Frequent Flaring in the TRAPPIST-1 System—Unsuited for Life?

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Abstract

We analyze the K2 light curve of the TRAPPIST-1 system. The Fourier analysis of the data suggests \( P_{\text{rot}} = 3.295 \pm 0.003 \) days. The light curve shows several flares, of which we analyzed 42 events with integrated flare energies of \( 1.26 \times 10^{32} \)–\( 1.24 \times 10^{33} \) erg. Approximately 12% of the flares were complex, multi-peaked eruptions. The flaring and the possible rotational modulation shows no obvious correlation. The flaring activity of TRAPPIST-1 probably continuously alters the atmospheres of the orbiting exoplanets, which makes these less favorable for hosting life.

Key words: stars: activity – stars: chromospheres – stars: flare – stars: late-type – stars: low-mass – techniques: photometric

1. Introduction

TRAPPIST-1 (2MASS J23062928-0502285) is an ultracool, M8-type dwarf, which is known to host seven terrestrial planets, of which three of them have equilibrium temperatures that makes the existence of liquid water on their surface possible (Gillon et al. 2016, 2017). The discovery obviously raised the question of the planetary habitability. This involves several complex factors, one of them being the magnetic activity of the host star, as a large fraction of M dwarfs has been observed to be magnetically active. Numerous high energy events (e.g., flares) could erode the atmospheres of these worlds that are located very close to their host star and thus render them uninhabitable over time (Khodachenko et al. 2007; Yelle et al. 2008). TRAPPIST-1 indeed seems to exhibit chromospheric activity as shown by its Hα emission level (Gizis et al. 2000; Reiners & Basri 2010) and significant X-ray and EUV (XUV) radiation (Wheatley et al. 2017). Lycα observations suggest moderate activity, although the detected XUV radiation could be strong enough to strip the atmospheres of the inner planets in a few billions years (Bourrier et al. 2017). In this paper, we examine raw cadence K2 observations from the Kepler Space Telescope in order to retrieve information about its activity and impacts on habitability.

2. Observations

During this analysis, only uncalibrated (raw) K2 measurements are available to the community. In order to analyze the K2 images and extract flux variations from the raw K2 data series, we converted the uncalibrated per-pixel time series to numerous individual image files. These raw, per-cadence FITS files were converted to individual image stamps involving various tasks of the FITSH package (Pál 2012). Although the transposed version of these data (i.e., target pixel files) has been made available for TRAPPIST-1 almost immediately, we chose this approach in order to have the possibility to incorporate pointing information retrieved from the nearby stamps. Handling uncalibrated data yields more prominent systematics that are induced directly by the different sensitivity of the neighboring pixels and, hence indirectly by the pointing jitter—which is comparable with the FWHM of the instrumental PSF in the case of K2. In the following, we detail how these systematics can be reduced while the the amplitude and shape of the flare-like events are not distorted.

In total, 107968 short cadence (SC) image stamps are available for this campaign. For all of these frames, we computed the flux-weighted centroid of the target PSF and searched for discontinuities and/or outliers in the \( x \) and \( y \) positions. This particular background, readout, and shot noise level of the target star allowed us to obtain an rms of \( \sim 0.005 \) pixels in the time series of the centroid positions. We note here that this statistical rms agrees well with the per-image formal uncertainties of the centroid positions estimated directly from the aforementioned noises and the PSF shape.

By rejecting obvious cases (e.g., frames acquired during reaction wheel momentum resaturation phases) as well as individual lower quality images (affected by cosmic hits, etc.), we involved 100337 SC images for further analysis. We note here in this data series that there are 216 distinct sections where the pointing were stabilized only by the control of the two reaction wheels.

Analyzing and extracting flux variations related flare activity needs a different approach than what is used in highly precise photometric measurements (such as searching for planetary transits). This is even crucial in the case of K2 where the resaturation phases occur in periods of \( \sim 6\) hr, which is comparable to the timescales of the flares. Hence, we performed a global decorrelation of the light curve by involving a function that has a part built from sine and cosine of the fractional pixel coordinates, namely

\[
\sum_{k=0}^{N} \sum_{l=0}^{N} \left[ A_{k,l}[x,y] \cos(2\pi k \Delta x) \cos(2\pi l \Delta y) + B_{k,l}[x,y] \cos(2\pi k \Delta x) \sin(2\pi l \Delta y) + C_{k,l}[x,y] \sin(2\pi k \Delta x) \cos(2\pi l \Delta y) + D_{k,l}[x,y] \sin(2\pi k \Delta x) \sin(2\pi l \Delta y) \right].
\]

Here, \( \Delta x \) and \( \Delta y \) are the fractional centroid coordinates (i.e., \( 0 \leq \Delta x, \Delta y < 1 \)), \([x] \) and \([y] \) refers to the integer part of the centroid coordinates, and hence \( x = [x] + \Delta x \) and \( y = [y] + \Delta y \). Furthermore, we extended the decorrelation function with additional terms proportional to the fitted shape parameters.
of the PSF (in order to decorrelate against changes in the effective focal distance). Of course, the unbiased light curve rms would even be smaller by considering a different set of $A_1[1|y|\ell_0]$, $B_1[1|y|\ell_0]$ ... coefficients on each section between two subsequent resaturation phases, but here we incorporated a global fit in order to avoid any aliases from the similarities between flare events and trends arising from thruster usage. In the above procedure, we used an iterative sigma-clipping technique to perform the linear regression that yields the respective coefficients. By analyzing the obtained light curve shown in Figure 1, we found that its sigma-clipped rms is only 10% larger than the expected photometric uncertainty derived from the background, readout, and shot noise.

3. Fourier Analysis

Fourier analysis of the light curve was performed using MUFRAN\(^3\) (Kolláth 1990)—a code that can do discrete Fourier transformation of data and pre-whiten light curves with the detected frequencies. For the analysis, we used the detrended data set manually cleaned from flares and binned to 0.05 days. The resulting Fourier spectra and spectral window are plotted in Figure 2.

One important feature of the K2 data is the presence of instrumental trends. Without stabilization around the third axis, the instrument slowly rolls about its optical axis, which causes a rotation of the field of view. This is corrected by the on-board thrusters in \(\approx 6\) hr periods. These corrections cause artifacts in the Fourier spectrum at 5.87 and 5.91 hr \((f_{\text{corr}} = 4.085180 \pm 0.406396 \text{ days}^{-1})\). Our values somewhat differ from artifacts in earlier data (e.g., Pál et al. 2015), as the corrections have been refined over time. The artifacts can be identified by performing the Fourier analysis on the $x$ and $y$ coordinates of the target (also shown in Figure 2).

The most significant peak in the light curve is at $f = 0.303469 \text{ days}^{-1}$, $P_1 = 3.295 \pm 0.003$ days, as also found by Luger et al. (2017). This probably corresponds to the rotation period of the spotted star. Interestingly, Gillon et al. (2016) identified $P_{\text{rot}} = 1.40 \pm 0.05d$ from ground-based TRAPPIST photometry. This latter value is consistent with the measured $v \sin i = 6 \pm 2 \text{ km s}^{-1}$ (Reiners & Basri 2010), which yields $P_{\text{rot}} = 0.9866$ day (0.74–1.48 days with the given error) using $R = 0.117 R_\odot$ (Gillon et al. 2016) and assuming $i = 90^\circ$. However, our Fourier spectrum of the K2 light curve does not show any significant feature that indicates a similar rotation period.

After pre-whitening the light curve with this signal, a weaker peak remains with $f = 0.342994 \text{ days}^{-1}$, $P_2 = 2.915$ days. Such signals near the rotational frequency are often associated with differential rotation, however this would yield to a strong surface shear $(R_1 - R_2)/R$ of $\approx 0.12$, which is incompatible with such a rapidly rotating and actually fully convective M dwarf.

Two longer signals are also present, which correspond to 22.3 and 37.5 days, but from the $x$ and $y$ coordinates of the star we get similar signals of 25–26 days as well, and therefore the reality of these periods is questionable.

4. Flares in the Light Curve

The K2 light curve indicates strong flaring activity on TRAPPIST-1. We identified 42 flare events in the data by visual inspection of the detrended light curve. Of these events, five (12%) were complex, multi-peaked eruptions, and are plotted in Figure 3. This ratio is quite similar to that found in the much larger sample of the M4-type GJ 1243 (Silverberg et al. 2016).

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\(^3\) http://www.konkoly.hu/staff/kollath/mufran.html
4.1. Flare Energies

The energies of these events were estimated following the method of Kovári et al. (2007). This method is based on integrating the flare intensity over its duration, which yields the relative flare energy (also often mentioned as equivalent duration in the literature):

$$\varepsilon_f = \int_0^\infty \left( \frac{I_{0+} - I_0}{I_0} \right) dt,$$

where the intensity is calculated from the magnitude:

$$\frac{I_{0+}}{I_0} = 10^{\frac{\Delta m_{kp}}{2.5}}.$$

Here, \(I_{0+}\) and \(I_0\) are the intensity values of the flaring and the quiescent stellar surfaces, respectively. From the relative flare energy, \(\varepsilon_f\), the integrated energy of the flare event can be calculated by multiplying it by the quiescent stellar flux:

$$E_f = \varepsilon_f F_*.$$

The quiescent flux can be estimated if we assume blackbody radiation from the effective temperature \(T_{\text{eff}} = 2550\ K\) and radius \(R = 0.117\ R_\odot\) (Gillon et al. 2016):

$$F_* = \int_\lambda^\infty 4\pi R^2 F(\lambda) S_{Kp}(\lambda) d\lambda.$$

Here, \(F(\lambda)\) is the power function and \(S_{Kp}(\lambda)\) is the Kepler response function. The derived energies and their occurrence rates are plotted in Figure 4. The detection of the smallest flare events is limited by the light curve scatter (typically \(\approx 0.01\) mag) and mainly the sampling of the data (\(\approx 59\) s). Thus the weakest events appear only as a single measurement point; these were not analyzed as they could be of instrumental origin. The weakest analyzed event in our study has \(E_f = 1.26 \times 10^{30}\) erg, while the strongest eruption has a \(Kp = 1.78\) mag peak and produced \(E_f = 1.24 \times 10^{33}\) erg energy.

If \(dN\) is the number of flares in the energy range \(E + dE\), then the following power law can be written as

$$dN(E) \propto E^{-\alpha} dE,$$

(see e.g., Hawley et al. 2014, and the references therein). By integration, the cumulative flare frequency distribution can be expressed in logarithmic form as

$$\log \nu = a + \beta \log E,$$

where \(\nu\) is the cumulative frequency of flares with a given energy larger than \(E\), while \(\beta = 1 - \alpha\) (Gizis et al. 2017). This relationship, seen in Figure 4, can be fitted by a linear function, which gives the slope \(1 - \alpha\), where \(\alpha\) is often used to characterize how the flare energy is dissipated. The best fit yields \(\alpha = 1.59\), which suggests that TRAPPIST-1 flare energies are mostly nonthermal (cf. Aschwanden et al. 2016), and are similar to other very active M dwarfs in the

Figure 3. Light curves of the five complex flare events.

Figure 4. Cumulative flare frequency distribution fitted by a linear function.
the possible rotational modulation of 3.295 days. The green line shows a median of the data. Bottom: Histogram showing the occurrence rate in different phases.

Hawley et al. (2014) sample. The flare energies detected on TRAPPIST-1 are somewhat higher to those found on the other nearby planet-hosting M5.5-class Proxima Centauri, where Davenport et al. (2016) reported eruptions with $10^{29}-10^{31.5}$ erg energies based on MOST observations, with a similar flaring activity characterized by $\alpha = 1.68$.

4.2. Possible Connection between Flares and Spotted Regions

If we accept the dominant signal in the Fourier spectrum ($P_1 = 3.295 \pm 0.003$ days) as a modulation caused by the rotation of the spotted surface, we can evaluate if there is any connection between cool surface spots and flaring activity that could indicate a connection of photospheric and chromospheric activity, as seen on the Sun and also found on other stars (e.g., on the BY Dra-type EY Dra, Korhonen et al. 2010; or V374 Peg, Vida et al. 2016; and other BY Dra-type stars, Pandey et al. 2005; on the K-dwarf PW And, López-Santiago et al. 2003; RS CVn-type binaries, e.g., II Peg, and $\lambda$ And, Frasca et al. 2008; and on the W UMa-type VW Cep, Frasca et al. 1996).

In Figure 5 we plotted the light curve phased with the following ephemeris:

\[
\text{HJD} = 2457738.362703 + 3.295 \times E.
\]

With this phasing, we find that flares can be found at every phase, although they are somewhat more frequent at the light curve minimum (around phase 0.25), i.e., where the surface spottedness is higher. Interestingly, the strongest flares seem to appear around the light curve maximum (phases 0.55–0.75). This behavior is very similar to the somewhat hotter, but still fully convective, M4-type V374 Peg (Vida et al. 2016).

4.3. The Complex Flare Event at HJD 2457812

The light curve shows several complex flare events (as shown in Figure 3), of these the largest occurred at HJD 2457812 (on day 74 in the light curve). This event consisted of three large eruptions and at least two smaller ones. We fitted the event with the sum of three separate analytical flare models following the method and parametrization described in Davenport et al. (2014), as shown in Figure 6. After the subtraction of the fit from the light curve, two smaller eruptions are suspected on the decay phase of the complex event (see the inset in Figure 6).

It is possible that this complex flare was triggered by an earlier event. Such events, called sympathetic eruptions, are often seen on the Sun, but they were also observed on other stars (e.g., Vida et al. 2016 and references therein). Since the median waiting time between consecutive flares on TRAPPIST-1 is 28.1 hr, and the two smaller flares occurred approximately 7.7 and 3.4 hr before the main eruption, they are likely connected with each other. One interesting and similar example that is known in details is the 2010 August event on the Sun, which was modeled by Török et al. (2011). According to the model, these sympathetic flares are triggered by nearby eruptions in an appropriate magnetic field structure of the corona.

5. Discussion

Venot et al. (2016) examined the possible influence of stellar flares on the orbiting exoplanets and their atmosphere. The basis of their analysis was the great flare on AD Leo in 1985 that was observed in high detail with both UV spectroscopy and high temporal resolution multi-passband photometry (Hawley & Pettersen 1991). That complex flare event on AD
Leo, which by chance has very similar light curve shape to the largest flare seen in the K2 light curve of TRAPPIST-1, which has an amplitude of $V \approx 0.5$ mag. Venot et al. (2016) concluded that atmosphere of the two super-Earth-like hypothetical planets, which would orbit AD Leo, would be altered irreversibly and significantly after such an eruption. Their model suggests that the post-flare steady state would only return on the scale of $\approx 30,000$ years, and thus the planetary atmosphere would be constantly altered by eruptions due to the high flaring rate. Although the flaring frequency on TRAPPIST-1 is somewhat lower than on AD Leo, the flaring rate derived from the K2 data suggests that the planetary atmospheres in the TRAPPIST-1 systems would not have a steady state, which is disadvantageous for hosting life.

These eruptions pose a threat to habitability, since during a flare the UV radiation level is also increased, which can both erode planetary atmospheres on the long term and directly harm life on the surface. Segura et al. (2010) suggested that stellar flares do not necessarily directly affect the habitability as much of the UV radiation can be absorbed by photochemical reactions in the stratosphere (supposing an Earth-like atmosphere), which would prevent it from reaching the planetary surface. However, the authors also suggested that due to the repeated flare events, the atmosphere of the planet can be continuously disturbed—these long-term effects still need to be understood. Such UV absorbers, like ozone in the planetary atmosphere, can reduce the negative effects of the flares—the detection of such atmospheric features would suggest that the planets are more likely to have habitable environments (Rugheimer et al. 2015; O’Malley-James & Kaltenegger 2017).

We can also do a rudimentary estimation how such an eruption temporarily changes the limits of the habitable zone based on the model of Kopparapu et al. (2013). In quiescent state of TRAPPIST-1, the conservative habitable zone for a 1-Earth mass planet spans between 0.024 and 0.049 au ($T_{\text{eff}} = 2550$ K, $L/L_\odot = 0.000525$). During the flare, supposing $1–1.5$ mag brightening of the star results in an increased luminosity of $L/L_\odot = 0.0013–0.0201$. These values yield to the habitable zone limits of 0.038–0.077 and 0.048–0.097 au respectively, a very significant change. Of course, the short timescale of a flare is too brief to significantly change surface temperatures of the planets or actually shift the habitable zone boundaries, although the possible cumulative effect of flaring may still change the habitable zone boundaries compared to the conservative models that take into account only the quiescent stellar flux. Our simple estimation illustrates the magnitude of energy changes in the planetary system, which is caused by the increased stellar energy output during a strong flare. This very crude calculation also indicates that habitability around TRAPPIST-1 and similar late-type dwarfs could be questionable. However, further spectroscopic observations of the TRAPPIST-1 system could help us to understand how the magnetic activity of the host star influences planetary atmospheres and how it possibly interacts with their magnetic field.

It is possible, however, that a sufficiently strong magnetic field of the orbiting exoplanet could shield the atmosphere from the harmful effects of such eruptions. Kay et al. (2016) found that for typical coronal mass ejection (CME) masses and speeds measured on M dwarfs, the orbiting rocky planets would need magnetic fields between tens to hundreds of Gauss, while hot Jupiters would only require magnitudes between a few and 30 G. The authors concluded that rocky exoplanets possibly could not generate a sufficient magnetic field to shield their atmosphere from these eruptions (e.g., Earth exhibits a magnetic field of $\approx 0.5$ G). According to Vidotto et al. (2013), planetary magnetic fields should be stronger. An Earth-like planet in the habitable zone around an M dwarf should have magnetic fields of the order of $\approx 10^5$ Gauss in order to possess a magnetosphere comparable to that of the present-day Earth.

Moreover, typical solar flares release energies of the order of $10^{27}–10^{32}$ erg. One of the most energetic event, known as the “Carrington Event” in 1859, released about $10^{31}$ erg energy and resulted in one of the strongest geomagnetic storms to reach the surface of the Earth. Such powerful flares (and possibly those related CMEs) on TRAPPIST-1 occur more often and hit the planetary surfaces from much shorter distances of $\approx 0.011–0.063$ au (Gillon et al. 2017). This implies that magnetic storms in the TRAPPIST-1 exoplanetary system can be $10^2–10^4$ times stronger than the most powerful geomagnetic storms on Earth, which also would question the existence of a complex, highly organized life in this system.

The flaring activity of the TRAPPIST-1 system does not necessarily rule out the existence of life, but it raises doubts of hosting life as we know it on Earth. The conditions in the TRAPPIST-1 system are probably rather hostile for an Earth-like biosphere, but even on Earth there are organisms that can tolerate extreme conditions. It is possible that biota of the TRAPPIST-1 system can survive the activity of the host star by living underground or underwater, or for example by using photoprotective bioluminescence as theorized by O’Malley-James & Kaltenegger (2016). However, the constantly changing planetary atmospheres will make the detection of biomarkers much more difficult.

These questions on habitability are important since the estimated age of TRAPPIST-1, which is at least 500 Myr (Filippazzo et al. 2015; Luger et al. 2017 estimated 3–8 Gyr), could possibly make the formation of life in ideal conditions, as the earliest life on Earth dates back to approximately 4 Gyr (Dodd et al. 2017), although complex life took much longer time to form (see Grosberg & Strathmann 2007 and references therein).

6. Summary

1. The Fourier spectrum of the light curve indicates a possible rotation period of $P_{\text{rot}} = 3.295 \pm 0.003$ days.
2. The light curve shows several flares with integrated flare energies of $1.26 \times 10^{30}–1.24 \times 10^{33}$ erg, of these $\approx 12\%$ are complex and multi-peaked.
3. We did not find an obvious correlation between the spottedness and flaring activity.
4. The frequent strong flares of TRAPPIST-1 are probably disadvantageous for hosting life on the orbiting exoplanets, as the atmospheres of the exoplanets are constantly altered and cannot return to a steady state, however this magnetic activity does not necessarily rule out the possibility of life.

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