

ASTROPHYSICS OF “EXTREME” SOLAR-LIKE STARS

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RESUMEN

Sólo unas pocas estrellas enanas rojas en la vecindad solar han experimentado eventos excepcionales llamados súper-erupciones. Éstas han sido detectadas por los satélites de alta energía (entre ellos el satélite *Swift* de la NASA) y se ha demostrado que son acontecimientos de gran alcance (tanto en intensidad como en energía) y potencialmente peligrosos para cualquier tipo de vida extraterrestre. La física de estos eventos puede ser entendida como una extrapolación de la actividad (mucho) más débil de la que ocurre en las llamaradas más potentes que se producen en el Sol. Sin embargo, el origen (el ¿por qué?) de estas super-llamaradas actualmente se desconoce. Un estudio reciente presenta la emisión óptica y de rayos X mas la evolución a largo plazo de la súper-llamarada de la estrella enana roja DG CVn que tuvo lugar en 2014. En dicho artículo se comenta acerca del contexto de estas observaciones y de las propiedades que se pueden derivar a través del análisis de las mismas.

ABSTRACT

Only a few red dwarf flaring stars in the solar neighbourhood have undergone exceptional events called superflares. They have been detected with high-energy satellites (*Swift*) and have been proven to be powerful events (both in intensity and energy) and potentially hazardous for any extraterrestrial life. The physics of these events can be understood as an extrapolation of the (much) weaker activity already occurring in the most powerful solar flares occurring in the Sun. Nevertheless, the origin (why?) of these superflares occur is currently unknown. A recent study presents the optical and X-ray long-term evolution of the emission by the super-flare from the red-dwarf star DG CVn undertaken in 2014. In that paper we comment on the context of these observations and on the properties that can be derived through the analysis of them.

Key Words: gamma-rays: observations — stars: activity — stars: flares

1. INTRODUCTION

Recently, the study of stars similar to the Sun (i.e. those in or close to the main sequence), including its younger and/or older counterparts, is a topic of “top” research. Also, thanks to the discovery of new extra-terrestrial planets (mainly through the discoveries from the *Kepler* mission and others) scientists are currently getting new insights into the importance of the interaction between stars and their respective planets. This interaction may be so im-

portant that it might constitute one of the main drivers into the existence of life in those planets. Not so far from the Sun, we know about the role of the Sun-Earth interaction. Solar storms and powerful ejections in the direction to the Earth considerably affect our daily communications. These powerful solar ejections are due to its magnetic field lines (originated by the solar “dynamo”) that sometimes reach its external surface and create these powerful energetic events through the so called “magnetic reconnection” process. It is only thanks to the magnetosphere of the Earth that we are protected from this ejection of particles and radiation (in X-rays and optical) from the Sun. At least it has been like this during the last hundredth of years (i.e. where the activity of the Sun has been monitored so far). Nevertheless, in other (more active) stars than the Sun this natural barrier might not be enough. They might experience such large ejection events that would decrease any chance of possibility of life in their hosted extra-terrestrial planets to zero. This is a scientific case worth to explore (both in the X-ray and the op-

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tical energy ranges), in order to give us insights into the importance of the stellar activity and its influence in their boundaries.

The main goal of the X-ray *Swift* satellite (Gehrels et al. 2004) is the detection of Gamma-Ray Bursts (GRBs) due to its high angular field of view and rapid (time) reaction. Nevertheless, it has also been revealed to be a fantastic tool for the study of the X-ray emission from transient sources (with often an unpredictable emission behaviour). Observations in the optical are performed by big and medium-sized telescopes on Earth. The former are not suitable for performing the rapid follow-up needed for the study of optical transients (as we will explain hereafter). These transients events are typically of short duration (from fractions of a second to a few days), because the physical processes that originate them are of limited duration/spatial extent. Robotic smaller telescopes are very well suited for performing such studies. This is due to several factors: their observing flexibility, their rapid response and slew times and the fact that they can be located worldwide working remotely (therefore allowing continuous monitoring). Additional observations are triggered after the transient has been detected with large X-ray/Optical Observatories. In this way we can perform deep studies on the nature of these sources.

1.1. *The Burst Optical Observer and Transient Exploring System and its Spectrographs*

BOOTES (acronym of the Burst Observer and Optical Transient Exploring System) is a worldwide 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 at Huelva (BOOTES-1), Málaga (BOOTES-2), Granada, Auckland (BOOTES-3), Yunnan (BOOTES-4) and San Pedro Mártir (BOOTES-5), located at Spain, New Zealand, China and Mexico, respectively. There are plans of extending this network even further (South Africa, Chile,...). These telescopes are medium-sized ($D = 30 - 60$ cm), autonomous and very versatile. They are very well suited for the continuous study of the fast variability from sources of astrophysical origin (GRBs and Optical Transients).

Currently two spectrographs are built and working properly in the network at Málaga and Granada (in the optical and infra-red, respectively). In the following Sections we will show preliminary results obtained so far with COLORES at BOOTES-2.

1.2. COLORES

COLORES stands for Compact Low Resolution Spectrograph (Rabaza et al. 2014). It is a spectrograph designed to be light-weight enough to be carried by the high-speed robotic telescope 60 cm (BOOTES-2). It works in the wavelength range of $(3800 - 11500)$ Å and has a spectral resolution of $(15 - 60)$ Å. The primary scientific target of the spectrograph is a prompt GRB follow-up, particularly the estimation of redshift.

COLORES is a multi-mode instrument that can switch from imaging a field (target selection and precise pointing) to spectroscopy by rotating wheel-mounted grisms, slits and filters. The filters and the grisms (only one is mounted at the moment) are located in standard filter wheels and the optical design is comprised of a four-element refractive collimator and an identical four-element refractive camera. As a spectroscope, the instrument can use different slits to match the atmospheric seeing, and different grisms in order to select the spectral resolution according to the need of the observation.

The current detector is a 1024×1024 pixels device, with 13 micron pixels. The telescope is a rapid and light-weight design, and a low instrument weight was a significant constraint in the design as well as the need to be automatic and autonomous. For further details on description, operation and working with COLORES we refer to M. Jelinek PhD thesis (and references therein).

2. THE RED-DWARF STAR DG CVN

DG Canum Venaticorum (DG CVn; with coordinates (J2000) $\alpha = 13^{\text{h}}31^{\text{m}}46.7^{\text{s}}$, $\delta = 29^{\circ}16'36''$; also named G 165-8AB; Gliese & Jahreiß 1991 and 1RXS J133146.9+291631; Zickgraf 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 $P \approx 7$ yr and magnitudes $V = 12.64, 12.93$, for the primary and the secondary components, respectively (Riedel et al. 2014; Weis 1991). 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 ($\pi \approx 80$ 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 $v \sin(i) = 55.5 \text{ km s}^{-1}$, 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. 2015). Because the two components of the system are separated by 3.6 AU ($\approx 2500 R_*$) 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. 2015) 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, we refer to Caballero-García et al. (2015) for a discussion on its age.

3. THE OPTICAL AND X-RAY ACTIVITY DURING THE SUPER-FLARE IN 2014

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 (Gehrels et al. 2004) Burst Alert Telescope (BAT; Barthelmy et al. 2005). Within two minutes of this T_0 , *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 $T_0 + 11$ 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” (Ćwiok 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 $T_0 + 1100$ s. The BOOTES-2 (Castro-Tirado et al. 1999, 2012) telescope began to observe DG CVn from $\approx T_0 + 11$ min, starting to take spectra later at $\approx T_0 + 1$ 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 $T_0 + 1.2$ d, SCORPIO (Afanasyev et al. 2005) on the 6 m BTA-6 telescope at SAO in the Caucasus at $T_0 + 15$ d and CAFE (Aceituno et al. 2013) on the 2.2 m telescope at Calar Alto at $T_0 + 53$ d. Fig. 1 shows the data from the first flare: the optical lightcurve from PI together with the 15-25 keV *Swift* data, from $T_0 - 150$ s to $T_0 + 300$ s. Optical and X-ray observations by *Swift* XRT of the second flare are shown in Fig. 2.

3.1. 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 (Ćwiok et al. 2007; 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 first optical flash only lasted about 60 s, with the source brightening by over 4 mag, to $V \approx 7$ 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.

4. RESULTS

Caballero-García et al. (2015) studied the spectral evolution of DG CVn during an episode of important optical and hard X-ray activity from 23rd April 2014 onwards. During this period at least two flares have been detected to occur quasi-simultaneously in both energy bands. It was explained in that paper that the origin of the (few tens of seconds) hard X-ray delay with respect to the optical emission (Fig. 1) by the Neupert effect (Neupert 1968), which was observed before (apart from the Sun) in UV Ceti and Proxima Centauri during normal soft X-ray flares. The novelty of that study is that this effect has been observed, but for the hard X-ray emission.

The X-ray luminosities during the peaks of emission are $L_X(0.3 - 10) \text{ keV} = 1.4 \times 10^{33}, 3.1 \times 10^{32} \text{ erg s}^{-1}$. Although the flare X-ray luminosities are certainly high similar values

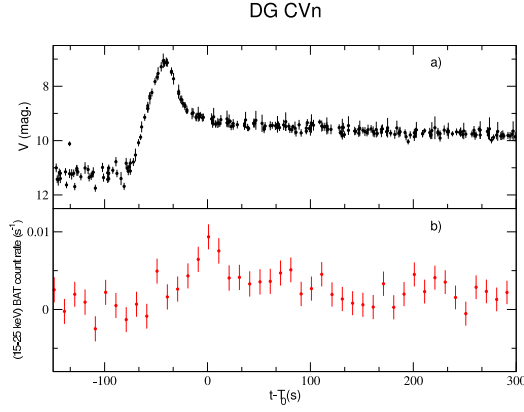


Fig. 1. Hard X-ray delay versus the optical emission of the prompt emission (first flare) from DG CVn. **a**, Optical light curve from the PI (from $T_0 - 150$ s onwards); **b**, *Swift*/BAT light curve in the 15–25 keV energy range (i.e. hard X-rays). The time (in seconds) is measured with respect to the BAT trigger time (T_0 ; D’Elia et al. 2014). Figure taken from Caballero-García et al. (2015).

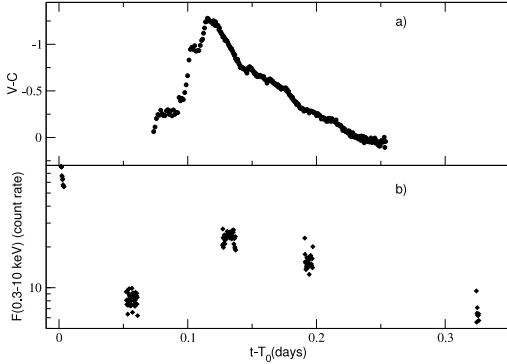


Fig. 2. **a**, Optical light curve variations (with respect to a photometric standard star) in V filter during the second flare of DG CVn at $t - T_0 = 0.127$ d (credits: K. Gazeas); **b**, *Swift*/XRT light curve in the 0.3–10 keV energy range (the Flux is measured in ct s^{-1}).

($L_X(0.3 - 10) \text{ keV} \geq 10^{32} \text{ erg s}^{-1}$) 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 (1996) and the previous super-flare from EV Lac (Osten et al. 2010).

5. DISCUSSION AND CONCLUSIONS

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. 2010). Therefore, this indicates the potential of such events as powerful releases of energy. If so, that would decrease to zero the possibilities of existence of life in any possible hosted planet in these stellar systems.

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