Early optical follow-up of the nearby active star DG CVn during its 2014 superflare

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ABSTRACT

DG CVn is a binary system in which one of the components is an M type dwarf ultra fast rotator, only three of which are known in the solar neighborhood. Observations of DG CVn by the Swift satellite and several ground-based observatories during its super-flare event on 2014 allowed us to perform a complete hard X-ray – optical follow-up of a super-flare from the red-dwarf star. The observations support the fact that the super-flare can be explained by the presence of (a) large active region(s) on the surface of the star. Such activity is similar to the most extreme solar flaring events. This points towards a plausible extrapolation between the behaviour from the most active red-dwarf stars and the processes occurring in the Sun.

Key words: gamma-rays: stars – stars: flare – stars: activity – line: formation

1 INTRODUCTION

On April 23rd 2014, at 21:07:08 UT one of the stars from DG CVn flared bright enough (300 milliCrab in the 15-150 keV band) to trigger the Swift satellite’s Burst Alert Telescope (BAT; Barthelmy et al. 2005). Within two minutes of this T0, Swift had slewed to point its narrow-field telescopes to the source, which revealed gradually decreasing soft X-ray emissions with a second weaker flare occurring at T0 + 11 ks, followed by several smaller flares. This behaviour was observed in both the optical and X-ray bands. On the ground, the wide-field “Pi of the Sky”

(Cwiok et al. 2007, Mankiewicz et al. 2014) (PI) instrument was observing, covering Swift’s field of view, and recorded the optical behaviour of DG CVn even before the burst began and continued until T0 + 1100 s. The BOOTES–2 (Castro-Tirado et al. 1993, 2012) telescope began to observe DG CVn from ≈T0 + 11 min, starting to take spectra later at ≈T0 + 1 h with the low-resolution spectrograph COLORES (Rabaza et al. 2014), covering the period of the second flare. Observations with BOOTES–2 continued for several weeks following the trigger. Deeper spectra were obtained later with instruments/spectrographs on larger telescopes: OSIRIS (Cepa et al. 2000) on the Gran Telescopio de Canarias (GTC) at T0 + 1.2 d, SCORPIO (Afanasiev et al. 2005) on the 6 m BTA-6 telescope at SAO in the Caucasus at T0 + 15 d and CAFE (Aceituno et al. 2013)

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DG CVn

DG Canum Venaticorum (DG CVn; with coordinates (J2000) α = 13h31m46.7s; δ = 29°16′36″; also named G 165-8AB; Gies & Jahreiss [1991] and 1RXS J133146.9+291631; Zackgraf et al. [2003]) is a bright (V = 12.19; Xu et al. 2014) and close (D = 18 pc) visual dM4e binary system (Riedel et al. 2014; Henry, Kirkpatrick & Simons 1994; Delfosse et al. 1998). It is also a radio emitting source (Helfand et al. 1999). It has been seen that the system has Ca, H and K lines in emission (Beers, Bestman & Wilhelm 1994). The components have an angular separation in the sky of 0.17 arcsec (Beuzit et al. 2004), an orbital period of P = 7 yr and magnitudes V = 12.64, 12.93, for the primary and the secondary components, respectively (Riedel et al. 2014; Weiss 1999). It is classified as a (joint spectral type from unresolved multiples) M4.0V spectral-type star (Riedel et al. 2014). It is also a red high proper motion dwarf-star (π = 80 mas; Jiménez-Esteban et al. 2012).

One of the components of DG CVn (it is not known which one) has been reported to be chromospherically active (Henry, Kirkpatrick & Simons 1994) and one of the only three known M dwarf ultra-fast rotators in the solar neighborhood. The projected rotational velocity is v sin(i) = 55.5 km s⁻¹, as measured from rotational broadening of the H emission lines seen in high-resolution spectra (Delfosse et al. 1998). Recently it has been reported the detection of intense radio emission (the highest ever detected in an active red-dwarf) coinciding with the time of the first and the second flares reported in this paper (Fender et al. 2014). Because the two components of the system are separated by 3.6 AU (≈2 500 Rₖ), the two stars are not magnetically interacting. Therefore the intense radio emission has been interpreted as a consequence of the processes occurring in one of the stars (we will be referring to this as DG CVn hereafter). For this star to rotate so rapidly a tertiary close companion (i.e. apart from the distant known companion) is expected to exist, but recent studies (Fender et al. 2014) indicate that this might not be the case and that the youth of the system is the cause. Therefore, this system is considered to be a young star (30 Myr; Riedel et al. 2014; Delfosse et al. 1998). Nevertheless it lies outside the spatial and kinematic boundaries of all known stellar young associations (Riedel et al. 2014).

DG CVn has been discovered to be an optically variable source (Robb, Balam & Greimel 1999). The light curve shows periodic sinusoidal variations with a peak to peak amplitude and photometric period of Δ R = 0.03 mag and Pₗₒₙₖ = 0.10836(2) d, respectively. This variation is thought to be produced by a hot spot, whose projected area changes as the star rotates. The light-curve was fitted well with a spot of approximately 3.5 degrees in projected radius with a temperature of 1.3 times the surrounding photosphere. This

Figure 1. Hard X-ray delay versus the optical emission of the prompt emission (first flare) from DG CVn. a, Optical light curve from the PI (from T₀ = 150 s onwards); b, Swift/BAT light curve in the 15–25 keV energy range (i.e. hard X-rays). The time (in seconds) is measured with respect to the BAT trigger time (T₀; D'Elia et al. 2014).

Figure 2. The X-ray brightening was accompanied by an increase of brightness of the optical continuum and the relative intensity of some spectral lines during the second flare episode. a, Optical BOOTES–2 light curve in V filter during the second flare of DG CVn at t − T₀ = 0.127 d; b, Swift/XRT light curve in the 0.3–10 keV energy range (the Flux is measured in cts s⁻¹); c, Intensities of the Balmer lines (relative to the continuum) vs. time obtained with the BOOTES–2/COLORES spectrograph. The uncertainties of the peak intensities are comparable to the size of the symbols. The time (in seconds) is measured with respect to the BAT trigger time (T₀; D'Elia et al. 2014).
is the maximum possible value, since the effects of gravity darkening, that might be important for highly rotating stars, might have not been taken into account.

2 OBSERVATIONS

2.1 X-rays, γ-rays and optical

The BAT instrument on-board the Swift satellite detected a superflare from DG CVn and triggered observations at 2014–04–23, 21:07:08 UT (i.e. hereafter called $T_0$; D’Elia et al. 2014). During this (so-called) main flare the hard X-ray source had a peak intensity in the BAT (15-50 keV) band of $\approx 300$ mCrab or 0.06 count cm$^{-2}$ s$^{-1}$. The initial Swift X-Ray Telescope (XRT; Burrows et al. 2003) flux in the 2.5 s image was $4.10 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (0.2–10 keV). In the optical/UV the source was too bright and saturated Swift/UVOT during the first flare (Drake et al. 2014). An optical counterpart coincident with DG CVn (and also with the X-ray source 2XMM J133146.4+291635) was identified (Xu et al. 2014) at 21:41:20 UT on 2014–04–24. Initial reports of the optical-light curve indicated significant enhancement in brightness at the position of the transient and a subsequent fading of 0.92 mag/hour for the first hour of observation after the peak flux (23:30:00–30:30 UT), followed by a decay rate of 0.34 mag/hour for the rest 2.5 hours of observation (Gazeas & Sapountzis 2014). The MAGIC telescopes started observations of the transient event at 21:48:54 UT, about 30 s after the alert was received, and kept collecting data for the next 3.3 h. A preliminary analysis gave an integral flux upper limit of $1.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ at $\approx 200$ GeV with a confidence limit of 95%, corresponding to 5.3% of the Crab Nebula flux in this energy range, assuming a Crab-like spectral index (Mizovat 2014).

Several more smaller flares were observed with UVOT and XRT (Drake et al. 2014) after the initial trigger. They decreased in peak brightness as the overall brightness declined. When the Swift X-Ray Telescope (XRT) started observing at $T_0 + 117$ s, the soft X-ray 0.3-10 keV rate of DG CVn was $\approx 100$ cts s$^{-1}$ and then decayed moderately, reaching a count rate of $\approx 50$ cts s$^{-1}$ by $\approx 328$ s after the trigger. The soft X-ray emission had declined to a level of 4-15 cts s$^{-1}$, but at $T_0 + 11$ ks DG CVn was observed to have had a second, smaller flare that peaked at $\approx 30$ cts s$^{-1}$ in the XRT detector. We will refer to this as the second flare hereafter.

2.2 Observations with “Pi of the Sky”

The “Pi of the Sky” (Pi) experiment is designed to monitor a large fraction of the sky with a high time resolution (10 s) and self-triggering capabilities (Cwiok et al. 2003, Mankiewicz et al. 2014). This means that Pi may be performing observations of the field of sources well before the trigger time ($T_0$), the latter given by high-energy instruments (like Swift/BAT). This approach resulted in the optical monitoring of DG CVn even before $T_0$. Pi observed DG CVn from $T_0 - 700$ s until $T_0 + 1100$ s. In Fig. 1 the light curve is shown since $\approx T_0 - 150$ s onwards (since no significant brightness variations were detected before).

As can be seen, the optical flash only lasted about 60 s, with the source brightening by over 4 mag, to V=7 at maximum (occurring at $t = T_0 - 41.3 \pm 0.4$ s), and ending before the maximum of the hard X-ray emission which triggered the BAT alert ($T_0$). Then, a slow decrease of the optical brightness was observed reaching $V = 11$ after about 0.5 h.

2.3 Observations with BOOTES

BOOTES (acronym of the Burst Observer and Optical Transient Exploring System) is a world-wide network of robotic telescopes. It was originally designed from a Spanish-Czech collaboration that started in 1998 (Castro-Tirado et al. 1999, 2012). The telescopes are located in Spain (BOOTES–1, BOOTES–2 and BOOTES–IR), New Zealand (BOOTES–3) and China (BOOTES–4). Currently, one optical spectrograph is built and working in the BOOTES network, i.e. COLORES at BOOTES–2. COLORES stands for Compact Low Resolution Spectrograph (Rabaza et al. 2014). It works in the wavelength range of (3 800 – 11 500) Å and has a spectral resolution of (15 – 60) Å. The primary scientific target of the spectrograph is prompt GRB follow-up, particularly for the estimation of redshift, but it is also used to study optical transients. COLORES is a multi-mode instrument that can switch from imaging a field to spectroscopy by rotating wheel-mounted grisms, slits and filters within an otherwise fixed optical system. BOOTES–2/COLORES started observing DG CVn at $\approx T_0 + 11$ min and started to take spectra later at $\approx 0.04$ d (i.e. $\approx 1$ h) after $T_0$, following the evolution of the source for several months. In this paper we report only on the observations when the source showed emission Balmer lines (i.e. when it was “active”). See Tab. 1 and 2 and Fig. 3 for a log of the observations and the evolution of the spectra during the period of activity from the source ($t - T_0 \leq 5$ d).

BOOTES–4 observed DG CVn from $t - T_0 = 450$ s to $t - T_0 = 0.01$ d continuously in the clear and the Sloan g’,r’,i’ and the UKIDSS Z,Y filters. The best resolution achieved was 0.5 s. DG CVn showed a monotonic decrease in flux during this period. Magnitudes close to the quiescent value were obtained from $t - T_0 = 0.7$ d onwards.

2.4 Observations with GTC/OSIRIS and BTA/SCORPIO

We observed DG CVn with the Optical System for Imaging and low-intermediate Resolution Integrated Spectrograph (OSIRIS; Cepa et al. 2000), located at the focal plane of GTC (10.4 m), on 2014–04–23 (see Tab. 1). We used three grisms with three different spectral resolutions, i.e. R 1000 R, R 2500 R and R 2000 B. The blue spectra, R 2000 B, cover the (3 950–5 700) Å energy range with high-resolution, i.e. R 1000 R, R 2500 R and R 2000 B. The red spectra, the R 1000 R and R 2500 R grisms cover the energy range (5 100–10 000), (5 575–7 685) Å, respectively. They are very similar to the spectra obtained with BOOTES–2/COLORES, with the most noticeable features being the presence of molecular absorption bands and the intense H$_β$ emission line, at $\approx 6563$ Å, typical for the spectra emitted by “active” late-spectral type stars.

We also obtained a medium-high spectral resolution spectrum with the Spectral Camera with Optical Reducer for Photometric and Interferometric Observations (SCORPIO; Afanasiev et al. 2005), mounted on the BTA (6 m) telescope from the Special Astrophysical Observatory (SAO) on May 8th, 2014. Less intense Balmer emission lines can be seen. This indicates that the source still maintained a (low) level of activity at this time.

2.5 Observations with CAHA/CAFE

We observed DG CVn with the Calar Alto Fiber-fed Echelle Spectrograph (CAFE), located at the focal plane of the Calar Alto (CAHA) (2.2 m) telescope, on 2014–06–15 (see Tab. 2). This is...
Figure 3. **BOOTES–2/COLORES** spectra taken before, during and after the second flare event. a. The spectra were taken at $t - T_0 = 0.049, 0.054$ d. These show intense Balmer emission lines ($H_\beta$, $H_\gamma$, and $H_\delta$) and some absorption-emission features at $\lambda = 4890, 4985, 5160$ Å. The regions used for the fitting of the pseudocontinuum are marked with the red line; b. Spectra obtained during the time of the flare. Time-evolution of the (relative to the continuum) intensities of the $H_\beta$ Balmer and transient emission line at $\lambda \approx 5160$ Å; c. Spectrum at the late phase of the burst ($t - T_0 = 2.976$ d). Emission Balmer lines are marginally detected and the strength of the absorption features ($\lambda = 4890, 4985, 5160$ Å) has increased. The feature at $\lambda = 5160$ Å underwent a large change in time – from a blue-wing emission and a shallow absorption (panel a) to a gradual increase of absorption which even replaced the emission line (panel c). This line was in a deep absorption in the following nights. The intensity is normalized to unity at $\lambda = 5050$ Å in panel c; d. Spectrum showing the He II (4686 Å) emission line taken close to the time of the second flare ($t - T_0 = 0.07$ d). a high ($R \approx 62,000 \pm 5,000$) resolution spectrograph working in the (3960 – 9500) Å wavelength range. The spectral resolution is < 0.01 Å.

The high-resolution spectrum of DG CVn during 2014–06–15, at the 2.2 m CAHA (+CAFE), contains plenty of absorption lines (mainly TiO bands), with few emission lines. The only instances of significantly broad (absorption) lines are cited in the following. Balmer lines are not seen either in absorption or in emission. Indeed, the spectrum is typical of a cold late-type (“non-active” at that time) star. There are prominent broad absorption lines at 7970 – 8010 Å, that dominate the spectrum in this energy range. They correspond to VO molecular transitions. These molecular transitions appear only for late-type M dwarf stars (M7 or later; Keenan & Schroeder [1952; Kirkpatrick, Henry & McCarthy [1991]). Therefore the red-dwarf might be smaller than previously considered. Nevertheless, a proper spectral classification of the emitting star on the basis of the observed high-resolution spectral features is out of the scope of this paper.

We observe at 8662 Å the Fe I doublet in absorption. The presence of this doublet is indicative of a late spectral type star in a “non-active” state at that time. This absorption doublet line disappears when the star turns activity on, due to the chromospheric heating produced during the stellar flares (Martin [1999]). The activity of DG CVn is greatly diminished during our CAFE observations and this translates into deeper Fe I and absorption lines in general.

### Table 1. Log of the photometric observations reported in this work.

| Obs. Date   | $\Delta t$ | Telescope/Instrument |
|-------------|------------|----------------------|
| 2014-04-23  | – 2014-04-23 | -0.002 – 0.003 PI    |
| 2014-04-23  | – 2014-04-27 | 0.0075 – 3.305 BOOTES-2 |
| 2014-04-23  | – 2014-04-24 | 0.005 – 0.759 BOOTES-4 |

1 The start time of an observation.
2 The elapsed time from the start of the GRB (in days).
3 RESULTS

3.1 Optical and X-ray emission during the first flare

The delay of the initial peak of the X-ray emission (Swift/BAT in the 15-25 keV energy range) with respect to the peak in the optical is clearly seen in Fig. 1. We ascribe these observations to the so-called Neupert effect (Neupert 1968), observed before (apart from the Sun) in UV Ceti and Proxima Centauri (Guedel et al. 1996, 2002, 2004) with radio and X-ray observations of normal stellar flares. From the Sun and these stars it was seen that the X-ray light curve is observed to follow approximately the time integral of the V-band emission (radio emission in the case of the Sun). The interpretation is given in the framework of the chromospheric evaporation (Neupert 1968), i.e. high-energy electrons travel along magnetic fields, where the high-pitch angle population emits prompt gyrosynchrotron emission and the low-pitch angle population impacts in the chromosphere to produce prompt radio/V band emission. The hot thermal plasma (soft X-rays) evolves as a consequence of the accumulated energy deposition, hence the integral relation. The novelty in our case is that this relationship is observed to happen in the hard X-ray emission as well, contrary to previous expectations.

In the chromospheric evaporation the soft X-ray emission is a signature of the thermal emission from the heated plasma. This plasma is heated after the impact by the accelerated particles, that are responsible for the early optical/radio-emission. Therefore, the detection of hard X-ray emission following the integral of the impulsive optical emission is something unexpected. This indicates that, contrary to what has been previously understood, either the plasma heats-up to E>15 keV or that the particles emit radiation following a non-thermal kinetic distribution.

3.2 Optical spectroscopic observations

In the following we report on the optical spectroscopic observations performed with BOOTES-2/COLORES from the beginning of the second flare (approx.) onwards. The optical spectrum from DG CVn is characterized by a strong and variable red continuum with broad molecular TiO, CaI, MgI, NaI absorption lines/bands superimposed. There are also intense Balmer emission lines. We notice that the intensities of the lines reported in this paper are not absolute fluxes, but relative values with respect to the continuum. To calculate the relative intensities reported in this work, local continuum segments were taken at λ = 3 990 – 4 195, 4 200 – 4 385, 4 635 – 5 080, 5 100 – 5 240 Å for each Hα, Hβ, and Hγ emission Balmer line, respectively. We label the continuum calculated from these segments “pseudocontinuum”, since it is not the true continuum, because it is very much affected by absorption band features in the spectrum (not constant a priori). We considered these Balmer emission lines to be excellent indicators of the spectral variability compared to the Hα line. We did this in order to avoid possible effects due to (minimal) saturation, because the Hα line was very bright. The “relative” intensity of these lines (with respect to the continuum) is variable with time, showing a constant “plateau” during the early phase of the burst (t – T0 ≲ 0.1 d), with the exception of a “depression” (i.e. broad minimum at t – T0 ≲ 11 ks) that coincides both in time and duration with the second flare event (Fig. 4). After the “plateau”, the (relative) intensity of the Balmer lines progressively decreased with time until t – T0 ≲ 3 d. Eventually they remained minimally oscillating around a mean value close to unity (i.e. the continuum flux level).

The long term evolution of the spectrum can be roughly characterized by the decrease of the intensity of the Balmer emission lines. At the early stage of the burst (t – T0 ≲ 3 d) these lines are prominent and clearly visible in the spectrum. These lines show that the star is chromospherically “active” at the moment they are present. Eventually (t – T0 > 15 d), these lines disappear and the spectrum becomes emission-featureless. This is the typical spectrum of a “non-active” cold red-dwarf star.

But apart from the intense Balmer emission lines and broad molecular bands there are further weaker absorption and emission lines. We based our identification of these lines on the similarities with those shown in the spectra from cold red-dwarf stars (Pettersen, Cochran & Barkel 1985). We find a number of spectral line features, at λ = 4 890, 4 985, 5 160 Å. The first and the second are emission-like and the third shows an emission+absorption line feature. After looking in more detail into the time evolution of the λ = 4 890 Å emission-like line we realized that this feature is close to the boundary of the TiO absorption band. The feature at λ = 4 985 Å looks like a weak emission that is only sometimes present. The λ = 5 160 Å feature is often seen in absorption but sometimes it looks like a combination of absorption line and emission on its blue wing. These two lines correspond to TiO (4 985 Å) and MgH+TiO (5 160 Å) absorption bands, when compared with the higher resolution OSIRIS R2000B spectra taken during the 3rd day of BOOTES-2 observations. Nevertheless, still marginal residual emission at 5 160 Å is seen in the OSIRIS R2000B (we will discuss this feature hereafter). Also time evolution of the CaOH depression (at λ = 5 530 Å) is shown in Fig. 4. The presence of the CaOH depression is a way to distinguish normal M stars from Me (emission) stars (Pettersen, Cochran & Barkel 1985). The CaOH depression was weaker in the early phase of the burst (t – T0 < 0.1 d) and then it increased in the late phase (t – T0 > 0.2 d). A wider broad dip minimum in the strength of the CaOH similar to that seen for Balmer lines at t – T0 < 0.12 d is also observed for CaOH.

In Fig. 4 we show that both Hγ and the CaOH absorption band decrease in relative strength at the time of the second flare. The time evolution of the Balmer lines and the CaOH absorption line are correlated during the early phase of the burst t – T0 < 0.2 d. Close to the end of the burst, the Balmer emission lines become marginal and the CaOH absorption band maximal. We will discuss hereafter that both CaOH and Balmer lines features are good tracers of the behaviour of the continuum from the source. In Fig. 4, we show that the line at λ = 4 890 Å (TiO) is the least time variable feature. We have checked whether this feature could be a good indicator for the local continuum taken around Hα and found similar values to those obtained when using the local pseudo-continuum.

This makes us confident on our choice of the local continua when calculating line (relative) intensities.

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**Table 2. Log of the spectral observations reported in this work.**

| Obs. Date | Δf | Telescope/Instrument |
|-----------|----|----------------------|
| 2014-04-23 – 2014-04-27 | 0.044 – 3.305 | BOOTES-2/COLORES |
| 2014-04-25 | 1.232 – 1.236 | GTC/OSIRIS-R1000R |
| 2014-04-25 | 1.233 – 1.238 | GTC/OSIRIS-R2500R |
| 2014-04-25 | 1.238 – 1.246 | GTC/OSIRIS-R2000B |
| 2014-05-08 | 14.87 – 14.88 | BTA/SCORPIO-I |
| 2014-06-15 | 52.99 | CAHA/CAFE |

1 The start time of an observation.
2 The elapsed time from the start of the GRB (in days).
There are also transient emission features in our spectra at $\lambda=5\,160, 5\,850, 4\,647\,\AA$. These lines are compatible with blueshifted Mg I, He D3 and He II (at $\lambda = 5\,183, 5\,876, 4\,686\,\AA$, respectively). They are blue-shifted by $\approx 15\,\AA$ ($\approx 37\,\AA$ in the case of He II), i.e. the same amount of shift as the $H_\alpha$ line (as shown hereafter), thus indicate chromospheric origin like the Balmer emission lines. Indeed, these lines have been seen during solar total eclipses (Voulgaris et al. 2010), supporting their chromospheric origin. Also, the $5\,876\,\AA$ line appears in emission in very strong solar flares (Johns-Krull et al. 1997 and references therein). Apart from this, these transient lines are absent during most of our spectral observations. Namely, these lines show an increase of their intensity during $t-T_0 \approx 10\,\text{ks}$, coinciding with the time of the second flare event (see Fig. 3). During the rest of the time the $5\,160\,\AA$ feature becomes purely a MgH+TiO absorption feature. We will discuss the importance of these transient emission features hereafter.

### 3.3 Shifts of the $H_\alpha$ line

Looking into the COLORES red spectra of DG CVn (in a period out of X-ray activity) in more detail, we see that the emission $H_\alpha$ line is shifting and we can tentatively see that it has a double-peaked profile. This is better seen in the higher resolution OSIRIS (Fig. 5) and SCORPIO spectra. The $H_\alpha$ line shows a complex P-Cyg profile, with two emission components neither of which are centred at the nominal centre of an $H_\alpha$ emission line. The brightest and the faintest peaks are red and blue-shifted by variable amounts, with the centre of the lines moving in the (6 572-6 579) $\AA$ and (6 548-6 555) $\AA$ wavelength ranges, respectively. The centre of the complex (i.e. absorption component) of the two lines is static (6 563±1) $\AA$, coinciding with the centre of the $H_\alpha$ emission line at rest.

The double profile $H_\alpha$ has $\approx 15\,\AA$ red-shifted and a blue-shifted components. If we interpret these shifts as moving material around DG CVn, it would be moving in and out of the star at a speed of $500\,\text{km\,s}^{-1}$. This is far greater than the previously measured rotational speed of the star (i.e. $50\,\text{km\,s}^{-1}$) and indicates the likely presence of important chromospheric activity. Additionally, the stationary absorption line corresponds to photospheric absorption from the surface of the active star. Unfortunately, neither $H_\beta$, $H_\gamma$, nor $H_\delta$ show the same effect, due to their lower intensities.

Previous studies observed a solar flare with high-resolution spectroscopy found that the $H_\alpha$ emission line during the flare was also double-peaked during flaring activity periods (Johns-Krull et al. 1997). As in our case the line was also asymmetric, with the red wing having more emission than the blue. This effect was interpreted as redshifted emission coming from chromospheric condensations and falling towards the photosphere, or else as blueshifted absorption coming from optically thin material and rising towards the corona. They found broad emission $H_\alpha$ line profiles ($\approx 100\,\text{km\,s}^{-1}$). In our case the line profiles are broader ($\approx 500\,\text{km\,s}^{-1}$), indicating the presence of a more extreme/powerful flare event giving rise to them.

### 4 DISCUSSION

#### 4.1 On the estimation of the age of the system

The age of DG CVn still has not been well established. Originally it was estimated to be between the ages of the stellar associa-
Conclusions

In this paper we have studied the spectral evolution of DG CVn during an episode of important optical and hard X-ray activity. During this period at least two flares have been detected to occur quasi-simultaneously in both energy bands. We have explained the origin of the (few tens of seconds) hard X-ray delay with respect to the optical emission (Fig. 1) by the Neupert effect, which was observed before (apart from the Sun) in UV Ceti and Proxima Centauri during normal soft X-ray flares. The novelty of our study is that we observe this effect, but for the hard X-ray emission. The X-ray luminosities during the peaks of emission are \( L_{\text{X}}(0.3 – 10) \text{ keV} = 1.4 \times 10^{33} – 3.1 \times 10^{35} \text{ erg s}^{-1} \). Although the flare X-ray luminosities are certainly high similar values (\( L_{\text{X}}(0.3 – 10) \text{ keV} \approx 10^{35} \text{ erg s}^{-1} \)) have been detected for a dozen of cases in main-sequence red-dwarf stars. Recently these values have been superseded by an intense episode of activity from the red-dwarf binary system SZ Psc (Drake et al. 2015). Also the duration of the flaring episode is no exception, with similar values reported for the (9 day) flare of CF Tuc observed by Kurster & Schmitt (1994) and the previous super-flare from EV Lac (Osten et al. 2011). Such episodes of increased X-ray/optical activity have never been observed in the Sun so far. However, the same physics underlying the giant X-ray/optical solar flares serves to explain the superflares observed in active-like stars (as DG CVn; Aulanier et al. 2013). Nevertheless, since the most powerful solar flares have been of only about \( 10^{32} \text{ erg s}^{-1} \) (Carrington 1859) the scale-up of solar flares models would require enormous starspots (up to 48 degrees in latitude/longitude extent) to match stellar superflares, thus much bigger than any sunspots in the last 4 centuries of solar observations. Therefore (Aulanier et al. 2013) conjecture that one condition for Sun-like stars to produce superflares is to host a dynamo that is much stronger than that of the Sun. It is also worth to mention that some recent studies (Kitze et al. 2014; Candelaresi et al. 2014; Wu et al. 2015) point out to both the (possible) few instances and the possibility of Solar-type stars undergoing superflares with luminosities as high as \( 10^{35} – 10^{37} \text{ erg s}^{-1} \) under certain conditions, by using data from the Kepler satellite (Koch et al. 2014).

In our work optical spectral observations began one hour after the onset of the burst, thus allowing a detailed study of the spectral properties of DG CVn during the evolution of the second flare. Balmer emission lines are prominent during the whole period of activity of the star. The optical spectra are similar to the spectra emitted by “active” late-spectral type stars. A significant decrease in the (relative to the continuum) intensity of the Balmer lines is observed during the second flare (Fig. 2). Balmer lines represent the formation and evolution of the optically thin medium above the stellar photosphere (i.e. the chromosphere). On the other hand, the variable strengths of the CaOH and TiO features represent the variations of the photosphere of DG CVn itself (where the absorption lines and the continuum emission are thought to come from). The Balmer and CaOH depressions are due to an increase of the continuum emission as well. The presence of absorption bands is due to the molecules present in the photosphere of DG CVn. As the continuum level increases the (relative to the continuum) strength of the Balmer lines and the CaOH absorption band decreases, as observed during the second flare. Therefore, the decrease of intensity of these spectral features is not real, but an artifact of an increase of the surrounding continuum.

It is in the chromosphere where the Balmer and the rest of emission lines originate. The chromosphere is more tenuous and hotter than the photosphere. Therefore only emission lines from

Figure 5. GTC/OSIRIS spectra from Obs. 1–6 measured from the data taken on the 2014/04/25 night (in black, red, green, blue, yellow and brown, respectively).
light elements can be seen, except in the coronal transition region, where the high temperatures can ionize Fe. An increase in the intensity of the Mg I (5183 Å), He D3 (5876 Å) (and He II; 4686 Å) emission lines have been detected during the second flare of DG CVn. This indicates a correlation between the photospheric and the chromospheric activity. In other words, a change in the properties of the continuum is related to properties of the chromosphere of the red-dwarf star. We will discuss in the following on the most likely origin of this change.

The super-flare observed from DG CVn during April 2014 may correspond to an episodic high-intensity flare event from a red-dwarf star. This flare event is originated from one or more active regions on the star. If there is only one active region giving rise to the observed flaring activity this star would be spinning very rapidly, with a period of a few hours ($P_{rot}\approx2.5h$), thus giving rise to the optical phenomenology observed. Photometric studies of DG CVn performed earlier have revealed a periodicity of $P_{phot}=0.10836(2)$ d (Robb, Balam & Greimel 1999). Indeed, Robb, Balam & Greimel (1999) claimed that a hot spot model fit their single-band data best. This period is very close to the elapsed time between the first and the second flares, which might argue in favour of one hot spot being the responsible for both flares. Nevertheless, the presence of a second active region (responsible for the second flare) can not be discarded. Indeed, many active stars have active regions separated by 180 degrees in longitude. This would “double” the rotational period of the star. Also, given that rapidly rotating stars often have rotational modulation might also be due to the fact that the associated active region(s) responsible for the optical flare might be also circumpolar.

Further spectroscopic and photometric observations of DG CVn would help in order to identify which is (are) the active component(s), their inclination and the actual rotation of the star. The use of spatially resolved measurements and multi-band photometric data would help us to understand the exact origin of the variability.

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