The view from K2: Questioning the traditional view of flaring on early dM stars

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ABSTRACT

We use K2 short cadence data obtained over a duration of 50 days during Campaign 0 to observe two M1V dwarf stars, TYC 1330-879-1 and RXJ 0626+2349. We provide an overview of our data analysis, in particular, making a comparison between using a fixed set of pixels and an aperture which follows the position of the source. We find that this moving aperture approach can give fewer non-astrophysical features compared to a fixed aperture. Both sources show flares as energetic as observed from several M4V stars using both Kepler and ground-based telescopes. We find that the flare energy distribution of the sources shown here are very similar to the less active M3–M5 stars but are \( \sim 8 \) times less likely to produce a flare of a comparable energy to the more active M0–M5 stars. We discuss the biases and sources of systematic errors when comparing the activity of stars derived from different instruments. We conclude that K2 observations will provide an excellent opportunity to perform a census of flare activity across the full range of M dwarf spectral class and hence the physical mechanisms which power them.

Key words: Physical data and processes: magnetic reconnection – stars: activity – Stars: flares – stars: late-type – stars: individual: TYC 1330-879-1, 1RXJ 062614.2+234942

1 INTRODUCTION

The Kepler satellite provided a unique resource to study the activity levels of stars over a wide spectral type. Such observations can help address questions such as why there is a marked change in activity levels around spectral type M4 (West et al. 2008). We initiated a campaign using Kepler in Q14 to observe M dwarfs over a range of spectral type and in Ramsay et al. (2013) we reported observations of two M4V stars which showed strong flare activity.

However, the loss of two of Kepler’s four reaction wheels limited the accuracy with which it could be pointed, with a resulting degradation of the photometric accuracy. NASA, in collaboration with the spacecraft manufacturers Ball Aerospace, were able to re-design the mission so that by pointing at fields in the ecliptic plane, the roll of the spacecraft is minimised. Pointing stability is achieved by the firing of micro-thrusters. The Kepler team found that K2 (which the mission has now been renamed) can deliver photometry which is accurate to within a factor of 2–4 of the original Kepler data (see Howell et al. 2014, Vanderburg & Johnson 2014 and Aigrain et al 2015).

K2 will provide a unique set of observations which (with additional complementary data) will provide a basis for determining how the activity of stars, including late type dwarfs, is related to mass, rotation, age and metallicity. During an engineering test of K2 early in 2014, observations were made of the M4.5V flare star AF Psc with a cadence of 30 min (Ramsay & Doyle 2014). These tests showed step-like features could be present in the light curves due to limitations in the pointing stability, and that care had to be taken to correctly distinguish stellar flares from instrumental artifacts.

Here we present K2 observations of two M1V stars in ‘Campaign 0’, which were the only M dwarf stars to be observed with 1 min cadence in this campaign. We outline the issues we faced in analysing the data and make a comparison with light curves extracted using Kepler software and a well-established photometric package where the aperture...
was allowed to move over the pixel array during the course of the observation. We compare the flare activity of these M1V stars with the previously observed M4V stars together with a range of M dwarfs of varying activity levels as observed from ground based telescopes.

2 TARGETS

We performed a search for late type dwarfs in the Campaign 0 field of view. The catalogue of bright M dwarfs of Lépine et al. (2013) gave two sources which were in Field0 and ‘on-silicon’. TYC 1330-879-1 (hereafter TYC1330) is a M1.0V dwarf (V = 11.6) and 1RXJ 062614.2+234942 (hereafter RXJ0626) is an M1.5V dwarf (V = 11.8). TYC1330 is ∼ 20 pc distant and RXJ0626 is ∼ 30 pc distant. (see Table 1 for the key parameters for both sources).

3 K2 DATA

The K2 Campaign 0 was carried out between MJD = 56728.0 – 56804.7 (2014 Mar 12 – 2014 May 27). However, there were two gaps in the data and the resulting coverage was 50.0 days. (This compares with 8.9 days for the engineering test data). We call the three contiguous sets of data sections 1, 2 and 3. During sections 1 and 2, K2 was operated in ‘coarse’ pointing, whilst during section 3 it was operated in ‘fine’ pointing during which the resulting photometric precision being a factor of two better. Observations of TYC1330 and RXJ0626 were made in short cadence (SC) where the effective exposure is 58.8 sec (long cadence data which has an exposure of 30 min is also available).

During Campaign 0 a 50×50 pixel array was downloaded for each target and 73470 individual images were obtained for each source. To correct for the drift in the satellite pointing, thrusters are used to periodically re-saturate the reactions wheels. This results in a significant movement in the targets position on the array every ~2 days and it can take around a dozen or more SC images for the pointing to stabilise. Vanderburg & Johnson (2014) outline a technique to remove the effects of correlated systematic variations. As a service to the community they have provided light curves for all LC data (but not SC data) taken during Campaign 0.

Since data reduction of K2 data is more complex than that of Kepler data, we have compared the results of extracting light curves from the SC datasets using the PyKe software (Still & Barclay 2012) which was developed for the Kepler and K2 mission by the Guest Observer Office with a well established aperture photometric package (AUTOPHOTOM, Eaton, Draper & Allan 2009) which is part of the STARLINK software collection. In each approach we analysed each section separately then combined the resulting light curves. We used K2 data from Data Release 2.

Using kepmask and kepextract (which are part of the PyKe suite of tools) we extracted a light curve using data from pixels centered on the target. We explored using different numbers of pixels and found that clear discontinuities are seen when smaller number of pixels are used. However, beyond a certain number of pixels, the noise in the resulting light curve increases. At this stage in the reduction, a distinctive modulation in each target star was apparent, which we took to be the stellar rotation period. To remove the effects of this modulation we used kepflatten. It is now possible to remove much of the correlated noise in the light curves using kepflatten which was developed using the method outlined in Vanderburg & Johnson (2014). The light curve produced after each step of the process is shown in Figure 1. Data have been normalised so that it is divided by the mean of each section of data. Considerable time was spent in selecting optimal parameters for the different PyKe tasks. However, as is clear from the second lower panel of Figure 1 there are features in the light curve which may due to the result of an imperfect removal of the signature of the stellar rotation period or the presence of residual systematic trends in the data.

We then used AUTOPHOTOM which has been used by several groups over many years to analyse ground based images (Eaton, Draper & Allan 2009). Images were extracted from the SC data file using kepimages. Epochs of thruster events were easily identified since the mean pixel value for these events was zero. These images and the next 24 images were not considered further in our analysis since the spacecraft pointing took some time to stabilise.

To extract photometry we used an aperture of fixed size and allowed the center of the aperture to track any movement of the star across the pixel array. We also defined a source free region which tracked the movement of the star across the pixel array. We also defined a source free region which tracked the movement of the star across the pixel array. We also defined a source free region which tracked the movement of the star across the pixel array.

In previous papers we have pin-pointed flares in the light curve derived using kepflatten as done before. Although the rms of the resulting light curves derived using AUTOPHOTOM and PyKe tasks are very similar, the former has fewer features which are likley to be instrumental. For instance, the last 2 days of the light curve shown in Figure 1 (i.e. immediately after the flare at Day ~ 4.5 to the end) has an rms of 0.084 percent using AUTOPHOTOM (the bottom panel of Figure 1) compared to 0.089 percent using PyKE (second from bottom panel). For the remainder of the analysis we used the light curves derived using AUTOPHOTOM and subsequent removal of the long term trends due to stellar rotation.

In previous papers we have pin-pointed flares in the light curve by flagging all times which were above a certain threshold above the mean. However, given the presence of discontinuities in some parts of the light curves, in this study we identified potential flares by examining the light curves by eye. This is a tractable approach since our sources do not exhibit vast numbers of flares and we have only two sources to examine. Moreover, since we had two simultaneous SC

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1. http://keplerscience.arc.nasa.gov/K2/Performance.shtml
2. http://keplergo.arc.nasa.gov/PyKE.shtml
3. http://starlink.jach.hawaii.edu/starlink

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Table 1. We show the K2 Ecliptic Plane Input Catalog (EPIC) number of our targets; their sky co-ordinates; their KepMag (all taken from the EPIC catalog which can be accessed from [http://archive.stsci.edu/k2/epic](http://archive.stsci.edu/k2/epic)). The optical spectral type, spectroscopic and photometric parallaxes and the equivalent width of the Hα line are all taken from Lépine et al. (2013). The rotation periods are derived from the K2 data.

| Star        | EPIC ID (J2000) | RA (J2000) | DEC (J2000) | Kep Mag | Spectral Type | Spec Parallax (pc) | Phot Parallax (pc) | Hα EW (Å) | Period (days) |
|-------------|----------------|------------|-------------|---------|---------------|-------------------|-------------------|-----------|--------------|
| TYC 1330-879-1 | 202059229 | 06:46:45.6 | +15:57:42.1 | 10.5     | M1.0V         | 22.7±4.8          | 16.7±3.9          | -0.6      | 5.04         |
| RXJ 0626-1-2349 | 202059204 | 06:26:14.5 | +23:49:28.5 | 11.3     | M1.5V         | 28.6±5.9          | 31.3±6.9          | -0.7      | 7.90         |

Figure 1. The light curve of TYC1330 derived from section 2 data made using different approaches and stages in the analysis. In the upper panel we show the light curve made using a moving fixed aperture photometric package (Autophotom). In the lower panels we show the light curve derived using the Kep tool kepextract followed by the removal of the long term trend (kepflatten) and the removal of systematic trends using kepff. In the bottom panel we show the light curve derived using Autophotom after long term trend and systematic trends have been removed.

light curves, if an event was seen in both light curves it was deemed instrumental and not considered further, as was also the case for events consisting of one time point. As kepff identifies and flags times of thruster events (and other instrumental effects), we removed any event which was within two dozen images of these events using the SAP QUALITY flag. For both stars, 31 flares were detected. We show the five most luminous flares identified in each star in Figure 2.

Each of the events which we have identified as flares have a characteristic stellar flare profile – i.e. a sharp rapid rise to maximum followed by a quasi-exponential decay. The rise to maximum has been resolved and typically takes 1–5 mins. The duration of the flares are typically ~10–20 mins, while in one event, (TYC1330 MJD=56769.23) two flares are seen in rapid succession, while in RXJ0626 (MJD=56770.825) the profile of the peak in more complex than others (this event was recorded as one flare). It is clear that none of these flares would have been resolved in long cadence mode data.

4 RESULTS

4.1 Rotation Period

For both light curves we removed any trends which were longer than the stellar rotation period. Given that various offsets have been applied to sub-sections of data more detailed work would be required to search for evidence of differential rotation in these light curves (see Lurie et al (2015) for evidence for such an effect in the M5V star GJ 1245B). We determined the rotation period of each star using the standard Lomb Scargle periodogram. We found a rotation period of 5.04 days for TYC1330 and 7.90 days for RXJ0626.
We show in the top panels of Figure 4 the K2 data folded on the rotation period where phase 0 has been chosen to correspond to minimum flux.

TYC1330 show a peak-to-peak amplitude of 2.7 percent and 2.3 percent for RXJ0626. Both light curves show a minimum which is likely due to an enhancement in the number of spots which are darker than the surrounding photosphere and are visible at this rotational phase. There is also a local minimum in the light curve of both stars but is much deeper in RXJ0626. This may suggest that the star spots have two distinct locations (perhaps one in each hemisphere).

Nielsen et al. (2013) and McQuillan et al. (2013) determine the rotation period of main sequence stars using Kepler data. They find that there is a general relationship between mass and rotation period such that the rotation period increases towards lower masses. However, for any given spectral class there is a large spread in rotation period: Kiraga & Stepień (2007) show that for stars with a mass between 0.5–0.6 $M_\odot$ (stars with a spectral type M1V has a mass $\sim$0.56 $M_\odot$, Baraffe & Chabrier (1996)) the rotation period can be a fraction of a day to tens of days. It is likely that other factors (such as age) effect the rotation period.

### 4.2 Flare Energies

We identified a total of 31 flares in both TYC1330 and RXJ0626. To determine the luminosity of these flares we estimated the luminosity of the two sources using the relationship from Lépine & Gaidos (2011):

\[
M_V \sim 2.2(V - J) + 2.5
\]

where (V-J) = 3.66 and 3.14 (also taken from Lépine & Gaidos) and implies $M_V$ =10.55 and 9.4 for TYC1330 and RXJ0626 respectively. We assume the Sun has $M_V$ =4.83 and $L = 3.8 \times 10^{33}$ erg/s which implies $L = 2.0 \times 10^{33}$ erg/s and $L = 5.6 \times 10^{31}$ erg/s for TYC1330 and RXJ0626 respectively. For each flare we then measured the amount of energy per time bin by comparing the flare energy with the quiescent flux level and the energy of the flare was summed up. The range of flare energy in TYC1330 was $2 \times 10^{31} - 6.6 \times 10^{33}$ erg and in RXJ0626 $7 \times 10^{31} - 5.1 \times 10^{33}$ erg. We estimate the spread in the (V-J), $M_V$ relationship of Lépine & Gaidos (2011) is $M_V \sim 0.5$ which translates to an uncertainty on the resulting luminosity of $\sim 40$ percent.

In Figure 5 we show the cumulative energy distribution of flares seen in TYC1330 and RXJ0626 together with those seen in KIC 5474065 and KIC 9726699 (Ramsay et
Questioning the traditional view of early dM stars

We find that for the two sources with very similar spectral type (M1V and M1.5V), the flare characteristics are similar, with more energetic flares compared to the two M4V stars (Figure B). This is intriguing since the activity levels of M dwarfs (as measured for instance by levels of Hα emission) has been found to be very low from M0V stars, reaching 40 percent of M5V stars being active while 90 percent of stars later than M5V are found to be active (e.g. West et al. 2008 and Schmidt et al. 2014).

In Ramsay et al. (2013) we compared the activity levels of the two M4V dwarfs KIC 5474065 and KIC 9726699, as measured using Kepler data, with other stars. To do this we estimated the equivalent energy of the flares in the U band (where many observations have been made). As before, we assume $E_{\text{Kepler}}/E_U = 2.4$. We therefore find that for TYC1330, flares have $L_U \sim 1 \times 10^{31} - 3 \times 10^{33}$ erg and for RXJ0626 $L_U \sim 3 \times 10^{31} - 2 \times 10^{33}$ erg.

We produced a cumulative flare frequency based on plots such as those shown in Ramsay et al. (2013) where we derive a linear relation of the form:

$$\log(N/T) = a + b \log E$$

We take the work of Hilton (2011) who determined the cumulative flare frequency of active M3–M5 and M6–M8 stars together with inactive M0–M2 and M3–M5 stars and less active M3–M5 (see Hilton (2011) and Hawley et al. 2014)). We supplement this by taking previous work on active M0–M1 stars and also the Solar flare distribution for Solar maximum and minimum (Figure K and see its caption for references). The Sun at Solar minimum lies below the M dwarfs while at Solar maximum it is consistent with several M dwarfs flare rate and energy output. Also included is data for active G dwarfs taken from Shibayama et al. (2013).

The rate of flaring for events in TYC1330 and RXJ0626 has a similar slope as the active M0–M1 and active M3–M5 stars, but is ~8 times less likely to produce a $10^{33}$ erg flare. It is however in excellent agreement with the group of less active M3–M5 dwarfs from Hilton (2011) and Hawley et al. (2014). The inactive M0–M2 stars from Hilton (2011) are much less active and do not produce flares above $10^{31}$ ergs.

In making a comparison between the cumulative flare rates of stars derived from different instruments (Figure K there are a number of factors which should be noted. The first is the flare energy calibration which as mentioned in §4.2 has a possible error of around 40 percent. Another is the conversion from the Kepler filter to U band: we used

Figure 3. The cumulative energy distribution of flares (in the Kepler band-pass) as seen in TYC1330 and RXJ0626. We also show the distribution of flare energy of KIC 5474065 and KIC 9726699 using Kepler data (Ramsay et al. 2013).

Figure 4. The light curve of TYC1330 (left hand panels) and RXJ0626 (right hand panels) folded on the ephemeris $T_o(MJD) = 56724.74(6) + 5.036(5)$ and $T_o(MJD) = 56721.5(1) + 7.90(2)$ respectively where the number in parenthesis is the error on the last digit and $\phi = 0.0$ has been defined as minimum flux. (The data has been plotted over two rotational cycles for clarity). In the lower panels we show the energy of the flares as a function of rotational phase.

al. 2013), which indicates how often a flare with a given energy is seen. Both TYC1330 and RXJ0626 show flares with energies $L \sim 10^{33}$ erg roughly every 8 days which is roughly twice as frequent as KIC 5474065. On the other hand TYC1330, RXJ0626 and KIC 5474065 show the same frequency of flares with energies a few $\times 10^{32}$ ergs. Given the uncertainty in the luminosities, the slope of flare energy distribution per time of each K2 source is similar.

In Figure 4 we show the light curve of both sources folded on the stellar rotation period. We also show the energy of the flares as a function of rotational phase where we define $\phi = 0.0$ as the point of minimum flux. This indicates that while flares are seen at all rotational phases, the most energetic flare seen in TYC1330 is close to minimum flux. This is what we would expect if the flares originate from active regions close to starspots, which being cooler give a lower flux when they are visible. On the other hand the most energetic flare seen in RXJ0626 is seen close to maximum brightness.
\[ E_{\text{Kepler}} / E_U = 2.4 \text{, compared to } E_{\text{Kepler}} / E_U = 1.54 \text{ used by Hawley et al. (2014) and } E_{\text{Kepler}} / E_U = 2.5 \text{ implied from observations by Hawley & Pettersen (1991). Another is the accuracy of the power-law which can result from a low flare count, in particular for the inactive dwarfs. This is less of an issue with the present K2 data which has 62 flares from 2400 hours of observations. Although the slope for the present K2 data is in excellent agreement with that for the less active M3–M5 dwarf ground-based data, Hawley et al. (2014) noted that using Kepler data, the active M3–M5 dwarfs have a slope which is steeper compared to ground based data. }

Another uncertainty is the question of whether the flare star is located in a binary system. For instance Rappaport et al. (2014) find that 17 percent of M dwarfs with rotation periods shorter than two days show evidence for being in a binary or multiple system. At this stage we do not know whether the K2 M1 stars (or indeed the Kepler M4 stars) are in a binary system, but if they were this could give enhanced activity. However, perhaps the biggest unknown is the question of activity cycles for these dwarfs: we note that if M dwarfs show stellar magnetic cycles then their flare distributions would be expected to move in the vertical axis of Figure 5 in the same manner as the Sun. Work based on dM stars observed by Kepler coupled with new K2 data could help resolve this problem.

The two objects in the active M0–M1 branch are YY Gem (an M1/M1 binary) and V1005 Ori (M0V). YY Gem has a rotational period of 20 hours while there is no known rotational period for V1054 Oph. TYC1330-879 has a rotational period of 5 days. We speculate that the lower flare activity rate of both TYC1330-879 and RXJ0626 is age related with the slower rotators being older and less active. A similar conclusion was made by West et al. (2008) based on M dwarf observations. Both YY Gem (~200 Myr) and V1005 Ori (~30 Myr) are relatively young objects.

Optical spectroscopy shows that both TYC1330 and RXJ0626 have weak Hα emission (equivalent width \(<1 \AA\), c.f. Table 1). Traditionally, M dwarfs with Hα having an equivalent width of \(<1 \AA\) were termed inactive, e.g. West et al. (2008). The fact that these two objects produce flares may not be a surprise. However, the fact that they produce flares with an energy more than two orders of magnitude above the previous assumed limit for inactive M3–M5 stars is surprising. This shows the value of having an Earth orbiting instrument capable of long duration observations (i.e. months), compared with an Earth-based telescope and shows the potential impact that future K2 observations can make in the field of stellar flare observations.

6 CONCLUSIONS

We have compared the K2 short cadence light curves of two M1 V stars derived using a well established photometric package using a moving aperture with that derived using tools specifically written for Kepler and K2 data. We find evidence for the moving aperture approach can give smoother light curves making it particularly suitable for identifying flares. Our targets show flares roughly once every two days, despite the fact that their low Hα emission would have classed them as inactive. We compare their flare energy distribution with other M dwarfs observed using Kepler and find that TYC1330 and RXJ0626 shows more flares with energies of \(10^{33} \text{ erg}\) compared with our two comparison M4V stars as observed using Kepler in SC mode. Comparing their equivalent U band luminosity with other dwarfs, both TYC1330 and RXJ0626 show cumulative energy distributions with a similar slope as active M0–M5 stars, but their flaring rate is a factor of 8 lower. The K2 mission will allow a wide range of late type dwarf stars to be targeted and assess their activity rates as a function of age and rotation period.

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Questioning the traditional view of early dM stars

Figure 5. The cumulative flare frequency (in seconds) versus U-band flare energy (in erg) for different classes of dwarf stars and TYC1330 and RXJ0626. Data is taken from Hilton (2011): Active M3-M5, 332 hours on 4 stars observing 157 flares; Active M6-M8, 59 hours on 4 stars observing 39 flares; Less Active M3-M5, 147 hrs on 8 stars observing 28 flares; Inactive M0-M2, 256 hours on 16 stars observing 9 flares; Inactive M3-M5, 153 hours on 6 stars observing 3 flares; Active M0-M1, data from Moffett (1974), Doyle & Mathioudakis (1990) and Dal & Evren (2011), 156 hours on 2 stars observing 63 flares. In addition, we include from Shibayama (2013) a line for solar maximum and minimum which used a bolometric/GOES X-ray flux relation derived from work by Kretzschmar (2011). Data for active G dwarfs are taken from Shibayama et al (2013) which took 46,000 hrs of observations on 4 stars observing 116 flares.

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