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A major optical flare on the recently discovered X-ray active dMe star G 102-21

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Abstract. During the course of UBV photoelectric measurements made at the Catania Astrophysical Observatory we have observed an unusually intense optical flare on the nearby M dwarf G 102-21, the optical counterpart of a strong X-ray source recently detected by ROSAT.

The amplitude of the magnitude increase ($\Delta U \sim 7.3$ mag) and the total energy release in the UBV bands ($E_{UBV} \sim (1.4 \pm 0.3) \times 10^{35}$ erg) put this event among the strongest flares ever detected on UV Ceti-type stars. The U-B and B-V colours of the flare emission did not significantly change during most of the flare development. While the B-V is quite a typical colour for stellar flares, the U-B is much bluer when compared with typical values given in literature. This unusually strong ultraviolet component of the flare emission, together with the very fast flare decay, suggest a possible flare site close to the limb. We find that the observed amount of flare energy could be explained by the fast release of energy stored in a magnetic filament located in between the two G 102-21 stellar components, with a surface magnetic field $\geq$3600 G.

The characteristics of the quiescent optical emission are also discussed.

Key words: stars: activity – stars: flare – stars: G 102-21 – X-rays: stars

1. Introduction

The nearby dwarf G 102-21, a dM3 star (Lee, 1984), is the optical counterpart of an X-ray source recently discovered by Micela et al. (1995). These authors report on 14 ks ROSAT observations performed over $\sim$ 3 days and showing that G 102-21 was rather bright in the 0.1 - 2 keV band, with at least 0.25 cnts s^{-1} on ROSAT/PSPC at $\sim 30'$ off-axis angle. Assuming a thermal spectrum at T $\sim$ 1 keV, as obtained from a thermal spectral fit to the data, Micela et al. (1995) estimated a minimum luminosity of 8×10^{28} erg s^{-1} assuming a distance of 15.6 pc.

G 102-21, other than being rather luminous in X-rays, is also remarkably active and variable virtually at all time scales detectable by ROSAT to such an extent that no quiescent phase is apparent. Therefore, the aforementioned minimum count rate of 0.25 cnts s^{-1} was assumed by Micela et al. (1995) as the quiescent emission level. They also found clear evidence of an X-ray flare, the maximum luminosity of which was at least seven times the "quiescent luminosity". This seven-fold increase, however, has to be regarded as a lower limit of the peak flare luminosity because of the incomplete flare coverage by ROSAT, that might have missed the peak phase.

All these features put G 102-21 in the high X-ray luminosity and activity tail of the young M star distribution obtained by Barbera et al. (1993).

Optical spectroscopic observations, which were prompted by the discovery of the high level of the G 102-21 X-ray luminosity, have shown intense and highly variable H_α and H_β line emissions and have revealed G 102-21 to be a short period binary ($P \leq 17.3$ h) with two components of similar spectral type. For a complete description, analysis and interpretation of the ROSAT/PSPC and spectroscopic observations we refer to Micela et al. (1995).

All the aforementioned signatures of activity make this late type dwarf an interesting target for photometric observations. In this paper we present some results of optical photometry including the detection of an unusually intense flare.

2. The data

The photometric data presented in this paper were collected at the *Mario Fracastoro* station of the Catania Observatory on Mt. Etna on the nights 1993, December 17-18 and 18-19, with an improved version of the URSULA twin-beam photometer fed by a 91-cm Cassegrain telescope. The URSULA photometer is capable of simultaneous observations of a variable and a comparison star, so that short term sky fluctuations or thin clouds equally influence both star fluxes and their ratio remains virtu-

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ally unaffected. The typical observation accuracy is therefore improved to a few millimagnitudes (see De Biase et al. (1988) and references therein for further technical details on the URSULA photometer).

Our aims were: *a*) to obtain accurate determinations of the V magnitude and B-V and U-B colour indices; *b*) to search for low amplitude variability and microflare activity, which characterize the light curves of many active stars of similar spectral type (cf. Ventura et al. 1993; Peres et al. 1993 and references therein, Ventura et al. 1995).

For magnitude and colours determinations, sequential UBV measurements of G 102-21 and of the comparison star HD 37741 were performed using only one channel of the two beam photometer. At the beginning of these single channel measurements, on the first night of observations (Dec, 17-18), the major flare shown in Fig. 3.2 occurred. The analysis of this event is the subject of Sect. 3.2. The fulfillment of our initial goal of determining the UBV magnitudes of G 102-21 was obtained with the data acquired on the following night (Dec 18-19) during an apparently quiescent optical phase (Sect. 3.1).

In order to search for low-amplitude variability and being interested in ascertaining whether such phenomena are time related to flare occurence, on Dec 17-18, shortly after the end of the flare event, we performed simultaneous measurements of G 102-21 and of a nearby field star [RA(2000.0)=05:40:42, DEC(2000.0)=+12:38:19] by the two virtually identical channels of the URSULA photometer, with 5 sec integration time. However, it was possible to collect only 10 min of useful measurements. These double beam data were analyzed by Fourier transform technique for unequally spaced data (Scargle 1982) and also by the MAC autocorrelation technique (Burki et al. 1978). This though rather short time series allows us to assess that no variability with amplitude larger than 0.002 mag and characteristic time scales in the domain 10 - 600 s was present in the optical emission (λ_{eq}=4100 Å, $\Delta\lambda$=2500 Å) of G 102-21 about 40 min after the flare end.

Following the observations reported in the present paper, we have monitored G 102-21 with the URSULA double-beam photometer for 33.8 h during the years 1994-1995. Neither flares, nor signatures of low-amplitude variability on short time-scale were detected. We have also analyzed these data looking for rotational modulation and found no significant results.

3. Results

3.1. The G 102-21 quiescent state

After correction for atmospheric extinction and transformation to the UBV standard system, from the data acquired on the night 18/19 Dec 1993 we obtained the following quiescent magnitude and colors for the system:

V = 11.48±0.01; B-V = 1.44±0.03; U-B = 1.10±0.06

Taking into account that G 102-21 is a binary system with almost identical components, the V magnitude of each of them is V=12.23. The B-V colour is consistent with the value given in the 3rd Gliese catalogue (B-V=1.46) (Gliese and Jahreiss 1991). No information on the U-B colour is present in the literature. Following Schmidt-Kaler (1982), the B-V colour of G 102-21 is consistent with spectral type M1, while the U-B colour is typical of spectral type M3, consistent with the classification, based on spectroscopic data, given by Lee (1984) and Micela et al. (1995).

The bolometric magnitude and radius of G 102-21 can be inferred from its distance d, V magnitude and B-V colour by using the empirical correlations among global parameters derived by Rodonò (1986) from a sample of active M dwarfs, limited but covering rather uniformly the M dwarf parameters' space:

$$BC = -4.816\,(B-V) + 5.430 \quad (1)$$

$$M_{bol} = V - 5\log d + 5 + BC \quad (2)$$

$$\log(\frac{R}{R_\odot}) = -0.2\,V + \log d - 0.327\,BC + 0.138 \quad (3)$$

The rms variance intrinsic to the relation (1) is ±0.36; since in our case $B-V = 1.44 \pm 0.03$, we get for the bolometric correction BC=-1.50± 0.39. From the estimated value of V (12.23), and assuming $d = 21.3 \pm 3.6\,pc$ (Gliese and Jahreiss 1991), the absolute bolometric magnitude and radius of each G 102-21 component are: M_{bol} = 9.09 ± 0.54 and $R = 0.32 \pm 0.17\,R_\odot$, respectively. The uncertainties on M_{bol} and R have been derived taking into account the quoted errors on V, $B-V$, d and BC.

3.2. The optical flare

Shortly after the beginning of our single-channel observations on the night 17/18 Dec 1993, a very strong flare occurred. The flare light curve is shown in Fig. 3.2 as (I_f-I_0)/I_0 versus time, were I_0 is the mean pre-flare flux and I_f the total (star+flare) observed flux during the flare event.

The integration times were 10, 8 and 8 s in the U, B and V bands, respectively. Accounting for the dead time mainly due to the filter-wheel rotation, each band was sampled every 28.2 s. The flare started on Dec 18th at 02:02 UT, reached a first peak at about 02:04 UT, followed by an impulsive phase lasting ∼130 s, and reached the U-band maximum at about 02:09 UT. The descent phase, characterized by secondary impulsive energy release episodes, lasted about 620 s, with an abrupt return to the quiescent level between 02:16 and 02:19 UT. The observed flux increase at flare maximum (ΔU = 7.29, ΔB = 3.88 and ΔV = 3.03 mag) makes this event one of the largest amplitude flares ever detected. The amplitudes of the most intense flares observed to date on UV Cet type stars are in fact ΔU=6.6 for YZ CMi (Kunkel 1969) and more than about 7 magnitudes in the photographic band (hence very likely larger in the U-band) for the event detected on the dM4e star AF Psc, for which a total energy release of ∼4 10^{35} erg was estimated (Greenstein 1977). In stellar associations, few cases of flare-like brightening with ΔU >8.5 mag on very young stars still in their contraction phase have been reported (Haro and Chavira 1969, Moffett 1974). But most of the variability of young stars, still accreting material from the dense interstellar clouds into which they are embedded, seems to be related with the formation of accretion disks and jet-like mass ejection episodes.

Assuming the distance of 21.3 pc given in the 3rd Gliese catalogue (Gliese and Jahreiss 1991) and the quoted magnitudes, the total energy released in the U, B and V bands are:

$$E_U = (8.9\pm 3.0) \times 10^{34} \text{ erg}; \quad E_B = (2.8\pm 0.9) \times 10^{34} \text{ erg}; \quad E_V = (2.3\pm 0.8) \times 10^{34} \text{ erg}$$

respectively, where the quoted errors essentially depend on the uncertainty on the adopted distance for G 102-21 (±3.6 pc). The equivalent durations, defined as the time interval during which the undisturbed star would radiate as much energy as that released by the flare event, were: $\sim 79^h$, $\sim 3.4^h$ and $\sim 1.5^h$ in the U, B and V bands, respectively.

The energy released in the U band accounts for 64% of the total energy radiated in the UBV bands, that is comparable to the energy released by the previously mentioned AF Psc flare, and is about twice the energy released by YZ CMi during the ΔU=6.6 mag flare reported by Kunkel (1969). This YZ CMi flare was characterized by a U-band decay rate of about 0.023 mag min^{-1}, while the G 102-21 flare showed the remarkably faster decay rate of about 0.7 mag min^{-1}.

The time scales of the G 102-21 flare can be compared with the typical flare time-scales given by Pettersen's (1989) empirical relationships between the flare energy E_U and t_{rise} (the impulsive rise time to the flare peak) and $t_{0.5}$ (the decay time from maximum to half-peak luminosity):

$$\log t_{rise} = 0.25 \log E_U - 6.0 \pm {}^{0.3}_{0.7} \quad (4)$$

$$\log t_{0.5} = 0.3 \log E_U - 7.5 \pm {}^{0.3}_{0.7} \quad (5)$$

The G 102-21 flare impulsive phase duration ($\sim$130 s) is consistent with relation (4), while the decay time ($\sim$60 s) is a factor of about 3 shorter than the minimum $t_{0.5}$ compatible with the inferred range of E_U values.

Lacy et al. (1976) derived empirical relations between the flare energies E_U, E_B and E_V in the U, B and V bands, respectively:

$$E_U = (1.20\pm 0.08)\, E_B; \qquad E_U = (1.79\pm 0.15)\, E_V$$

These relations are claimed to be valid over a wide parameter range (cf. Gurzadyan 1980), while the optical band energies we derive for the G 102-21 flare show quite different ratios (E_U=3.2 E_B and E_U=3.9 E_V) indicating a definitely much more ultraviolet bright, i.e. much hotter event. Moreover, following the empirical relation between the absolute magnitude M_V and the mean energy dissipation during a flare (Gurzadyan 1980), the energy released in the U band exceeds the predicted value by more than three orders of magnitudes. Clearly, we observed a rather peculiar and rare event that may not be representative of typical stellar flares. Actually, according to the empirical relations derived by Shakhovskaya (1989) from a large sample of stellar flares, the expected mean flare occurence rate of such an energetic event on typical red-dwarf flare stars is of the order of 10^{-3} hr^{-1}.

3.2.1. Flare colours

In Fig. 3.2 we show the U-band light curve together with the time evolution of the B-V and U-B colours of the flare emission, i.e. after subtracting the quiescent emission. Having the data in the three optical bands been acquired sequentially with constant time intervals between successive observations in the same colour, we have interpolated between the observed points by straight line fits in order to derive the U-B and B-V colours at the times of the U-band measurements. The single data errors of the pure flare B-V and U-B colours were derived taking into account the count statistics and the uncertainty of the interpolated B and V counts arising because of the rapidly changing count rate.

As soon as the first plateau was reached ($\sim$02:03 UT), and up to the end of the impulsive main phase ($\sim$02:09 UT), the U-B and B-V colours were constant at -2.37±0.05 and 0.51±0.05, respectively, while they decreased to -2.52±0.06 and 0.36±0.05, respectively, after the end of the main peak ($\sim$02:10 UT) and up to the beginning of the abrupt and rapid descent phase ($\sim$02:15 UT). The U-B colour of the pure flare radiation is extremely negative when compared with typical U-B flare colours of dMe flare stars, which usually fall in the range from -0.5 to -1.5 (Kunkel 1970; Cristaldi and Rodonò 1975; Gurzadyan 1980). Instead, the B-V value is quite a typical colour for stellar flares.

It must be noted that the evolution of the flaring plasma typically produces continuous changes of flare colours in the two colour diagrams along tracks that are different from one flare to another. However, from this point of view the G 102-21 flare, showing virtually constant colours during most of the flare time evolution, is not a peculiar stellar flare (cf. Cristaldi and Longhitano, 1979). It is worth noting that this flare shows an unusually strong ultraviolet component.

3.2.2. Flare energy and magnetic field

The most energetic events observed on the Sun are two-ribbon flares, which are associated with eruptive filaments. The total energy available for producing a flare is the energy stored in the preflare configuration at the time when a filament instability occurs (cf. Van Tend and Kuperus 1978). Doyle et al. (1989) give the following equation for estimating the maximum energy storage in a filament above a magnetic active region on a single star:

$$W = 1.6\, 10^{37} \left(\frac{l}{R_\odot}\right) \left(\frac{R_*}{R_\odot}\right)^2 \left(\frac{B_{surf}}{1000\, G}\right)^2 \quad erg \quad (6)$$

where l is the semi-length of the filament and B_{surf} the surface magnetic field. Assuming that only 0.003 of the magnetic energy released during the flare actually produces plasma heating (Kopp and Poletto 1984), the total amount of energy (E_{flare}) available to be radiated in the case of G 102-21 is of the order of:

$$E_{flare} = 1.6\, 10^{33} \left(\frac{l}{R_*}\right) \left(\frac{B_{surf}}{1000\, G}\right)^2 \quad erg \quad (7)$$

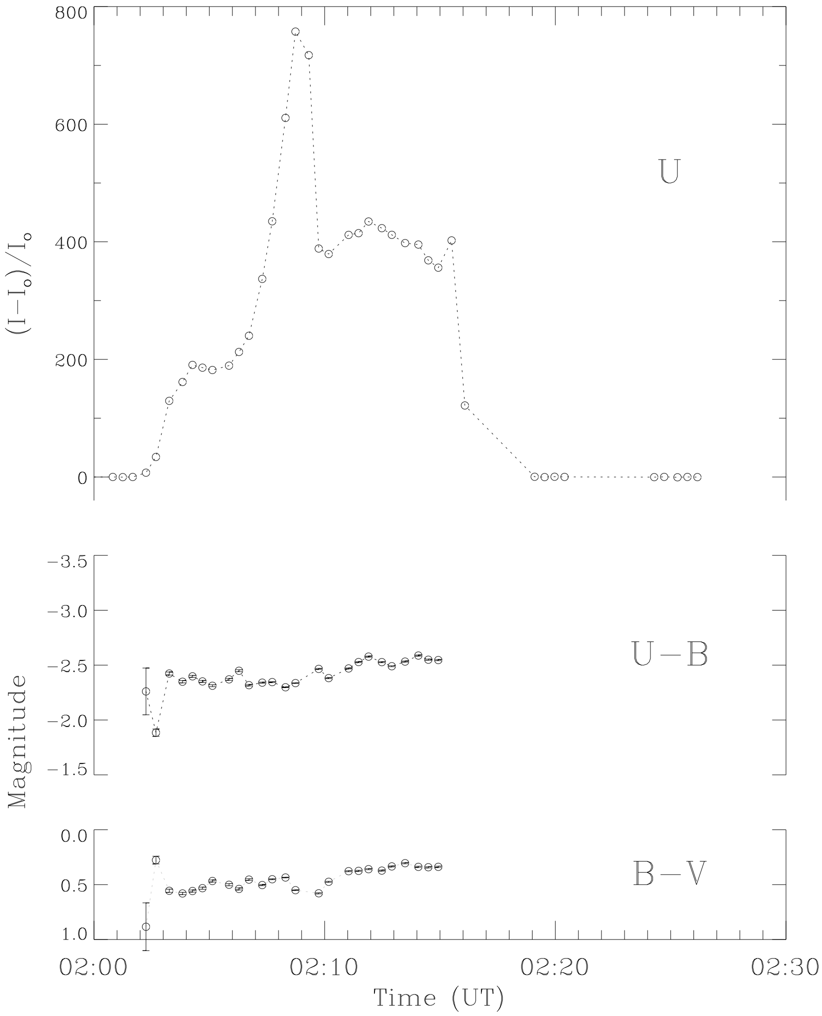

Fig. 1. *Top panel:* The U-band light curve of the G 102-21 flare on 1993, December 18 given as (I_f-I_0)/I_0 versus time, where I_0 is the pre-flare quiescent intensity and I_f the total (star+flare) intensity during the flare. *Middle and bottom panels:* Pure flare U-B and B-V colours. Since the observations were taken sequentially in the three optical bands, we have interpolated by straight lines between the observed points in order to derive the colours at the times of the U-band measurements. The colour error-bars reflect both the count statistics and the uncertainty arising from the interpolation of the B and V counts at the time of U-band measurements.

where R_*=0.32 $R_\odot$ according to the value derived in Sect. 3.1.

The bolometric energy lost during a flare can be estimated as $E_{flare} \sim 30\, E_{UBV}$ (Byrne 1989; Pettersen 1989). Assuming a distance of 21.3 pc (Gliese and Jahreiss 1991), for the G 102-21 flare we then have $E_{flare} \sim 4.2\, 10^{36}$ erg and

$$\left(\frac{l}{R_*}\right)\left(\frac{B_{surf}}{1000\,G}\right)^2 = 2625 \tag{8}$$

If we assume a filament of semi-length equal to 1 R_*, a surface magnetic field as high as $\sim$5.1 10^4 Gauss results; a lower value of B_{surf} would imply a much longer filament. More realistically, a less extreme surface magnetic field is derived if the binary nature of G 102-21 is taken into account. According to van den Oord (1988), the storage of energy within a filament in a binary system can be a factor of $(1.6\, a/R_*)^2$ greater than on a single star:

$$W' = \left(1.6\,\frac{a}{R_*}\right)^2 W \tag{9}$$

Micela et al. (1995) found spectroscopic evidence that G 102-21 has two components of comparable luminosity and mass, and, assuming a tidally locked binary, they estimated an orbital-rotational period $P \leq 17.3$ h. By using Kepler's third law $a^3 = GP^2(M_1 + M_2)/4\pi^2$ and assuming $M_1 = M_2 = 0.3\, M_\odot$ (appropriate for dM3 stars), a binary separation $a \leq 2.8\, R_\odot$ results. This would make the observed flare energy output consistent with a $B_{surf} \geq 3600$ Gauss, again for a loop semi-length of 1 R_*. This value is almost comparable with the magnetic field in the solar active regions and with that typical for dM3 stars derived by assuming equipartition (B^2=$8\pi P_{gas}$). In fact, according to Zwaan and Cram (1989), the mean surface magnetic field is given by:

$$B^2 = 8\pi P(\tau_5 = 1) \tag{10}$$

Here τ_5 is the monochromatic optical depth at λ=5000 Å, and P is the gas pressure in the field-free atmosphere. Assuming $P(\tau_5) = 3\, 10^5$ dyne cm^{-2}, as given by a Kurucz atmosphere model computed for T_{eff}=3500 K and log g = 4.5 (as appropriate for dM3 stars), the photospheric magnetic field on G 102-21 turns out to be B = 2700 Gauss. The above analysis has to be taken as an order of magnitude estimate; however, even allowing for the uncertainty inherent in the above formulae, assumptions and measurements, it appears very likely that for such a rather intense flare the binary nature of the system could play, indeed, an important role in the storage of energy in the preflare configuration.

4. Discussion and conclusion

We have presented the observations and an analysis of the unusually strong optical flare that has occured on the very active X-ray dMe binary G 102-21. The flare event has proven unusual in terms of both the high total energy output in the optical spectral domain ($E_{UBV} \sim (1.4 \pm 0.3) \times 10^{35}$ erg) and of a remarkably negative value of the pure flare colour (U-B = -2.46±0.13, during most of the flare development).

The unusually strong U-B colour of the flare and the apparently abrupt descent of the flare light curve to the quiescent level are both typical characteristics of a flare occuring close to the stellar limb. In fact, according to Avrett et al. (1986) (cf. their model F3), a flare close to the limb has a Balmer continuum about 2.2 times more intense than a flare close to the disk center. The Paschen continuum, on the other hand, does not change from the disk to the limb. Since the U-band flux contains part of the Balmer continuum, the strong ultraviolet excess of the G 102-21 flare could be explained if the flare site were close to the stellar limb. Assuming this hypothesis and taking into account the ratio of 2.2 between the Balmer continuum of a limb flare and a disk flare, the U-B colour of the G 102-21 flare, if on the disk, should have been about 0.85 mag redder than observed, i.e. ~-1.61 mag. This value is in the range of U-B flare colours typically reported in the literature.

Moreover, the unusual shape of the flare light curve, i.e. the apparently abrupt descent to the quiescent level, can also be explained in terms of its disappearance behind the limb of the flaring site due to the star's rotation. Similar, but very few cases have been observed (Cristaldi and Rodonò 1970, Foing et al. 1994). In this case, the longitude extent ΔL of the flaring region is given by $\Delta L = 2\pi dt/P$, with dt the disappearance time and P the rotational period. Taking $dt \sim 4$ min and $0.65^h \leq P \leq 17.3^h$, i.e. P greater than the minimum rotational period allowed before break-up ($P \sim 0.65$ h for M=0.3 $M_\odot$ and R=0.32 $R_\odot$, as adequate for a dM3 star) but less than 17.3 h according to Micela et al. (1995), a longitude extent of the flare site of $1.4^0 \leq \Delta L \leq 37^0$ results.

If the energy released during the course of the flare had been previously stored in a filament, as for solar two-ribbon flares, then, for a loop semi-length of 1 R_* and a binary separation $\leq 2.8\,R_\odot$, a surface magnetic field $B_{surf} \geq 3600$ Gauss is required. Such a mean magnetic surface field is consistent with that provided by the equipartion argument for a dM3 star.

In concluding we note that this star is a very active one in the X-ray band, where virtually no quiescent phase has so far been detected, and in the optical band, where it has generated one of the largest flares ever detected on dMe stars, and also shows high activity in the line emission. It is, therefore, an interesting target for future observations.

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