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# Relationships between physical and observational parameters during flares on M-dwarfs

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**Summary.** A great number of short and weak *non white-light flares* has been analysed. The precise measurement of the equivalent width of the Balmer lines has allowed us to estimate the physical parameters of the chromospheric flaring plasma making use of a procedure that assumes a simplified slab model for flares. The detected flares cover areas smaller than  $\sim 2.3\%$  of the projected stellar surface, and show the presence of plasma with electron densities between  $6 \times 10^{13}$  and  $2 \times 10^{14} \text{ cm}^{-3}$  (similar to those reported for flares observed by other authors) and electron temperatures between 12000 and 24000 K. We have investigated the relationships between these physical properties and other flare parameters, finding that the released energy and the peak flux are correlated with the flare duration and the area covered by the flaring plasma, but not with the temperature of the underlying source. With this work, we have significantly extended the existing sample of flares analysed using “good-quality” spectroscopic observations in the optical wavelength range (3550–5180 Å).

## 1 Introduction

Solar flares were discovered by Carrington and Hodgson on September 1, 1859 [2, 19]. However, it was not until 1948 that Joy & Humason detected, for the first time, a flare on a star different than the Sun [23]. Flares are interesting events since they show extreme conditions of temperature, density

and plasma motions. Although stellar flares have been studied for more than half a century, there are still many unknown aspects related with them.

Similarities between solar and stellar flares suggest that the same basic physical mechanisms might be involved. Flares are intense, temporary releases of energy. They produce changes over large areas, from photospheric to coronal layers, and radiate throughout all the electromagnetic spectrum, from  $\gamma$ -rays to radio waves (see reviews [15, 11]). Flares are thought to be caused by sudden reconnection of magnetic field lines in the corona [25]. During the reconnection, charged particles are accelerated and gyrate downward along the magnetic field lines. When these particle beams collide with the chromosphere, the gas in the affected region is heated and evaporated, increasing the density and temperature of the new post-flare loops. Although the complexity of the phenomenon makes difficult to define a typical flare pattern, Pallavicini et al. classified flares into two main types: *impulsive* or *compact flares* and *long decay* or *two-ribbon flares* [28, 30]. The first group occurs mostly inside single loops, while in the second group an entire arcade of loops is disrupted [31].

Flares from late Ke and Me dwarfs (UV Ceti-type stars) are the most similar to solar flares. However, the involved energies can be two orders of magnitude larger than in the solar case [1, 8]. Therefore, larger volumes or higher magnetic fields or both are required by stellar flares [29]. Due to instrumental limitations, stellar flares have been generally observed by using photometry. Nevertheless, spectral emission lines are the most appropriate diagnostics to constrain the physical properties and motions of the flaring plasmas. Unfortunately, only a few sets of observations with adequate spectral and temporal resolution were available (see [20] and references therein). Furthermore, there were few attempts to derive the physical properties of the flaring plasmas in stellar chromospheres [7, 12, 14, 21, 24, 26]. In this work, we have carried out the analysis of a high temporal resolution spectroscopic monitoring of stellar flares and we have made use of the model described in Sect. 2 to obtain the physical properties of the chromospheric flaring plasma. The technical information about the observations is given in Sect. 3. The results obtained with the model and the analysis of the relationships between the parameters that characterize the detected flares are shown in Sect 4.

## 2 The model

In this section we describe the model that has been used to estimate the physical parameters of the chromospheric flaring plasma (a detailed description can be found in [21, 22]). It was developed by Jevremović et al. and takes advantage of the fact that Balmer decrements (flux ratio between Balmer lines and  $H\gamma$ ) are relatively good indicators of the physical properties of flaring plasmas [24].

The model assumes a simplified picture of the flaring plasma as a slab of hydrogen with an underlying thermal source of radiation which causes pho-

toionization. The procedure (BDFP hereafter) minimizes the difference between the observed Balmer decrements and those that are calculated by the model. The calculated Balmer decrements are obtained by solving the radiative transfer equation using the escape probability technique of Drake and Ulrich [9, 10]. The BDFP makes the following assumptions: (i) the Balmer lines are formed in the upper chromosphere; (ii) the escape probability for the slab of Hydrogen is averaged over all directions assuming a uniform distribution of emitters; (iii) complete redistribution of frequencies; and (iv) the line profile can be represented by a Doppler core and broad wings that obey a power-law with slope  $-5/2$  to emulate the Stark effect. The minimization of the difference between the observed and calculated Balmer decrements is done with the multidirectional direct search algorithm of Torczon [32]. The best possible solution for the Balmer decrements provides the electron temperature ( $T_e$ ), electron density ( $n_e$ ) and optical depth in the Ly $\alpha$  line ( $\tau_{\text{Ly}\alpha}$ ) for the slab of Hydrogen, as well as the temperature of the underlying source ( $T_{\text{us}}$ ). In addition, the BDFP estimates the effective thickness of the slab and the surface occupied by the emitting plasma. This model has already been successfully applied to several flares (e.g. [12, 13, 21])

### 3 Observations

High temporal resolution spectroscopic observations were carried out at the *El Roque de los Muchachos Observatory* from La Palma (Spain) during different observing runs (April 2001, December 2002 and March 2003). The Intermediate Dispersion Spectrograph (IDS) was used with the R1200B grating at the 2.5 m Isaac Newton Telescope (INT). The covered wavelength range includes lines from H $_{11}$  to H $\beta$ . The spectral resolution of these spectra, measured as the full width at half maximum (*FWHM*) of the arc comparison lines is  $\sim 1.2$  Å. In order to obtain high temporal resolution, the exposure times were chosen as short as possible. They ranged between 15 and 360 s, and the CCD read-out time was always less than 60 s. Several UV Ceti-type stars were observed (some preliminary results can be seen in e.g. [3, 5, 6]), but this work has been focussed on AD Leo, a very active M3 dwarf located in the immediate solar neighbourhood (4.9 pc).

**Table 1.** Duration, peak flux, and released energy in the H $\beta$  line. Blanks are given when at least one of the flare phases was not completely observed.

Flare #:	1	2	3	4	5	6	7	8	9
Duration (min):	.....	25	.....	31	18	22	25	.....	17
$F_{\text{max}}(\text{H}\beta)$ ( $10^5$ erg s $^{-1}$ cm $^{-2}$ ):	0.90	1.82	0.34	0.70	0.34	1.19	0.94	0.74	0.57
$E(\text{H}\beta)$ ( $10^{29}$ erg):	.....	8.2	.....	4.1	1.5	7.7	7.2	.....	2.1

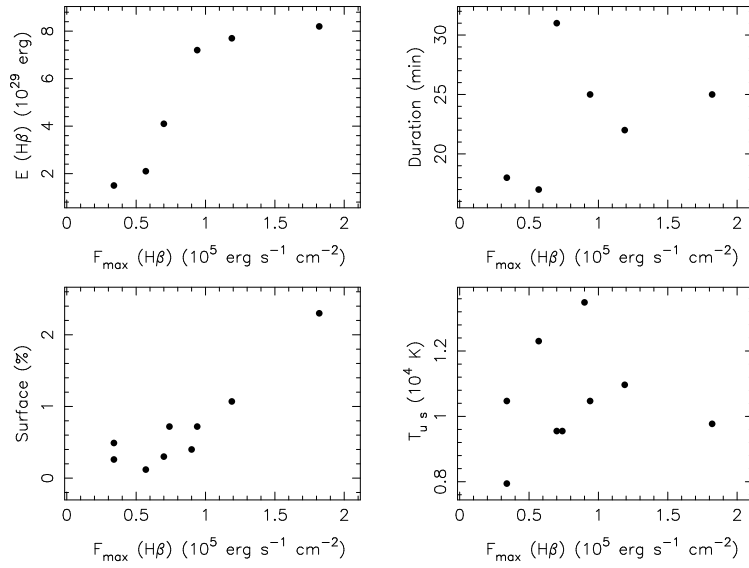
**Table 2.** Physical parameters obtained for the observed flares. The stellar surface percentage covered by each flare is also shown. The electron density is measured in  $\text{cm}^{-3}$  while temperatures are measured in K.

Flare #	$\log \tau_{Ly\alpha}$	$\log n_e$	$\log T_e$	$\log T_{\text{us}}$	Surface (%)
1	3.71	13.75	4.31	4.13	0.40
2	4.62	13.79	4.07	3.99	2.30
3	4.18	14.22	4.09	3.90	0.49
4	3.78	13.95	4.30	3.98	0.30
5	4.54	13.79	4.12	4.02	0.26
6	4.43	14.12	4.07	4.04	1.07
7	4.41	14.39	4.09	4.02	0.72
8	4.15	13.78	4.17	3.98	0.72
9	3.60	13.88	4.38	4.09	0.12

## 4 Results

We have modeled 9 flares that were detected on AD Leo during the nights 3–5 April 2001. Thus, the existing sample of flares studied using “good-quality” spectroscopic observations in the optical wavelength range has been considerably extended (see Sect. 1). The detected flares are *non white-light flares*. Conversely to the Sun, where flares do not generally show any detectable signature in white light, this class of flares is the least known on stars. The duration, flux at flare maximum ( $F_{\text{max}}$ ) and total energy ( $E$ ) emitted in the  $H\beta$  line are given in Table 1. A more detailed analysis of these flares can be found in [4]. They are short and weak flares that occur very frequently (flare activity  $> 0.71 \text{ hours}^{-1}$ ). Results from applying the model described in Sect. 2 are given in Table 2. The plasma affected by the observed flares reaches electron temperatures of 12000–24000 K, and electron densities in the range  $6 \times 10^{13}$ – $2 \times 10^{14} \text{ cm}^{-3}$ , which are in agreement with values reported by authors that use semi-empirical chromospheric models [16, 17, 27]. In addition, the estimated areas are consistent with the typical sizes found for both solar and stellar flares (see e.g. [13, 22]).

We have investigated the relationships between the flare parameters. Fig. 1 shows a clear correlation between the released energy and the flux at flare maximum. In addition, the released energy and the peak flux seem to be correlated with the flare duration and the area covered by the flaring plasma, but not with the temperature of the underlying source. These results are in agreement with those found by Hawley et al. using only 4 flares [18]. No clear correlations between the area, temperature and duration have been found: i.e. these parameters seem to be independent. Firstly, the flare duration could be related to the loop length, as in X-rays; secondly, the flare area could be related to the loop width, in the sense that the surface covered by the Balmer emitting plasma would be the projected area of the flaring loops; and finally, the temperature of the underlying source could be related with the depth reached



**Fig. 1.** Released energy in the  $\text{H}\beta$  line, duration, surface and temperature of the underlying source vs. the peak flux in the  $\text{H}\beta$  line in the detected flares.

by the accelerated particles. Thus, magnetic geometry appears to play a very important role in flares, as expected from the generally accepted flare model.

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