band pass was chosen versus V or R bands due to its generally higher amplitude transmission during flaring conditions. Three short-duration flares were captured,

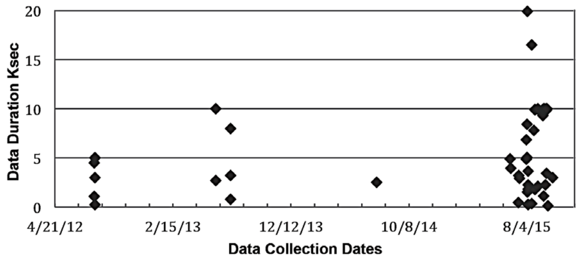

Figure 4. BY Dra data collection over the period July 30, 2012, through October 8, 2015, for a total of 80.2 hours or 288.8 Ksec, with (82%) collected between June 2015 and October 2015.

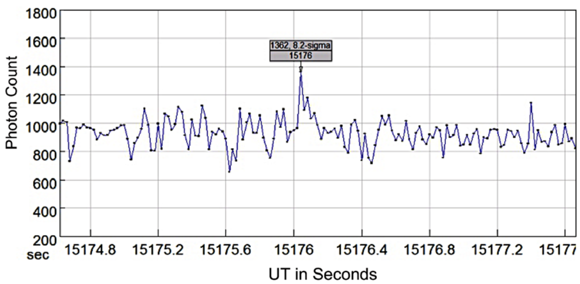

Figure 5. 2015-08-16, BY Dra sampled at 50s/sec (20ms gating period), mean 916, σ 54, data point sequence on peak: 1362 (8.2σ), 1092 (3.3σ), and 1178 (4.8σ). The time axis is in UT (seconds) for the date specified. The 1362 count peak was 0.43 mag. above mean with a flare duration of 120 ms. Annotation box on graph shows peak count and sigma value (top) and time at peak (lower).

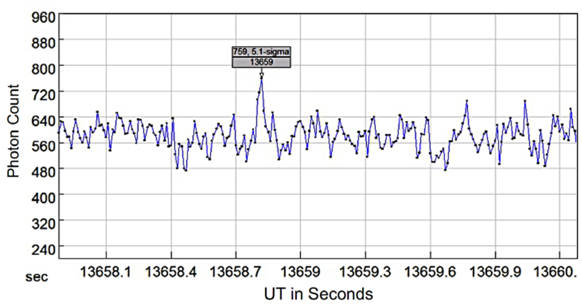

Figure 6. 2015-09-22, BY Dra sampled at 100 s/sec, mean 576, σ 36, data point sequence 694 (3.3σ), 715 (3.9σ), and 759 (5.1σ). The time axis is in UT (seconds) for the date specified. The 5.1σ peak was 0.30 mag. above the mean with a flare duration of 60 ms. Annotation box on graph shows peak count and sigma value (top) and time at peak (lower).

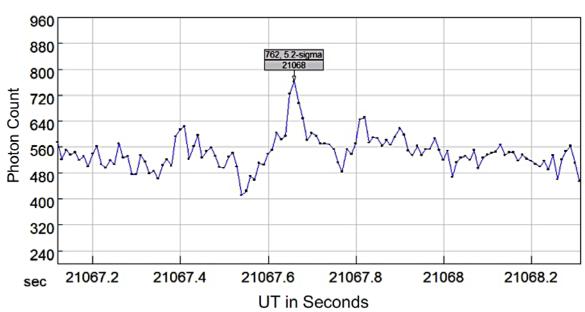

Figure 7. 2015-09-23, BY Dra sampled at 100s/sec, mean 540, σ 43, data point sequence 724 (4.3σ), 762 (5.2σ), and 696 (3.6σ). The time axis is in UT (seconds) for the date specified. The 5.2 σ peak was 0.37 mag. above the mean with a flare duration of 130 ms. Annotation box on graph shows peak count and sigma value (top) and time at peak (lower).

0.04 flare/hour. Two additional flares were captured during the July to October period but narrowly missed at least one of the statistical event criterions. Flare 1 is shown in Figure 5 with an 8.2σ, 0.43 magnitude peak above mean and 120 ms duration. Flare 2 shown in Figure 6 has a 5.1σ, 0.30 magnitude peak above mean and 60 ms duration. Flare 3 shown in Figure 7 has a 5.2σ, 0.37 magnitude peak above mean and 130 ms duration.

5. Discussion and conclusions

Atmospheric scintillation as source or inducer of the short-duration peaks is possible and cannot be ruled out without a simultaneous high-speed reference. Without a substantially more complex optical system the 5-second integration reference star represents a degree of assurance that no major perturbations have occurred.

In addition, Fourier PSD transforms were made of each data set. A wide range of noise amplitude and cutoff frequencies were present across the data sets. Where short-duration peaking occurred, digital band pass filters were employed to isolate the frequency domain signature of the event. No signature that was narrow or consistent enough could be identified. This area of investigation did not prove fruitful. This same issue was noted in Vander Haagen (2013).

The work done by Cristaldi and Rodono (1973) discovered a number of longer duration flares but did not calculate the flare rates. In that study the data collection method consisted of a 1-cm-per-minute chart recorder with an electronic time constant of 1 sec. Five flares of approximately 0.1 magnitude or less were identified within the B band ranging in duration from 1 to slightly over 2 minutes. With the two telescope systems used the flare rates were estimated, from their data, at 0.04 and 0.16 flares per hour. With the systems' slow response, flares of second and sub-second duration could not be identified.

This search did not identify any longer-duration flares. All the data were resampled to a 10-second integration so that the search criterion was appropriate for longer-duration flares. None were found. However, with 82% of the data in this search collected between late June and early October 2015 it is consistent that a period of low activity may have existed.

In conclusion, a statistical criterion was used to isolate short-duration optical flares from random photon events. Three short-duration optical flares were identified in the B band over an 80.2-hour observing period. The three flares ranged in duration from 60 to 130 ms with peaks 0.30–0.43 magnitude above the mean, yielding a flare rate of 0.04 flare/hour. Zalinian and Tovmassian (1987), using an electrophotometer with a 0.1-second time constant, identified two simultaneous BY Dra U- and B-band "spiky flares" exceeding 3σ at less than 0.2 second duration, producing a rate of 0.22 flare/hr. While their acceptance criterion was less stringent, reasonable agreement exists between the searches.

6. Acknowledgements

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