Optical Flares and Quasi-Periodic Pulsations (QPPs) on CR Draconis during Periastron Passage

Gary Vander Haagen
Stonegate Observatory, 825 Stonegate Road, Ann Arbor, MI; garyvh2@gmail.com

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Abstract The high cadence search at a primary sampling rate of 10 samples/sec of CR Dra revealed six B-band flares totaling 7,574 seconds duration at 26 to 62 mmag peak above the mean. The search for sub-second or spike flares was also conducted with negative results. The study collected 2.5×10^6 photometric measurements over 69.36 hours from 6 July through 10 October 2017. This represents a flare rate of 0.086 flare/hour. The analysis confirmed detection of quasi-periodic pulsations (QPPs) at periods of 71, 51, 39.5–40.9, 32, 28.4, and 21.3–21.7 seconds in the 2017-10-10 flare data within the impulsive and decay phases. Published B-band flare data from 1970–2017 over the binary's two-body separation of 2.96–2.1 AU and through periastron passage were tabulated and analyzed using chi square. The analysis confirmed that there is statistical significance for flaring at periastron verses the more distant separations at better than a 95% probability level. This conclusion should be confirmed with a second more homogeneous photometric study over a similar range of linear two-body separations.

1. Introduction

CR Draconis is one of approximately 100 nearby flare stars within 25 pc, a short period young Me dwarf binary type M5.6V (Wenger *et al.* 2000); B-mag 10.9, HIP 79796. One factor making CR Dra an attractive target for research is its known orbital elements and dynamical mass, making possible correlation of periastron passage with flaring events. Tamazian *et al.* (2008) used speckle measurements to refine the previous work of Blazit *et al.* (1987) to resolve the two-body system. These data revealed a highest probability mass sum of 1.00 Ms, a dynamical parallax of 58.43 mas or 17.4 pc, an orbital period of 4.040 ± 0.005 years, and subsequent ephemeris for the system.

The young Me dwarf star systems such as CR Dra have been of great interest for many years due to their energetic flaring activity. The solar analog has been used as the astrophysical starting point for understanding this star group with recent stellar research refinements. The Me dwarf represents a powerful electromagnetic dynamo with regions of very high magnetic flux interacting with other nearby areas to form magnetic bridges, loops, or tubes, and as the turbulent surface moves causing electromagnetic discontinuities thereby releasing large quantities of energy (Vlahos *et al.* 1995). This process is enhanced by rapid body rotation and very high magnetic fields. The understanding of how these discontinuities form and release their stored energy is under study with numerous theories in play. Vlahos describes the "statistical flare," a sequence whereby many magnetic loops in a highly inhomogeneous region are interacting, with random discontinuities releasing energy and others reforming. This energy release shows up as flares of varying intensity covering a wide range of wavelengths from x-ray to the longer visible wavelengths. This dynamo activity decreases as a star's temperature increases (Candelaresi *et al.* 2014), thereby the greater flaring activity of the young, lower temperature M-stars.

There is another flaring mode that shows up in both Sun and stellar studies, a sequence of fast quasi-periodic pulsations (QPPs) or oscillations (QPOs) that are not confined to either high or low energy flares (Doyle *et al.* 2018). Recent work on magnetically active M stars, including CR Dra, have shown QPPs occurring during both the impulsive and decay phases of flare activity. These pulsations modulate the flare intensity over a widely varying range of 16.2 ± 15.9 min., with the solar counterpart less than 0.1 times the length. The periods of such amplitude pulsation range from 20 to 100 seconds intermixed within the same flare and occur during either the impulsive or decaying phase or both. Doyle *et al.* propose that an understanding of the QPP and MHD modes (magnetohydrodynamic modes) may be linked. The MHD modes are current sheets or tubes with high currents surrounded by a toroidal magnetic field. In solar research these MHD tubes loop into the chromosphere and may exhibit several distinct types of waves: Alfven or magnetic tension components parallel to the magnetic field, slow magneto-acoustic waves with plasma compression and parallel to the magnetic field, or fast magneto-acoustic waves with plasma and magnetic pressure and not oriented to the magnetic field. The relationship between QPP and the MHD modes is still under study with no firm conclusion.

Research by Zalinian and Tovmassian (1987) and further work by Tovmassian *et al.* (1997) reported stellar optical spikes or sub-second flares. These flares are not necessarily associated with any long-duration events and may be single occurrences or several in a cluster ranging from mmag to high-energy events. Similar solar events are reported from x-ray to visible wavelengths, with their mechanism still debated. The most prevalent theory for the solar x-ray to radio emission types is interactions among electromagnetic fields, coronal plasma, and high energy accelerated particles in a synchrotron type process. No literature could be identified on the physical mechanism for optical solar spikes or those on young M dwarfs.

A final related event is coronal mass ejection (CME), a separate but related phenomenon whereby flares and CMEs can occur with or without the other. The CME causes mass loss and a likely change in the local stellar environment. Here, a magnetic flux tube's rapid expansion is theorized to produce shock waves that eject material and energetic particles from the inner corona outward at over 1,000 km/sec to distances as far as 1 AU, thus producing potential magnetic field interaction between the components of a binary system as distant as two AU. This phenomena and associated flaring activity will be of interest in binaries as they approach periastron (Tamazian *et al.* 2008).

As evidenced from the previous discussion, numerous astrophysical flaring theories have evolved, many as direct extensions of the solar knowledge base, with their extension to stellar flaring still in flux with no cohesive view that unifies the physical mechanisms for flares in the Me dwarf stars.

2. Research objectives

The research objectives were to extend the knowledge of CR Dra by the following means: 1) collect high cadence photometric data for detection of any sub-second or longer flare events; 2) analyze the photometric data looking for QPPs; 3) determine any correlation between orbital phase and flaring activity during periastron passage.

3. Optical system, data collection, and analysis tools

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 sensitivity comparable to a standard single channel vacuum photomultiplier yet a more robust mechanical and electrical design with the disadvantage of higher dark counts. The complete optical system and the data collection and reduction pipeline are discussed in detail in Vander Haagen and Owings (2014). The data pipeline produces an integrated file with all constituents ready for analysis, each file containing up to one million data lines containing a GPS synced UT stamp, target photon count, reference, and background data. Using a 500-nm low pass filter combined with the SPM response, the resultant band pass approximates standard B band. The B band was chosen since CR Dra emits greater flare energy at shorter wavelengths (Cristaldi and Longhitano 1979). The U band would have been the best choice for low-level flare detection but the SPM detector has very little response in that region.

The large photometric files from each night's run were analyzed using signal-processing software (SignalLab 2017). SignalLab software, SIGVIEW 3.1, is an analysis program capable of quickly handling files up to 10^6 lines of time-based data. Any portion of the data can be reviewed nearly instantly with a powerful suite of tools: statistical analysis, smoothing, averaging, filtering, resampling, probability distributions, FFTs including spectrograms (FFT segmented over time), and complex calculation capability for correlation and convolution, to mention a few. These data were inspected for potential flares using statistical techniques, resampled for better detection and analysis of longer flares, and viewed using digital filters and FFT for detection of possible periodic occurrences.

4. Flare search and QPP analysis

The first research objective was to collect high cadence photometric data for detection of any sub-second or longer events. The detection of very short or spiky flares is of particular interest to this researcher and represents a potentially fruitful area for better understanding of high speed flaring mechanisms where little data have been collected or research has taken place. Sub-second photometric events have been reported on M dwarfs, MK, and RS CVn stars. Short or spike flares as short as 10 to 100 ms duration have been observed unconnected with longer 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 on EV Lac in the U–B band by Zhilyaev *et al.* (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 mag above the mean.

The criterion was developed to isolate short duration flares in very large sample sizes (Vander Haagen 2015). The flares must consist of a minimum of three consecutive data points, two at or above 3σ and one at or above 5σ. Normal distribution statistics were used since the number of photons always exceeded 100. Statistics were collected 600 seconds prior to the event where possible using digital signal processing software (SignalLab 2017). The probability of this sequence being a random event is 5.2×10^{-13} N, where N is the number of integrations or samples taken during the observing interval and σ is for the positive events only. 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.

The search for slower or longer flares with flux change of 100 mmag or less was best served by resampling to a longer gating period, typically 1 to 5 seconds, thereby improving S/N ratios.

Data collection was conducted over a period 6 July 2016 through 10 October 2017. Figure 1 shows the spans in nightly data collection times in UT seconds and the dispersion over the dates. The total data collection time was 69.4 hours or 249.8 Ksec, comprising 2.5×10^6 data points. No sub-second or spike flares were detected using the statistical criteria over the full measurement data set.

Published photometric studies have been conducted on CR Dra over twelve occasions from May 1968 (Cristaldi and Rodono 1970) through October 2016 (Vander Haagen 2017). The historical flare data are summarized in Table 1, which also includes the latest data from this study. The very limited historical flare data were superimposed on the calculated orbital positions (Tamazian *et al.* 2008), and revealed "no plausible correlation between flaring activity and linear distance between components." However, no data had been collected any closer than 2.47 AU separation. During phase one of this study photometric data at two-body linear separations over 2.42–2.75 AU were added to the knowledge base (Vander Haagen 2017), with the full separation ranging 2.1 (periastron) to 2.95 AU. A single flare was identified on 2016-09-27 of 30 mmag, 4.1σ, and 560 seconds duration at a linear separation of 2.48 AU (corrected).

Six long-duration flares were detected as previously summarized in Table 1. The two shown in Figures 2 and 3 were

Table 1. Summary of the published flaring activity on CR Dra over the years 1968 through 2017.

Observation Date(s)	*No. Flares, Band*	*Linear-Distance (AU)*	*Flare Rate (fl/h), Total Hours (h)*	*Reference*
1968 May 28–July 14	0, U, B	2.34–2.59	0	Cristaldi and Rodono (1970)
1970 May 11–June 18	6, U, B	2.45–2.52	[1]	Cristaldi and Longhitano (1979)
1971 July 1	1, U, B	2.95	[2]	Cristaldi and Rodono (1973)
1974 June 7	1, B	2.47	0.025, 39.4	Kareklidis *et al.* (1977)
1974 June	0	2.47	—	Mahmoud (1991)
1975 June–August	0, B	2.93–2.96	0, 46.9	Mahmoud *et al.* (1980)
1978 May 10–17	1	2.41	—	Anderson (1979)
1980 July 19–20	0	2.41	0	Ambruster *et al.* (1987)
1991 June	0 (ROSAT)	2.95	0	Tsikoudi and Kellett (1997)
2007 March–July	0	2.78–2.93	0	Tamazian *et al.* (2008)
2007 April–July	20, U	2.83–2.92	0.69, 29.1	Dal (2012)
2016 May–Oct	1, B	2.42–2.75	0.016, 64.2	Vander Haagen (2017)
2017 July–Oct	6, B	2.17–2.1	0.086, 69.4	this study

Notes: 1. Six flares with estimated total duration of 153 seconds, no total monitoring time cited.
2. One 1,080-second flare, no total monitoring time cited.

detected on 11 September 2017, at 36 mmag peak, 7.9σ, and 1,800 sec duration. Figures 4 and 5 show the second flare series detected on 10 October 2017, separated into four interlaced flares reaching a peak of 62 mmag, 12.2σ at 9,696 sec UT and total duration of 5,774 sec.

The second research objective was to analyze the photometric data looking for possible QPPs. The review of data for QPPs was problematic due to the low S/N and very turbulent atmospheric conditions present. The FFT spectrogram searches employed SIGVIEW 3.1 with the total number of samples set at 16,384 and the number of time analysis segments set to 732. The results were tested for 95% confidence. From work by Doyle *et al.* (2018) the QPP periods prevalent in CR Dra were 20, 43, 60, and 110 secs, with similar Me stars also exhibiting 25- to 39-sec periods. Figure 6 shows the 2017-10-10 flare sequence. During the impulsive phase of flare #1 QPPs were exhibited with a 21-sec period followed by 28.4-, 54-60-, 71-, and 110-sec periods during the decay phase. A second burst in the flare #1 decay phase occurred with a 39.5- to 40.9-sec period. Flare #2 exhibited an impulsive flare of 51-sec period followed by a decay phase event of 32-sec period. The 21-, 39.5–40.9-, 54–60-, and 110-sec QPPs range 492 ± 100 sec in duration. Those reported by Doyle *et al.* (2018) are shown with an (*). Reviewing the spectrogram data of Figure 6, the QPPs longer than 28.4-sec period were not separable from atmospheric noise prevalent prior to the flaring events. The noise contribution was better understood by using the second channel of photometric data, the reference/guide star measurements with a cadence of 10 sec. These data were reviewed using a Sigview FFT-spectrogram as shown in Figure 7. The data show periods from 31 to 250 seconds versus the UT time in seconds. The turbulent regions are noted by the darker blue color with light blue and whites 3 to 15 times lower power spectral density (PSD) than the dark blue. The PSD contrast can be seen in the turbulent regions pre-flare on Figure 6, e.g., at 3800 UT. With these data the periods of 71, 51, 39.5–40.9, 32, 28.4, 21.3–21.7, and 32 seconds are not affected by atmospheric turbulence. However, potential QPP periods of 54–60 and 110 seconds are not separable from the atmospheric noise. There is partial correlation with Doyle's data at periods of 21.3–21.7 and 110 seconds unconfirmed. It is important to note that the body of knowledge of QPPs is very limited and the variability is unknown.

5. Periastron passage and flare activity

The third research objective was to determine any correlation between orbital phase and flaring activity during periastron passage. Figure 8 depicts the two-body phase diagram and data collection range for each study cited in Table 1 where sufficient data were available, e.g., flares detected if any and total time of study is known. It is hypothesized that there is a relationship between flaring and the two-body linear separation, that is, "there is greater flaring at periastron passage than at more distant separations." Assume that alpha = 0.05, or a 5% chance or less is allowed that the hypothesis is incorrect. For normal and ordinal data chi square is used as a test for statistical significance. The observational data are parsed to accommodate use in the chi square contingency table (Table 3). Total flare data collection time will be converted to seconds and divided into 100-sec bins (divide total study monitoring time by 100). Flare durations will be similarly binned into 100-sec segment bins. Observation time or flare durations will be rounded off to the next higher bin, e.g., 2,020 sec will be 21 bins and every flare will generate at least one bin. This gives some weight to shorter flare durations. Using this methodology Table 2 tabulates all the B-band study data from Table 1 and classifies them into two groups, YES flares in bin or NO flares in bin, at two separation distances, one group within 3% or less of periastron and the second more distant than 2.42 AU. It is important to note that these studies were not all of same sensitivity depth, the cadence is not stated in at least one case, and they were conducted over nearly 50 years where equipment and practices differed widely even though they were all B band.

The chi square statistic can be calculated manually or using any number of available web calculators. The data for analysis and binning are shown in Table 2. The chi square results are shown inTable 3 with the input data bins in bold and the expected frequency of occurrence as (xxx) as if there were no relationship between the two-body separation and flaring.

Table 2. B-band flare data tabulation; data from four research studies with CR Dra linear separation greater than 2.42 AU and one study less than 2.12 AU, periastron passage. Binning data is placed in the contingency table (Table 3).

Researcher	*Dates*	*Two-body Separation (AU)*	*Flares, Total Hours*	*Flare Duration (sec.)*	*100s Bins*	*Flare Rate (flares/hour)*
Group over 2.42 AU linear separation						
Christaldi et al.	1970 May–Jun	2.45–2.52	6, —	153	6	—
Kareklidis	1974 Jun	2.47	1, 39.4	326	4	0.025
Mahmoud	1975 Jun–Aug	2.96–2.93	0, 46.9	0	0	0
Vander Haagen	2016 May–Oct	2.75–2.42	1, 64.16	560	6	0.016
			150.5, 541.8 Ksec 5,418 Bins	1,039	16	0.013
Periastron Passage Group						
Vander Haagen	2017 Jul–Oct	2.17–2.1	2, —	1,800	18	
			4, —	5,774	58	
			69.4, 249.8 Ksec 2,498 Bins	7,574	76	0.086

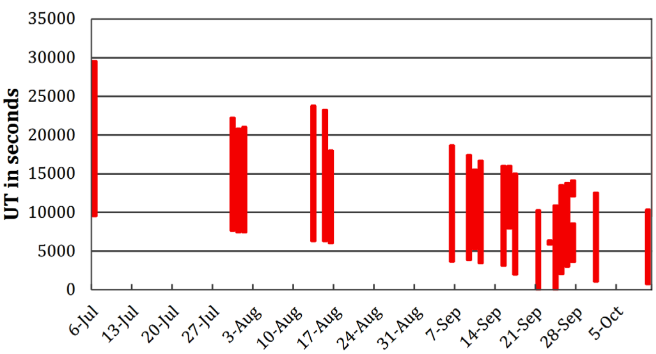

Figure 1. CR Dra photometry 2017 date versus data collection span in UT seconds (e.g., 3,601 sec UT = 01:00:01 UT).

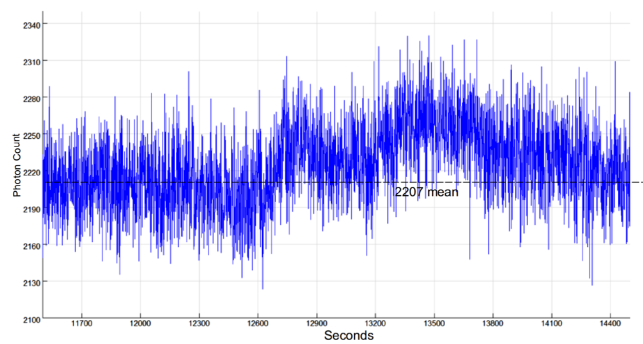

Figure 2. 2017-09-11 flare, time in UT seconds versus photon count, 10 samples/sec flares resampled at 1 sample/sec; 2-flare sequence, pre-flare mean 2,207, σ 28.

Comparing the actual flaring frequency with expected frequency show very significant differences. The [xxx] values are the calculated chi square statistic for each cell. Interpretation of the statistic requires looking up the normal distribution of chi square for a contingency table of two rows and two columns (degree of freedom = 1, (#rows-1) × (#columns-1)), and an alpha of 0.05. The value from the table is 3.841. The contingency tables total (112.3) must exceed the table value for statistical significance. This indicates that there is statistical significance of flaring at periastron verses the most distant data at better than a 95% probability level.

Revisiting Table 1, it is noted that a very high flare rate of 0.69 flare/hr was reported by Dal (2012) at 2.83–2.92 AU, which seems to contradict the results reported at periastron of 0.086 flare/hr. Note that these flares were detected in the U band. Data from Cristaldi and Longhitano (1979) on CR Dra in both U- and B-bands show a U/B flux ratio of 6 and on other similar stars more than 7. This places many of the flares in the Dal study below the detection threshold of this study and does not permit flare rates comparisons.

However, without a reasonable astrophysical flaring model for the Me dwarf and exacerbated by a void of any supporting literature on optical flaring of another Me dwarf of comparable orbital elements during periastron, the meaning of the statistical significance takes on uncertainty. A future study to confirm the statistical significance of flaring at periastron should include collection of homogeneous photometric data, B band with similar depth exposures, and collection system over a large portion of the orbital path. CR Dra and several other shorter-period nearby flaring binaries with resolved orbital elements would be likely candidates, such as CE Boo or EZ Aqr.

6. Conclusions

A high cadence photometric search was undertaken at 10 samples/sec. No sub-second or spike flares were observed in 2.5 × 10^6 photometric measurements over 69.36 hours from 6 July through 10 October 2017. Six long-duration flares were observed producing a flare rate of 0.086 flares/hr: on 2017-09-11, two flares with total of 1,800-sec duration, 36 mmag, 7.9σ, and on 2017-10-10 a second sequence of four flares of 5,774 sec duration peaking at 62 mmag and 12.2σ. The photometric data were further reviewed using FFT spectrograms to determine if QPPs were present during flaring events. The analysis confirmed that components at periods of 71, 51, 21.3–21.7, 28.4,

Table 3. Chi square calculation to determine statistical significance. The contingency table provides the following information: in bold, the input data on flare binning totals from Table 2; from the chi square calculation (the expected cell totals) and [the chi square statistic for each cell].

	Less than 2.17 AU		*Greater than 2.42 AU*		*Marginal Row Totals*
YES flare in 100 sec bin	**76**	(29.03) [75.99]	**16**	(62.97) [35.03]	92
NO flare in 100 sec bin	**2,422**	(2,468.97) [0.89]	**5,402**	(5,355.03) [0.41]	7,824
Marginal Column Totals	**2,498**		**5,418**		7,916 (Grand Total) [112.3]

Note: The sum of the chi square [statistic] from above is 112.3. For significance this calculated chi square statistic must exceed the normal distribution chi square, or 3.841 for an alpha of <0.05. This indicates the result is significant with less than 5% probability of error. This is a pass/fail criterion and does not denote strength of significance.

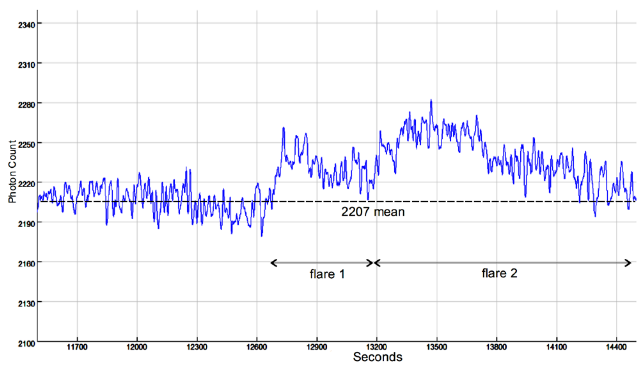

Figure 3. 2017-09-11 flare, time in UT seconds versus photon counts. Figure 2's 1 sample/sec data were smoothed; pre-flare mean 2207, σ 9.6, 1,800 sec total duration; 2-flare sequence, first peak of 2,261 at 12,733 sec, 26 mmag, 5.6σ; second peak of 2,282 at 13,473 sec, 36 mmag, 7.9σ.

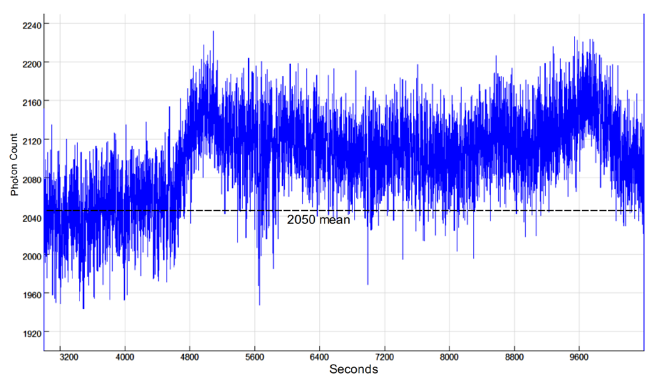

Figure 4. 2017-10-10 flare, time in UT seconds versus photon count, 10 samples/sec, 4-flare sequence resampled at 1 sample/sec; total duration 5,774 sec, pre-flare mean 2,050, σ 32.7.

39.5–40.9, and 32 sec were present in the 2017-10-10 flare data during the impulsive and decay phases. However, potential QPP periods of 54–60 and 110 seconds were not separable from the atmospheric noise. All the reported flare data for CR Dra were tabulated and entered into a chi square Contingency Table to determine the statistical significance of flaring at periastron passage. The chi square analysis confirmed to better than 95% probability that the higher flare rate at periastron was of statistical significance with the caveat previously noted.

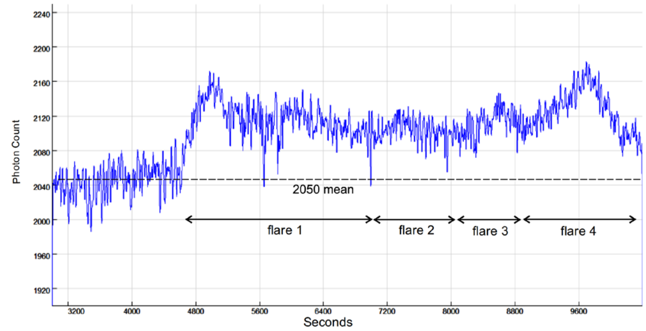

Figure 5. 2017-10-10 flare, time in UT seconds versus photon count. Figure 4's 1 sample/sec, 4-segment flare, smoothed; total duration 5,774 sec, pre-flare mean 2,050, σ 9. See Table 4.

Table 4. 2017-10-10 flare. See Figure 5.

	Peak UT (sec.)	*mmag*	*σ*	*Duration (sec.)*
1st	4,981	55	10.8	2,372
2nd	7,331	34	6.7	1,030
3rd	8,608	42	8.2	878
4th	9,696	62	12.2	1,494
				Total 5,774

7. Acknowledgements

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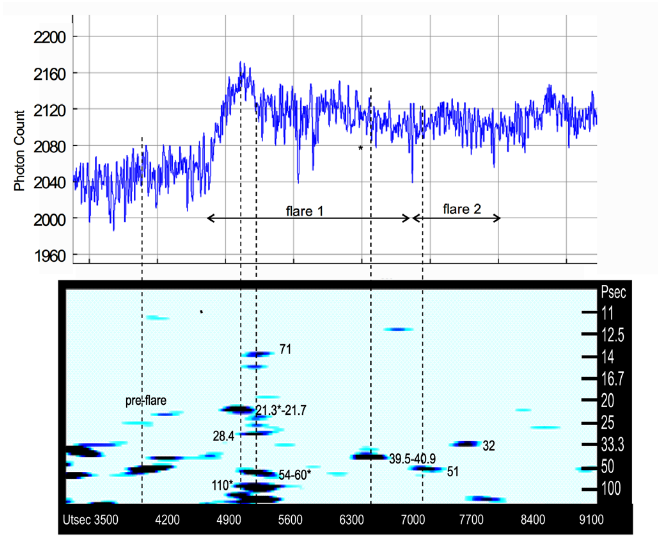

Figure 6. Upper panel: 2017-10-10-flare photon counts, time aligned with FFT spectrogram. Lower panel: FFT spectrogram shows time in UT seconds versus QPP periods in seconds. Flares cited by Doyle *et al.* (2018) are shown with (*). Periods longer than 28.4 sec were typical of the atmospheric noise spectrum just prior to the flare. No QPPs were detected in flares 3 or 4.

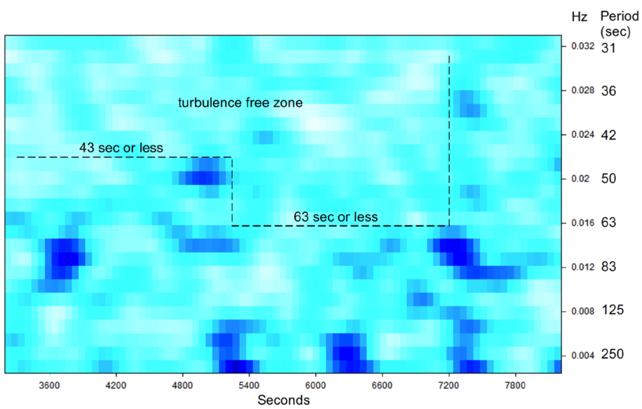

Figure 7. Spectrogram of reference/guiding camera data plotting atmospheric noise with periods between 31 and 250 seconds over the UT (seconds) time span where the QPP data were collected in Figure 6. The darker blue color represents an increase in power spectral density of 3 to 15 times over the background light blue or white, respectively. The periods identified in Figure 6 (71, 51, 39.5–40.9, 32, 28.4, and 21.3–21.7) are outside the atmospheric turbulence zone during this data collection period. Periods 54–60 and 110 seconds shown in Figure 6 are within the turbulence noise zone and are of questionable validity.

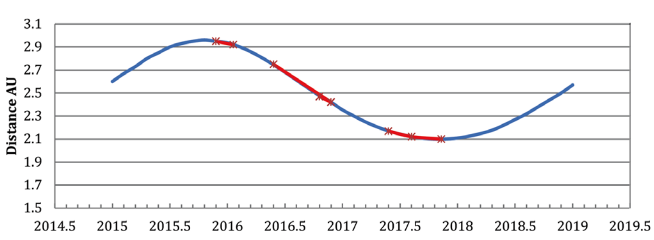

Figure 8. Date versus binary linear body separation in AU; the red-colored segments of the orbital phase are those covered by cited photometric studies. The previous studies by Kareklidis *et al.* (1977) and Mahmoud *et al.* (1980) were phased to fit on the current epoch phase diagram.

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