Short duration high amplitude flares detected on the M dwarf star KIC 5474065

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ABSTRACT

Using data obtained during the RATS-Kepler project we identified one short duration flare in a 1 hour sequence of ground based photometry of the dwarf star KIC 5474065. Observations made using GTC show it is a star with a M4 V spectral type. Kepler observations made using 1 min sampling show that KIC 5474065 exhibits large amplitude (δF/F > 0.4) optical flares which have a duration as short as 10 mins. We compare the energy distribution of flares from KIC 5474065 with that of KIC 9726699, which has also been observed using 1 min sampling, and ground based observations of other M dwarf stars in the literature. We discuss the possible implications of these short duration, relatively low energy flares would have on the atmosphere of exo-planets orbiting in the habitable zone of these flare stars.

Key words: Physical data and processes: magnetic reconnection – astrobiology – stars: activity – Stars: flares – stars: late-type – stars: individual: KIC 5474065, KIC 9726699

1 INTRODUCTION

Flares with duration of a few to tens of minutes and energies of ~ 10²⁸–³⁵ ergs have been observed on low mass dwarf stars for many decades (eg Bopp & Moffett 1973, Gershberg & Shakhovskaia 1983). The origin of these flares is thought to be similar to Solar flares in that they are produced during magnetic reconnection events (eg Haisch, Strong & Rodono 1991). Studying stellar flares from a wide range of stars can give important insight to how magnetic activity varies as a function of stellar mass and age. In more recent years, the affects of flares on the atmosphere of exo-planets around dwarf stars has been the subject of much interest (eg Segura et al 2010).

Historically the study of stellar flares was performed on known M dwarf stars. However, with the advent of large scale surveys such as SDSS it has become possible to identify events from many previously unknown flare stars (eg Davenport et al 2012). Whilst this will no doubt prove a goldmine for stellar flare researchers, the issue of separating extra-galactic transient events and flares from M dwarfs will become increasingly difficult in future surveys such as that made using LSST.

One survey which allows the virtually uninterrupted observation of sources is NASA’s Kepler mission which covers an area of 116 square degrees. The light curves extend over many months (or years) and have a precision of parts per million and allows models of stellar structure to be tested in a way not previously possible. A key point is that the actual targets which are observed using Kepler can be updated every month. Walkowicz et al (2011) presented Kepler observations of flares seen in cool stars, while Balona (2012) reported observations of stars with A/F spectral type and Maehara et al (2012) presented some examples of ‘super’ flares on Solar type stars.
In June 2011 we started the RATS-Kepler project whose aim was to identify sources which showed flux variations on short (<30 min) timescales (Ramsay et al. 2013). We do this by taking a series of short exposures (20 sec) using wide field cameras on telescopes such as the Isaac Newton Telescope on La Palma on specific fields for one hour. Light curves of each object are derived and variable sources identified. One variable source which we identified was KIC 5474065 which showed a short duration (<20 min) flare with an amplitude of 0.6 mag in the g band. We were successful in placing KIC 5474065 on the Kepler 1 min sampling target list. This paper presents the results of these Kepler observations and a comparison of the energy distribution of the flares with other low mass flare stars.

2 KIC 5474065

Although KIC 5474065 ($\alpha_{2000}=19h \ 53m \ 02.3s$, $\delta_{2000}=+40^\circ \ 40.6^\prime$) is included in the Kepler Input Catalog (Brown et al 2011), it does not have a measured temperature or surface gravity. It is, however, included in the Kepler-INT Survey (U=20.61, g=19.00, r=17.33, i=15.60; Greiss et al 2012a,b); the UBV survey of the Kepler field (B=18.79, V=18.07; Everett, Howell & Kinemuchi 2012) and also the 2MASS survey (J=14.015, H=13.397, K=13.215; Skrutskie et al 2006). The optical colours indicate a relatively late-type star. Since KIC 5474065 is variable (due to its rotational modulation and flare activity) some degree of caution is required when determining its colours unless it is known that multi-band observations are made simultaneously. However, Lépine & Gaidos (2011) show the relationship between the colour ($V-J$) and spectral type for late-type stars. For KIC 5474065, $V-J = 4.06$ implies a spectral type of M3 to M4.

3 GRAN TELESCOPIO CANARIAS SPECTROSCOPIC DATA

We carried out low-resolution spectroscopy with the Optical System for Imaging and Low Resolution Integrated Spectroscopy (OSIRIS) tunable imager and spectrograph (Cepa et al. 2003) at the 10.4 m Gran Telescopio Canarias (GTC), located at the Observatorio Roque de los Muchachos in La Palma, Canary Islands, Spain. The heart of OSIRIS is a mosaic of two 4k x 2k e2v CCD44–82 detectors that gives an unvignetted field of view of 7.8 x 7.8 arcmin$^2$ with a plate scale of 0.127 arcsec pix$^{-1}$. However, to increase the signal-to-noise ratio of our observations, we chose the standard operation mode of the instrument, which is a 2 x 2-binning mode with a readout speed of 100 kHz.

Two spectra each with an exposure of 300 sec were obtained using the OSIRIS R1000R grism in service mode on 11 May 2013. They were made as part of a GTC filler programme which utilises poor weather conditions. We used the 1.0 -width slit, oriented at the parallactic angle to minimise losses due to atmospheric dispersion. The resulting resolution, measured on arc lines, was R ~ 700 in the approximate 5250–9200 Å spectral range. The star Ross 640 was used to remove the instrumental response. The data were reduced using standard Figaro routine$^1$.

We show the optical spectrum of KIC 5474065 in Figure 1; it is clearly a late-type dwarf star. Examining Figure 1 of Bochanski et al (2007), KIC 5474065 is later than an M0V spectral type. Judging by the depth of the Na I (8190Å) feature and the Ca II triplet around 8500 Å it is most likely that KIC 5474065 has a M4V spectral type although M3V and M5V are also possible.

In order to determine the energies of the flares, we must first estimate the intrinsic luminosity of KIC 5474065. Lépine & Gaidos (2011) include $V J H K$ and parallax data for late type stars. We were able to extract data as a function of spectral type and estimate the mean $M_V$ using relationship between $(V-J)$ and $M_V$ outlined in Lépine & Gaidos (2011). We show in Table 1 the mean absolute $V$ magnitude for spectral types M3V–M5V and we assume the Sun has $M_V = 4.83$ and $L_\odot = 3.8 \times 10^{33}$ erg s$^{-1}$.

4 KEPLER DATA

The detector on board Kepler is a shutterless photometer using 6 sec integrations and a 0.5 sec readout. There are two modes of observation: long cadence (LC), where 270

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1 RAdip Temporal Survey-Kepler

2 http://starlink.jach.hawaii.edu

Table 1. The absolute magnitude and luminosity of stars with spectral types M3 V – M5 V based on the data in Lépine & Gaidos (2011).

| Spectral Type | $M_V$ | $L$ (erg s$^{-1}$) |
|---------------|-------|------------------|
| M3 V          | 11.2  | $1.1 \times 10^{31}$ |
| M4 V          | 12.4  | $3.6 \times 10^{30}$ |
| M5 V          | 13.5  | $1.4 \times 10^{30}$ |

Figure 1. The lower spectrum (solid line) shows the optical spectrum of KIC 5474065 obtained using GTC and Osiris. We indicate the wavelength of telluric absorption features as light grey vertical bands (taken from Kirkpatrick, Henry & McCarthy 1991) and we have not attempted to remove them. The upper spectrum (dashed line) shows the M4 template spectrum provided by Bochanski et al. (2007).
is possible that short duration low intensity flares are likely to be hidden in the noise in KIC 5474065.

KIC 5474065 was observed using Kepler in SC mode in Quarter 14; the start and end times of the observations are shown in Table 2. The on-time for SC mode was ~24.1 days and 75 days for LC mode. After the data are corrected for bias, shutterless readout smear and sky background, light curves are extracted using simple aperture photometry (SAP). Data which do not conform to ‘SAPQUALITY=0’ were removed (for instance, time intervals of enhanced solar activity) and the data were corrected for systematic trends.

The light curve of KIC 5474065, shown in Figure 2, exhibits two main features—one a clear quasi-sinusoidal modulation with a period of 2.47 days and a semi-amplitude of ~2 percent, and the presence of short but intense flares: two flares have an intensity $\Delta F/F \sim 46$ percent. For comparison, MOST observations of the dM3e star AD Leo (made using a 1 min cadence), show flares with $\Delta F/F \sim 28$ percent (Hunt-Walker et al 2012), while ‘super-flares’ with amplitude of 8 percent are seen on Solar-type stars (Maehara et al 2012). The rotational period of KIC 5474065 is typical of M4-5 dwarfs, e.g. YZ CMi has a rotational period of 2.78 days, while V577 Mon has a rotational period of 1.95 days.

For comparison, we also extracted the light curve of KIC 9726699 ($\alpha_{2000}=19h 51m 09.4s$, $\delta_{2000}=+46^\circ 29 01.2^\prime$) which has also been observed using Kepler in SC mode. Savanov & Dmitrienko (2011) presented an analysis of this data, but concentrated on determining the extent and duration and spots on its photosphere and did not discuss the flares themselves. Like KIC 5474065 it has a M4 V spectral type (Reid et al 2004), but it is more rapidly rotating (a rotation period of 0.593 days) which makes it similar to V374 Peg (0.45 days). The Kepler Input Catalog (Brown et al 2011) gives $g=13.9$ for KIC 9726699 making it more than 5 mag brighter than KIC 5474065 and hence the Kepler data of this source has a much higher signal to noise than KIC 5474065.

KIC 9726699 has been observed using Kepler in SC mode in four quarters, but here we have restricted our analysis to data from Q6. We show a 4 day section of the light curve of KIC 9726699 in Figure 3. It shows a relatively small number of large amplitude flares, but its light curve is dominated by short duration, low intensity, flares. For comparison, we show the light curve of KIC 5474065 also covering 4 days and on the same flux scale in Figure 3. Given that KIC 9726699 is very much brighter compared to KIC 5474065, it is possible that short duration low intensity flares are likely to be hidden in the noise in KIC 5474065.

| Mode | Start       | End        |
|------|-------------|------------|
| SC   | 2012-06-28 15:03:34 | 2012-07-29 12:02:49 |
| LC   | 2012-06-28 15:17:47 | 2012-10-03 19:40:10 |

Figure 4. The cumulative energy distribution of flares (in the Kepler band-pass) as seen in KIC 5474065 and KIC 9726699.

5 FLARE CHARACTERISTICS

To identify flares from KIC 5474065 in an automatic manner we first removed the effects of the rotational modulation. After some experiment, we identified the time interval when a flare occurred when $(f_i - \bar{f})/\sigma > 3$ where $f_i$ was the flux of the $i$th point, $\bar{f}$ was the overall mean of the light curve and $\sigma$ was the standard deviation of the overall light curve. The resulting flare times were then manually inspected and points which were clearly part of the same flare were edited to ensure no ‘double counting’ of flares were made. (If we defined a lower threshold for flare detection the flare rate goes up but the false positive rate also goes up as it becomes difficult to distinguish between a genuine flare and noise in the data). This strategy found 27 flares in the SC light curve of KIC 5474065—in other words, on average one flare was detected every 0.9 days, and on average there was one flare with an intensity $\Delta F/F > 0.2$ every 8 days. There was no evidence of any pre-flare dips such as that seen in V1054 Oph (Ventura et al 1995). For KIC 9726699 it was more difficult to fully remove the effects of rotation and we therefore set the detection threshold as $(f_i - \bar{f})/\sigma > 8$. However, we identified over 260 flares in the Q6 data of KIC 9726699. The fact that KIC 9726699 appears to be more active compared to KIC 5474065 is consistent with the well known correlation between rotation period and stellar activity, (eg Noyes 1985), although we note that short duration, low energetic flares would not have been detected in KIC 5474065 due to the much higher noise level.

To derive the flare frequency rate, we use the following formulae where $E = \sum_f$ is known as the flare equivalent duration, see Lacy et al. (1976) for further details;

$$E = \sum_f (I_{f+a} - I_o)/I_o \Delta T$$

where $I_o$ is the stellar intensity of the star in its quiescent state, $I_{f+a}$ the intensity during a flare and $\Delta T$ the integration time. Further, we assumed the underlying luminosity was $3.6 \times 10^{30}$ erg/s (Table 1) which is appropriate for a M4V spectral type. This gave for KIC 5474065 a range in flare energy, $L = 1.1 - 3.7 \times 10^{32}$ ergs, whilst for KIC 9726699 the range was $L = 0.01 - 2.2 \times 10^{32}$ ergs (these energies will...
Figure 2. The Kepler Short Cadence light curve of KIC 5474065 made in Q14. $\Delta F/F$ is the ratio of the difference between the flux at any point and the mean flux. The rotational period of 2.47 days is clearly seen as are the short duration flares. In the left hand panel we zoom in on four flares.

Figure 3. In the top panel we show a section of the Kepler Short Cadence light curve of KIC 9726699 made in Q6. $\Delta F/F$ is the ratio of the difference between the flux at any point and the mean flux. For comparison we show in the lower panel a section of the light curve of KIC 5474065 on the same scales which is 5 mag fainter than KIC 9726699.
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Figure 5. In the upper panels we show the mean light curve of KIC 5474065 (left) folded on \( T_0 = \text{BJD 2456106.97} + 2.47295492 \) E and KIC 9726699 (right) folded on \( T_0 = \text{BJD 2455371.310} + 0.593 \) E, where the light curves have been normalised so that the mean flux is unity and \( \phi = 0.0 \) is defined as photometric minimum and the light curves have been binned into 50 bins. In the lower panels we show the energy emitted in each flare as a function of rotational phase. Deviations from a smooth curve are a result of flares in the light curve.

The energy and duration of these flares are at the lower energy of those detected on another dM4.5 flare star, AD Leo (Pettersen et al. 1986).

Figure 6. A more detailed view of the KIC 9726699 flare distribution with the best fit to an M4.5 flare distribution. We now show the cumulative flare-frequency distribution of the flares in Figure 4. This shows that on average KIC 5474065 (KIC 9726699) shows a flare with energy \( L = 10^{31} \) ergs every 0.2 days (0.6 days) and a flare with energy \( L = 10^{32} \) ergs every 8.7 days (~117 days), compared to AD Leo which can produce a \( 10^{32} \) ergs flare every 1.5 days (see Table S).

We now show in Figure 5 the light curve of both KIC 5474065 and KIC 9726699 folded on the stars rotational period together with the energy of each flare as a function of the rotational phase. Since the modulation in the light curve is caused by the rotation of stellar spots into and out from view, the minimum flux corresponds to the viewing phase when the fractional surface area covered by spots is at its greatest (since the spots are cooler than the surrounding photosphere).

In the case of KIC 5474065, the three most energetic flares were seen in a very short phase interval, \( \phi = 0.74 \text{–} 0.79 \). Curiously, in KIC 9726699 the two most energetic flares were also seen at a similar phase (\( \phi = 0.84 \text{–} 0.85 \)) and separated by 6 rotational cycles. This indicates that the most active regions on the star are preferentially located in stellar longitude and last for timescales of (at least) several weeks (a conclusion also reached by Savanov & Dmitrienko 2010). In both sources, flares were seen at all rotational phases.

6 KIC 5474065 AND KIC 9726699 AS FLARE STARS

The monitoring of flares from M dwarf stars has been ongoing for the past 50 years, most of it in the Johnson U-band. Although all M dwarfs monitored over an extended timescale appear to show flares, only a few dozen have a well established flare-rate. In Figure 4, we summarise the results from several thousand hours of photometric monitoring (the caption indicates the original source of the data). Compared to the other M dwarf stars (which range from dM0 to dM8) shown in Figure 4, KIC 5474065 and KIC 9726699 show flares which are relatively energetic but occur less frequently.
KIC 9726699 also produces more frequent but less energetic flares than KIC 5474065, despite the fact that both have a dM4 spectral class. Generally speaking, stars of spectral class M4 and later are fully convective and therefore have a very different magnetic topology compared to stars with earlier spectral type. However, Morin et al. (2010) has shown this is not always the case as age may play a role in addition to mass and rotation period. V374 Peg has a similar rotation period as KIC 9726699, yet it can produce extremely energetic flares, e.g. Batyryshkina & Ibragimov (2001) detected an 11 mag superflare with an energy in excess of $10^{35}$ erg. A more plausible explanation may be the relative spot coverage on these two stars. For instance Notsu et al. (2013) found that the energy of superflares is related to the total coverage of starspots and therefore the amount of magnetic energy stored around starspots.

For those stars where monitoring exists over a number of years, the observed seasonably variability can be a factor of two, perhaps indicating cycles similar to the Sun. This has been determined in a number of ways but includes narrow band photometric filters centered on the Ca II H & K lines (e.g. Baliunas et al. 1995) and spectropolarimetric observations (e.g. Donati et al. 2008) spread over a considerable time interval. With the possibility of observing flare stars using Kepler with a cadence of 1 min for weeks at a time, it will be practical to map the activity of many stars over a timescale of years. This will also provide good motivation to re-examine the effects that stars which show many flares have on the chemistry of atmosphere’s of exo-planets in the stars habitable zone.

7 THE IMPACT OF FLARES IN THE IMMEDIATE STELLAR ENVIRONMENT

The implications of stellar flares on the atmosphere of an exo-planet orbiting around a flare star are important for the development of life as energetic flares could have a potentially hazardous influence on its habitability. For a M4 V dwarf star the habitable zone is roughly 0.04–0.14 AU (e.g. Kopparapu et al. 2013). For instance Segura et al. (2010) determined the potential effect of a flare as seen on the dM3e star AD Leo in April 1985. This flare which had a duration of 4 hrs was found to have an energy of $L \sim 10^{34}$ ergs in the UV/Optical wave-band (Hawley & Petterson 1991), more than one order of magnitude than the largest flare seen on KIC 5474065. Segura et al. (2010) determined that such a flare was not a direct hazard for life (as we know it) on an exo-planet 0.16 AU distant from AD Leo. The flares which we report here are both less energetic but also of much shorter duration. For KIC 5474065 the total radiated U-band flare energy budget during the SC monitoring interval was $\approx 10^{27}$ erg s$^{-1}$. Assuming that the total radiated energy over all wavelengths is one order of magnitude greater (e.g. Doyle & Butler 1985) implies a value two orders of magnitude less radiated energy than the large AD Leo flare referenced above which may suggest a minimum effect on any nearby planet. However, what effect a sequence of frequently occurring flares still needs to be investigated.

| Flare Energy (ergs) | AD Leo Flare Rate (days) | KIC 5474065 Flare Rate (days) | KIC 9726699 Flare Rate (days) |
|---------------------|--------------------------|-------------------------------|-------------------------------|
| $10^{30}$           | 0.09                     | 0.3                           |                               |
| $10^{31}$           | 0.29                     | 0.2                           | 0.6                           |
| $10^{32}$           | 1.5                      | 8.7                           | 117                           |

8 CONCLUSIONS

We present Kepler short cadence observations of the M4 V star KIC 5474065 which has a rotation period of 2.47 days. It shows two high amplitude short duration flares ($\Delta F/F > 0.4$) which have integrated energies of $\sim 7 \times 10^{32}$ ergs. Additional flares energies as low as $\sim 1 \times 10^{32}$ ergs are also seen. We compare the flare rate of a second M4 V star KIC 9726699 which is more than 5 mag brighter than KIC 5474065 and has a more rapid rotation period of 0.60 days. Compared to KIC 5474065, KIC 9726699 does not show such high amplitude flares but since the Kepler data has a higher signal to noise, it allows us to detect many short duration, low energy flares reaching energies as low as $\sim 10^{30}$ ergs. Although the effect of flares with energies of $10^{34}$ ergs on the atmosphere’s of exoplanets in the habitable zone have been investigated, it is of great interest to determine what effect the presence of many numbers of lower energy events will have on exoplanet atmospheres.

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Figure 6. The cumulative flare frequency (in seconds) versus U-band flare energy (in ergs) for a large group of M dwarfs plus that for KIC 5464065 and KIC 9726699. This data has been compiled from work by Moffett (1974), Lacy et al. (1976), Byrne et al. (1984, 1985), Pettersen (1975a,b, 1981a,b, 1983, 1985a,b), Pettersen et al. (1983, 1984, 1986), Pettersen & Sundland (1991), Doyle & Byrne (1986), Doyle et al. (1986, 1989, 1990), Hawley et al. (1989), Leto et al. (1997), Dal & Evren (2010, 2011) and Dal (2011, 2012).
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