Detection of an energetic flare from the M5V secondary star in the Polar MQ Dra

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ABSTRACT

MQ Dra is a strongly magnetic Cataclysmic Variable whose white dwarf accretes material from its secondary star through a stellar wind at a low rate. TESS observations were made of MQ Dra in four sectors in Cycle 2 and show a short duration, high energy flare (~ 10^{35} erg) which has a profile characteristic of a flare from the M5V secondary star. This is one of the few occasions where an energetic flare has been seen from a Polar. We find no evidence that the flare caused a change in the light curve following the event and consider whether a coronal mass ejection was associated with the flare. We compare the frequency of energetic flares from the secondary star in MQ Dra with M dwarf stars and discuss the overall flare rate of stars with rotation periods shorter than 0.2 d and how such fast rotators can generate magnetic fields with low differential rotation rates.

Key words: Physical data and processes: accretion, accretion discs – stars: binaries close – stars: activity – stars: flare – stars: low-mass – stars: magnetic fields

1 INTRODUCTION

Polars, or AM Her stars, are compact binaries where a strongly magnetic (B > 10 MG) white dwarf accretes material through Roche Lobe overflow from a dwarf secondary star. They are members of the wider group of compact accreting binaries called cataclysmic variables (CVs). Unlike many CVs which show dwarf novae outbursts, the strong magnetic field of the white dwarf prevents the formation of an accretion disc around the white dwarf and material gets channelled onto one or both of its magnetic poles. Strong shocks get formed above the photosphere of the white dwarf which results in X-ray emission and cyclotron emission which is strongly beamed (see Cropper 1990, for an early review).

Polars can exhibit different accretion states where they appear in 'high', 'intermediate' or 'low' states. Some systems, such as EF Eri, have spent much of the last two decades in a low state apart from short duration high states (e.g., Schwope et al. 2007). Although star-spots near the Roche Lobe on the secondary star may suppress mass transfer (Livio & Pringle 1994), it is still unclear why these state transitions occur. However, when a system is in a low or intermediate state, we have the opportunity to observe activity on the secondary star. In addition there is a small sample of Polars which accrete at a very low rate and whose secondary is not thought to be filling their Roche Lobe, so that accretion takes place through a stellar wind (e.g., Schwope et al. 2002). As a result they are excellent targets to study activity of the secondary star.

The mass and spectral type of the secondary star in a CV is related to the binary orbital period, with longer period systems (~25 hrs) having stars with late K spectral type, whilst those with periods shorter than ~2 hrs having stars with spectral type M5V or later (e.g., Knigge 2006). The polars therefore have secondary stars which straddle the boundary point (M4V) where stars are fully convective (later) or partially convective/radiative (earlier). Since fully convective stars also show evidence of stellar activity, it was thought that they must generate and maintain their magnetic field in a different way from Solar type stars. However, more recently, observations (e.g. Wright & Drake 2016) show that slowly rotating fully convective M dwarfs have X-ray properties identical to slowly rotating Solar type stars, whilst theoretical work (e.g. Yadav et al. 2016) has indicated that the nature of the dynamo mechanism changes as fully convective stars age and slow down. Observations made using Kepler, K2 (e.g. Raetz et al. 2020) and TESS (e.g. Gunther et al. 2020) enables the flaring rates of many low mass stars to be determined which helps address the question of how stable magnetic fields are generated in stars in general.

One low accretion rate Polar whose M5V secondary appears to underfill its Roche Lobe and accrete via a wind is MQ Dra (SDSS J1553+55) which shows very prominent broad emission features which were attributed to cyclotron radiation, which allowed the magnetic field strength to be determined (~60 MG, Szkody et al. 2003; Schmidt et al. 2005). Subsequent modelling indicated the mass transfer rate was very low (M ~ 6 x 10^{-14} M_{\odot} yr^{-1}), implying a very low specific accretion rate, (\dot{m} = 0.001 − 0.01 g cm^{-2} s^{-1}), and hence no strong shock would form. In contrast, the low accretion rate and the high magnetic field gives rise to widely separated and prominent cyclotron harmonics in the optical (Szkody et al. 2004; Schmidt et al. 2005). The parallax from the Gaia EDR3 catalogue (Gaia 2020) is 5.51±0.06 mas, implying a distance of 181.7^{+3.5}_{-3.3} pc.
Optical photometry of MQ Dra has shown that the amplitude and shape of the data folded on the orbital period is highly dependent on the filter used in the observations. The emission observed over the UV-optical-IR bands is a sum of beaming of the cyclotron emission; the white dwarf and the ellipsoidal modulation due to the changing viewing angle of the secondary star. In the $R$ band the amplitude reaches a peak-to-peak variation of $\sim 1$ mag and only one peak over the orbital period (Szkody et al. 2008). However, a double peak is seen in the $B$ and $J$ bands which could be a combination of cyclotron beaming and the ellipsoidal modulation of the secondary. In this short paper we present the photometric data of MQ Dra obtained using the TESS mission during Cycle 2 when it observed the northern ecliptic hemisphere. In particular, we identify an energetic stellar flare and discuss the activity levels on secondary stars in polars and compare them with field M dwarfs.

## 2 TESS OBSERVATIONS

TESS was launched in April 2018 and consists of four 10.5 cm telescopes that observe a $24^\circ \times 96^\circ$ strip (known as a sector) of sky for $\sim 28$ d (see Ricker et al. 2015, for details). Between July 2018 and June 2019, TESS covered most of the southern ecliptic hemisphere (Cycle 1) and between July 2019 and June 2020 covered most of the northern ecliptic hemisphere (Cycle 2). Although there is a band along the ecliptic plane which was not observed, at the ecliptic poles there is a continuous viewing zone where stars can be observed for $\sim 1$ yr. Each ‘full-frame image’ has an exposure time of 30 min. However, in each sector, photometry with a cadence of 2 min is obtained, with most targets being selected from the community via a call for proposals.

MQ Dra (TIC 161744828) was observed in Cycle 2 during sectors 16, 22, 23 and 24 in 2 min cadence (see Table 1). We downloaded the calibrated lightcurves of our targets from the MAST data archive\footnote{https://archive.stsci.edu/tess/}. We used the data values for PDCSAP_FLUX, which are the Simple Aperture Photometry values, SAP_FLUX, after correction for systematic trends. We removed photometric points which did not have QUALITY=0 flag. There is a prominent modulation on the known orbital period of 0.182985 d (4.39 hr) (Szkody et al. 2008) which is apparent in the data from all sectors. The relative amplitude appears to decline over the four sectors (0.63 mag sector 16, 0.49 mag sector 22, 0.38 mag sector 23 and 0.34 mag sector 24). It is likely that this is an instrumental effect (there are three separate Camera and CCD combinations for the observations for MQ Dra).

Examining the light curves from each sector, the observation from sector 24 showed a clear and short duration increase in brightness, from a mean level of 30 ct/s to a peak of 250 ct/s (left hand Figure 1). We show the detail of the event in the right hand of Figure 1: it shows a profile which has a rapid rise to maximum flux followed by a more gradual decline, the whole event lasting $\sim 40$ min. The profile is characteristic of a stellar flare which has an amplitude of 2.3 mag in the $R$-band (600 – 1000 nm). There is no indication that the orbital brightness profile changed over the following orbital cycles.

Given that the pixel size of the TESS cameras is 21 arcsec per pixel, it is possible that the flare we detect originated from a spatially nearby star. Indeed, Jackman et al. (2021) made a systematic study of flares from M dwarfs using Kepler and TESS data and conclude that for TESS data there is a 5.8 percent chance of a false positive flare event from the object of interest due to spatially nearby stars. We used\

| Sector | Start   | End    |
|--------|---------|--------|
| 16     | 58738.15| 58761.12|
| 22     | 58899.43| 58925.99|
| 23     | 58929.65| 58954.36|
| 24     | 58955.30| 58981.78|

Table 1. The start and end times of the TESS observations of MQ Dra where we show the sector and start and end time in BJD and calendar date.

In order to identify and characterise the activity levels on secondary stars in polars, we used TPF Plotter (Aller et al. 2020) to overlay the position of stars in the Gaia DR2 catalogue onto an image derived from a TESS Target Pixel File. This indicates which, if any, stars were in the aperture mask used to extract the light curve of the target, which is 3 pixels in size for MQ Dra. There are no stars down to $G=21$ mag within the aperture mask of MQ Dra. Further we found no evidence that the center of the stellar profile of the source observed by TESS changed systematically over the course of the flare event. We conclude that we identified a stellar flare from the secondary star of MQ Dra.

We can determine the orbital phase by fixing $\phi = 0.0$ to match the flux maximum in the $V$ and $R$ bands from Szkody et al. (2008), where this corresponds to the point of inferior conjunction, the point in the orbit where the secondary is closest to us, i.e., its hemisphere which is facing away from the white dwarf is facing us. In practise we align the data so that minimum corresponds to $\phi = 0.6$ (see Figure 1 of Szkody et al. 2008). In Figure 2 we show the data from sector 24 phased on these terms and find the flare occurred over $\phi \sim 0.3$–0.4: this implies the flare could have illuminated the white dwarf. There is some uncertainty about the binary inclination, with Szkody et al. (2008) showing that $i = 35^\circ$ or $i = 60^\circ$ give better fits to different aspects of their data. Although there is no evidence that MQ Dra changed its brightness after the flare it is possible any mass accretion event would have been seen at UV or X-ray energies.

## 3 FLARE ENERGY

The apparent brightness of MQ Dra is a combination of flux from the white dwarf, the secondary star and cyclotron emission, all of which vary over the orbital period and can result in an amplitude of 1 mag in the $R$ band. However, we know that the secondary star has a M5 V spectral type (Schmidt et al. 2005).

Using Gaia EDR3 (Gaia 2020), we selected those stars within 50 pc of the Sun and then obtained their bolometric luminosity from the TIC V8.0 catalogue (Stassun et al. 2019) which uses Gaia DR2 (Gaia 2018) to determine the luminosities. Using the work of Eric Mamajek\footnote{https://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt} (Pecaut & Mamajek 2013), we find that a M5 V star has on average a Gaia colour ($BP - RP$) $\sim 3.35$. Using the Gaia EDR3/TIC sample we find that the average bolometric luminosity of a M5 V star is 8.8$x10^{30}$ erg/s (the luminosity of a M4.5 and M5.5 star is 3.3$x10^{31}$ erg/s and 5.4$x10^{30}$ erg/s, respectively).

Rather than fit the brightness profile of the flare using a flare model, which is appropriate for automatically identifying and characterising flares from many light curves, we simply summed up the area under the flare after pre-whitening the light curve to remove the modulation on a period of 4.39 hr. This results in a flare luminosity of 2.6$x10^{34}$ erg. However, we need to correct this to take into account that the...
TESS observations of MQ Dra

Figure 1. The left hand panel shows the light curve taken from the first half of TESS sector 24 and the right hand panel shows the light curve focused on the flare where we have converted the time to show the time in mins from close to the start of the flare.

Figure 2. The data from sector 24 phased on the definition of Szkody et al. (2008) where $\phi=0.0$ marks the inferior conjunction of the secondary. This indicates the flare could have illuminated the white dwarf.

The temperature of the flare can be considerably hotter than the photosphere of the M dwarf. We assume that the temperature of the flare is $\sim 12000$ K and that the fraction of the emitted flux which falls within the TESS pass-band is $\sim 0.14$ (Schmitt et al. 2019). This implies a correction factor of $\sim 7$ to obtain the bolometric luminosity of the flare implying a bolometric luminosity of $\sim 2 \times 10^{35}$ erg, with a factor of 2–3 uncertainty to take into account the exact spectral type and temperature of the flare.

Observations of the Sun show that many flares are associated with a Coronal Mass Ejection (CME) which can cause aurora on planets including the Earth (see Fletcher et al. 2011, for a review). Indeed, it has been demonstrated that the most energetic (X class) X-ray flares are associated with a CME event (e.g. Yashiro et al. (2005)). Although detecting CME’s from stars other than the Sun are obviously much more difficult to identify, there are some examples including one from Proxima Centauri (Zic et al. 2020). However, some theoretical studies suggest that if a star has a strong magnetic field it could suppress CMEs (e.g. Alvarado-Gomez et al. (2018)).

However, given the high energy of the flare seen in MQ Dra and the solar flare-CME analogy, we consider it more likely that a CME was associated with this stellar flare.

We now determine how much material would be released if a CME was associated with the flare we detect from the secondary star in MQ Dra and compare that with the mass accretion rate onto the white dwarf. Using data largely derived from solar X-ray flares, Aarnio et al. (2012) and Drake et al. (2013) determined the relationship between flare energy and mass released from a CME (see also Odert et al. (2017)). For a flare with energy $E_{bol} = 2 \times 10^{35}$ erg (and converting to equivalent X-ray energy using an assumption $E_X = E_{bol}/100$, see Osten & Wolk (2015)) we find a mass of $\sim 2 - 4 \times 10^{18}$ g would be released. The mass accretion rate of MQ Dra has been estimated to be $\sim 6 \times 10^{-14} M_{\odot} \, \text{yr}^{-1}$ (Schmidt et al. 2005) which is equates to $\sim 9 \times 10^{15}$ g over 40 min. This is more than two orders of magnitude smaller than the amount material expected to be released from the CME. This suggests that either a CME was not associated with the flare (an option which we consider less likely), or that it was directed in a direction which precluded it being accreted by the white dwarf, or that if it was accreted by the white dwarf the radiation was emitted predominantly at UV or X-ray wavelengths.

4 DISCUSSION

Distinguishing short lived mass transfer events, which occur through Roche Lobe overflow, from stellar activity from the secondary star is difficult as high-cadence photometry is required to resolve the...
profile of the event. The majority of stellar flares show a sharp rise to maximum followed by a slower decline with the whole event typically lasting a few tens of min. A short duration accretion event is likely to have a more top-hat shaped profile. Observations of a burst from UZ For in a low state using X-ray and UV data from XMM-Newton, indicated it was likely due from an accretion event rather than a coronal flare (Still & Mukai 2001). In the optical, high amplitude flares from Polars are very rare. Although Shakhovskoy et al. (1993) reported a 2 mag flare from AM Her which lasted 20 min, not a single event with an amplitude greater than 2 mag was detected from AM Her in 13 years of RoboScope observations (Kafka et al. 2005). (There was evidence for lower amplitude, 0.2-0.6 mag, flare-amplitudes from Polars are very rare. Although Shakhovskoy et al. 2020). MQ Dra shows 10^{35} erg class flares at a similar rate to 2M0837+2050 (M8V) and 2M0831+2244 (M9V) (Paudel et al. 2019). Gunther et al. (2020) made a survey of ~25k low mass stars using data from the first two sectors of the TESS survey and found that very few stars in the M4-M10V range show 10^{35} erg class flares. In contrast the fraction of M dwarfs which show optical flares at all increases from M1V (~5 percent) to M6V (~45 percent, Gunther et al. 2020) implying high levels of flare activity at lower energy levels. This is likely related to the lifetime of a stars activity: using Hα as a proxy for activity (West et al. 2008) found the active lifetime of a M1V star was only a few 100 Myr but rises to ~7 Gyr by M5V spectral type.

One of the principal factors in determining the degree of flare activity is a stars age, with activity declining as stars get older, e.g., Skumanich (1986) and more recently by Davenport et al. (2019). Indeed, for M dwarfs stars with rotation periods shorter than 10 days, ~60 percent show flares (Gunther et al. 2020). However, Gunther et al. (2020) also noted that for stars with rotation periods shorter than 0.3 d, the flare rate dropped. Using a larger sample from all sectors in the southern hemisphere, Ramsay et al. (2020) confirmed this, finding that only a tenth of stars with rotation periods shorter than 0.2 d showed flare activity. This is the rotation period we expect for secondary stars in CVs, which we now return to.

Stars in a binary system are expected to rotate very close to the binary orbital period, implying a low differential rotation, which is expected to play a key role in generating a magnetic field in solar type stars (Scharlemann 1982). Observations of the pre-CV V471 Tau, which has a late K spectral type secondary Hussain et al. (2006), was found to rotate as a solid body. Despite the lack of differential rotation, the secondary star in V471 Tau is observed to be active (e.g. (e.g., Hakala et al. 1989, and references therein). However, observations of AE Aqr, which has a rapidly rotating white dwarf and a M4V secondary star, showed it was not fully locked and has small differential rotation (Hill et al. 2014). More recent work has shown that a strong magnetic field can be generated in fully convective stars in a different way to solar type stars (e.g., Yadav et al. 2015, 2016; Klein et al. 2021) indicating that fully convective stars could have strong magnetic fields (implying activity) even if their surface differential rotation is low.

The secondary stars in Polars are fast rotators with nearly all having rotation periods shorter than 0.2 d. The vast majority also fill their Roche Lobe, with only a small number, such as MQ Dra, underfilling their Roche Lobe. We now know that high energy bursts have been detected from Polars which fill and underfill their Roche Lobe. However, the impact of a star filling its Roche Lobe upon its differential rotation rate remains unclear. It remains to be seen what fraction of low mass stars with rotation periods <0.2 d are in binary systems. Could they show high energy flares if they were observed over a sufficiently long time interval?

To better understand the activity levels in secondary stars in compact binaries, we encourage high cadence photometric observations of Polars in intermediate or low states to search for low amplitude as well as the rare high energy events. In particular it is hoped that MQ Dra will be observed again in TESS Cycle 4 in either 2 min or 20 sec mode.

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Data Availability: The TESS data are available from the NASA MAST portal.

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