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Multiband photometric detection of a huge flare on the M9 dwarf 2MASSW J1707183+643933

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ABSTRACT

We present simultaneous UV-G-R-I monitoring of 19 M dwarfs that reveal a huge flare on the M9 dwarf with an amplitude in the UV of at least 6 magnitudes. This is one of the strongest detections ever of an optical flare on an M star and one of the first in an ultracool dwarf (UCD, spectral types later than about M7). Four intermediate strength flares ($\Delta m_{\rm UV} < 4$ mag) were found in this and three other targets. For the whole sample we deduce a flare probability of 0.013 (rate of $0.022\,{\rm hr}^{-1}$), and 0.049 ($0.090\,{\rm hr}^{-1}$) for 2M1707+64 alone. Deviations of the flare emission from a blackbody is consistent with strong H_α line emission. We also confirm the previously found rotation period for 2M1707+64 (Rockenfeller et al. 2006) and determine it more precisely to be 3.619 ± 0.015 hr.

Key words: methods: data analysis – techniques: photometric – stars: activity – stars: flare – stars: late-type – stars: rotation

1 INTRODUCTION

Numerous early and mid M dwarfs are known to show short timescale brightness eruptions – flares similar to those on the sun. They are probably caused by magnetic fields, whereby energy is locally converted to thermal energy by a reconnection of field lines, the consequence of which is a significant increase in the total stellar luminosity. Flares manifest themselves in various wavelength regions, from the radio to the X-ray and as line or continuum emission. The corresponding motions of plasma have been detected by emission line asymmetry (Fuhrmeister et al. 2005, e.g.). In the recent years, a few flares in the optical as well as emission line flares have also been observed in late M and L dwarfs (see below).

The creation process of magnetic fields in fully convective objects (such as UCDs) is not yet fully understood. But it must differ from the $\alpha\Omega$-dynamo present in higher mass stars because this depends on the interface between radiative and convective zones. However, the detection of flares as well as cool surface spots strongly suggests the existence of magnetic fields in UCDs. Recently, Chabrier & Küker (astro-ph/0510075) modelled an α^2-dynamo for ultracool dwarfs. Among other things, they are able to explain the saturation in the rotation–activity relation which has been observed in these objects (Delfosse et al. 1998; Mohanty & Basri 2003).

Amplitudes of flares on K and M dwarfs in the optical have been observed to increase strongly from the red (I-band) to the U/UV (Stepanov et al. 1995; Eason et al. 1992) and no signatures can be traced in the near-infrared. The duration of these events seems to positively correlate with their amplitude and ranges from seconds to a few hours.

Although several extensive photometric monitoring programs of L and T dwarfs have been carried out, only a few flares have been reported, probably because most of these surveys were conducted in the I-band or near-infrared (JHK). Nevertheless, flares have recently been detected by optical broadband photometry, for example by Koen (2005b) in an M8.5 dwarf with an R-band amplitude of almost 2 mag and by Scholz & Eislöffel (2005) in a young VLMS. Koen (2005a) reports of a possible flare event in an object as late as L8 (R-band amplitude of 0.15 mag). Emission line flares have also been reported, e.g. by Liebert et al. (1999) (M9.5 object), Liebert et al. (2003) (L5) and by Fuhrmeister & Schmitt (2004) (M9).

Rockenfeller et al. (2006) (henceforth R06) found periodic variability in the GRI-bands of 2M1707+64 at a period of 3.65 ± 0.1 hr with an amplitude of 0.014 mag in the I-band. By modelling the amplitudes they showed the modulation was best explained by localised cool surface spots in this late-type object (which has a spectral type and estimated age placing it near to the hydrogen burning limit). H_α quiescent emission was found by Gizis et al. (2000) at an equivalent width of 9.8Å, which suggests 2M1707+64 is a very active M dwarf, even during its non-flaring state.

Here, we report the detection of two flares on

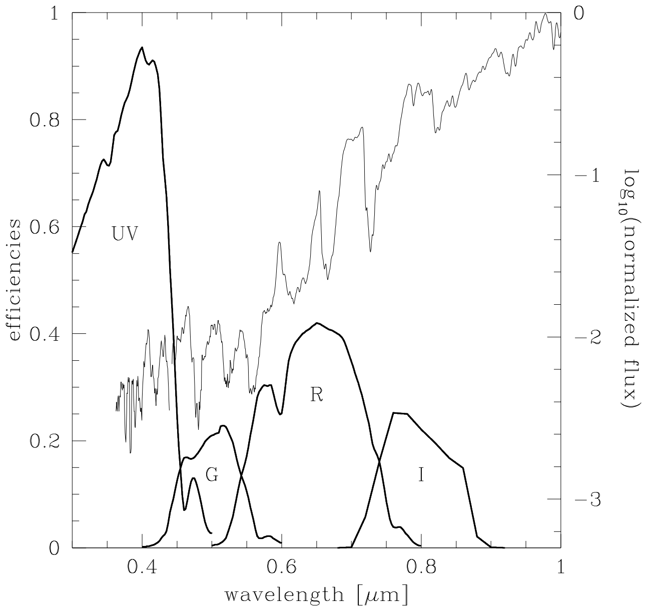

Figure 1. The total efficiencies of the BUSCA UV, G, R and I channels, taking into account the dichroics, the CCD efficiency and the Bessell-I filter used in the I-band. The efficiency of the UV filter drops off rapidly blueward of 0.3 μm due to the atmosphere. Over plotted for reference is a spectrum of the M4.5 dwarf DENIS P-J1158-1201 from Martín et al. (1999).

2M1707+64 of which one has exceptionally large amplitudes throughout the optical, with a peak of more than 6 magnitudes in the UV. We also report the detection of smaller (but still large) flares on three other late M dwarfs.

2 DATA ACQUISITION, REDUCTION AND ANALYSIS

Simultaneous multichannel UV,G,R,I observations of 19 M dwarfs were obtained over 20 nights in June 2002 and 2003 with the four channel CCD camera BUSCA at the 2.2m telescope of the Calar Alto Observatory, Spain. BUSCA uses dichroics to split the light beam into the four wavelength bands which are imaged by four separate CCD cameras. Fig. 1 shows the passbands. The UV, G and R passbands are defined by the CCD response and dichroic transmission function; for the I band we additionally used a Bessel I filter.

Follow-up observations of 2M1707+64 were performed in June 2005 on two nights (14th and 15th) – again in the four channels with BUSCA – during Directors Discretionary Time, as well as on three nights (24th, 26th and 29th June 2005) in the I-band with the 1.5 m telescope at Maidanak Observatory, Uzbekistan. All data were reduced in the same way as described in R06, except that the Maidanak data required an additional fringe subtraction. As in R06, light curves were obtained from differential photometry using a set of stable reference stars. Table 1 shows the observation log. See R06 for detailed information on the analysis of the 2002/03 BUSCA data, in particular time series analysis, determination of rotation periods and spot modelling.

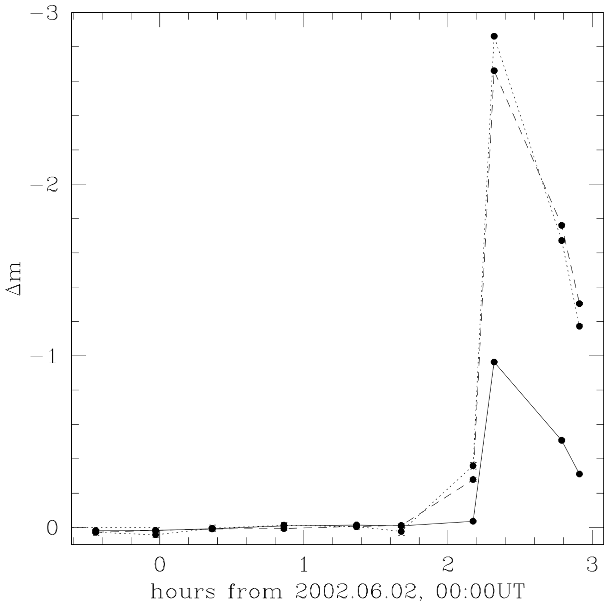

Figure 2. Relative light curves of 2M1707+64 on 2002.06.02, showing the I-band (solid line), R-band (dashed line) and G-band data (dotted line). The UV-band flare amplitude is larger than 6 magnitudes. The error bars are also plotted, but except for the G-band are too small to be visible.

3 FLARES ON 2M1707+64

The time series of 2M1707+64 shows a large increase in brightness toward the end of observations on the morning of 2002.06.02 with increasing amplitudes from I to UV (see Fig. 2). The wavelength dependence, the shape of the light curves and the duration of the event (more than 1.0 hr) are consistent with the signatures of stellar flares on late-type stars (Stepanov et al. 1995). Since the time sampling is quite coarse with respect to the duration of the event, our observations probably missed the maximum. Our reported amplitudes are therefore lower limits to the maximum flare amplitudes. Furthermore, because the target is not visible in the UV-band during its quiescent state we have estimated a lower limit to the UV-amplitude by equating the quiescent target magnitude to the limiting magnitude of the exposure (which is approximately the magnitude of the faintest star visible). The very large amplitudes in all four channels with no change in the reference stars prove that the brightening is intrinsic to the source and is not a result of second order extinction effects, which are far smaller (Bailer-Jones & Lamm 2003). The brightness evolution in the UV-band can be seen in Fig. 3.

The flare amplitudes in the I-, R-, G- and UV-band are 1.0, 2.7, 2.9 and 6 magnitudes, respectively, which is exceptionally large (compare the papers mentioned in the introduction). This is one of the strongest broadband optical flares ever reported (more so as we probably missed the maximum of the event). As a comparison, see Batyrshinova & Ibragimov (2001) who recorded a superflare on an M4 dwarf with an amplitude in the U-band of 11 mag.

If we initially assume that the radiation from the flare is thermal and so obeys a blackbody distribution, we can attempt to determine the plasma temperature ($T_{\rm P}$) and the

Table 1. Observation log of the four M flare dwarfs, listing the objects' names, the dates of observations, the duration of observation the individual nights (in hours) and the instrument/site.

object	dates	duration [hr]	instrument
2MASSW J1707183+643933	2002.06.01 / 02	6.4, 5.6	BUSCA
	2005.06.14 / 15	5.7, 3.9	BUSCA
	2005.06.24 / 26 / 29	5.6, 5.1, 4.4	Maidanak
2MASSW J1344582+771551	2002.05.29 / 2005.06.01	5.2, 6.2	BUSCA
2MASSW J1546054+374946	2003.06.06 / 07 /08	6.4, 2.6, 2.4	BUSCA
2MASSW J1714523+301941	2003.06.03 / 05	6.1, 5.4	BUSCA

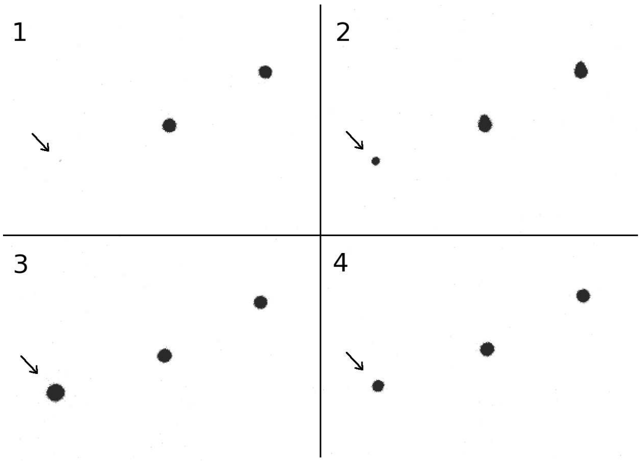

Figure 3. Set of four UV-band images of 2M1707+64 on 2002.06.02. The first image (upper left) shows the object during quiescent state, whereas the following three show the first three (out of four) images of the flare event – the numbers denote the time-order. Each image is a $\approx 2.4' \cdot 1.8'$ clip from the whole field, with North up and East to the left.

(projected) fractional area of the stellar surface that is effected by the flare (A). We used equation 1 of de Jager et al. (1986) for an optically thick plasma to simulate flare amplitudes over a wide parameter space ($5000\,\mathrm{K} < T_\mathrm{p} < 10^5\,\mathrm{K}$ and $10^{-7} < A < 0.5$). Because of the low effective temperature of 2M1707+64, we used an appropriate synthetic spectra of Allard et al. (2001) to model the flux during the quiescent state. The goodness-of-fit of an individual model was judged by a simple function $f(T_\mathrm{p}, A) = 1/4 \cdot (|\delta_\mathrm{UV}| + |\delta_\mathrm{G}| + |\delta_\mathrm{R}| + |\delta_\mathrm{I}|)$, where δ_i is the difference in magnitudes between the observed amplitude and the simulated amplitude in channel i. This reveals a degeneracy in the model (i.e. doubling the temperature and halving the area leads to the same value of f). Moreover, the large values of $f(T_\mathrm{p}, A)$ for all fits indicate that the blackbody approximation for this flare's emission is inappropriate (and/or that the quiescent spectral model is poor). Even the best-fitting simulations could only fit 2 out of 4 channels to within 0.1 mag (UV and G-band), the third within 0.6 mag (I-band) and the R-band always deviated by more than 1.8 mag. This could partly be explained by strong H_α line emission, which falls within the R-band. However, one has also to consider that the UV-amplitude is poorly constrained (we only have a lower limit) which limits the validity of the fitting procedure. Departure from blackbody is not unexpected. For example, from Table 2 of de Jager et al. (1986), we can similarly deduce non-blackbody emission for a flare on the K6V dwarf BY Draconis.

The BUSCA 2005 data reveal another flare on 2M1707+64 at the last data point on the morning of 2005.06.14. For this second flare we find (lower limits to the) amplitudes of 3.70, 0.94, 0.77 and 0.16 magnitudes in the UV, G, R and I-bands respectively. Although at the very end of observations, the size of the amplitudes and the absence of variations in the reference stars rule out an observational artifact. Again, the model fits with the lowest f-value show the R-band amplitude to deviate by more than 0.5 mag while the other three bands can be reproduced to better than 0.1 mag.

In total we obtained 22.3 hr of BUSCA data in 2002 and 2005 on 2M1707+64 which revealed two flares. With a total recorded flare duration of 1.1 hr this implies a probability that the object is flaring at any one time to be 0.049. Note, however, that the flare continued after the end of observations on that morning, so this is a lower limit (see Fig.2). If we instead just count flares, we deduce a flare rate of $0.090 \pm 0.063\,\mathrm{hr}^{-1}$ where the error is obtained by counting (Poisson) statistics. If we also take into account the 15.2 hr of Maidanak data whose sensitivity is restricted to strong flares (approx. $\Delta m_\mathrm{I} > 0.05$, compare Table 2), we obtain a flare rate of 0.029 ($0.053 \pm 0.038\,\mathrm{hr}^{-1}$).

4 PERIODIC VARIABILITY IN 2M1707+64

From the five nights of follow-up observations in June 2005 we detect periodic variations with periods (obtained from Scargle periodograms) in the individual nights ranging from 3.61 to 3.64 hours at a 99.9 % confidence level. This confirms the period we claimed in R06. The application of the CLEAN periodogram to the combined BUSCA-Maidanak data of 2005 yields a period of $P = 3.619 \pm 0.020$ (± 0.015) hr. The first uncertainty estimate (0.020 hr) was obtained by Monte-Carlo simulations which account for the time sampling (see R06). The second estimate is from the theoretical expression for the width of peaks in a periodogram, $\Delta P = P^2/(2T)$, where P is the period and T the total time span covered by the observations. This is only valid for uniform time sampling, an assumption which is strongly violated here. The former result overcomes this, although still assumes the signal to be sinusoidal with Gaussian noise.

We can exploit the non-uniform time sampling in this case to make a more robust estimate of the period uncertainty by constraining a single sinusoidal light curve to fit the data on all nights. The two consecutive BUSCA nights separated by several days from the three Maidanak nights in

2005 (see Table 1) gives a strong constraint on this fit. The best fit gives a period of 3.619 hr, the same as found with the CLEAN periodogram. To estimate the uncertainty in this, we fix the phase of the sinewave at 2005.06.27 00:00UT ($= t_0$) and vary its period until we achieve a phase shift of π over the 13 day difference between the 14/15 June observations and t_0. The difference between this period and the nominal one is 0.015 hr; we (conservatively) define this to be the uncertainty. It cannot be much larger, because if we further change the period until we reach a phase shift of 2π (which still gives a reasonable fit on 2005.06.14 & 15), we now see a significant deviation on 2005.06.24 & 29. Hence, under the assumption that the observed periodic variability on all five nights in June 2005 was caused by the same star spot(s), and that differential rotation is negligible (Barnes et al. 2005), we establish the rotation period (of the spot system) to be 3.619±0.015 hr, an accuracy of better than 1 min. Although the periodogram implies a similar uncertainty, the sinewave fit is more robust.[1] The lifetime of stellar surface spots can be much longer than two weeks (Strassmeier & Bopp 1992) so our assumption is reasonable. On the other hand, the lifetime of spots on very low mass stars and brown dwarfs has been little studied and may differ from G and K stars. If the spot distribution evolves significantly during the 2005 observations then the fitting method is not valid. The data from the five nights phased to 3.619 hr are shown in Fig. 4.

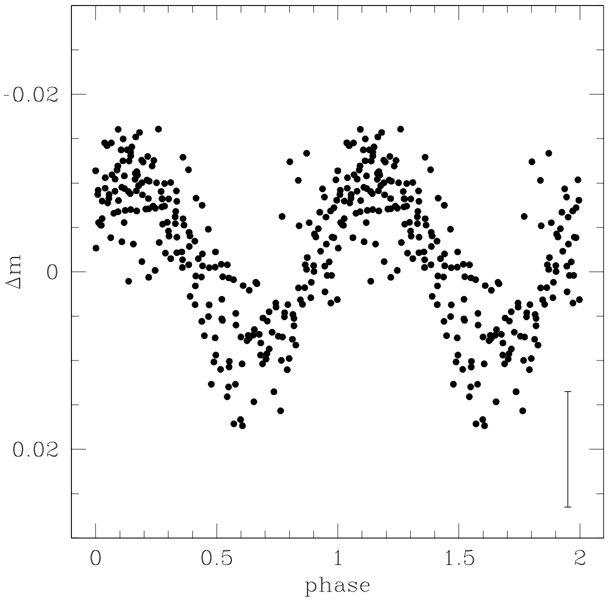

Figure 4. 2M1707+64: I-band light curve of the five nights between 2005.06.14 and 29 phased to a period of 3.619 hr. A typical error bar is also shown. Note that two cycles of the phased light curve are plotted.

5 FLARES ON OTHER OBJECTS

From our 20 night BUSCA survey (R06), we found three further flares, one in each of the following objects: 2M1344+77, 2M1546+37 and 2M1714+30. All three dwarfs have detectable quiescent H_α emission (Gizis et al. 2000). Amplitudes and further properties are listed in Table 2. R06 detected variability in the R-band in 2M1546+37 and 2M1714+30 at an amplitude of 0.012 mag in both cases. A tentative period of 6.9 hr was assigned to the latter in the R-band only. In all three cases the blackbody model fits the observed amplitudes relatively well and the following applies to all three flare events. If we again consider those simulations with low f-values, we find two classes of results. One well reproduces I, R and G amplitudes with a strong deviation in the UV-band ($\approx$ 1.1 mag) and the other fits the I, R and UV well with a deviating G-band amplitude ($\approx$ 0.2 mag). Since the UV-amplitude is not as well determined as the other three (see Sect. 3), the former seems to be more likely and thus indicates relatively good agreement with a blackbody emission. However, various emission lines have been observed in flare spectra in both bands (Eason et al. 1992) and could thus modify the continuum emission (that itself also could be non-blackbody) such that it deviates from a blackbody. This could explain any residual deviations.

6 CONCLUSIONS

From 227.6 hours of multiband monitoring of 19 M dwarfs (218.0 hr with BUSCA in 2002 (R06) and 9.6 hr with BUSCA in 2005), we detected five flares on 4 different targets. From this we infer a flare probability at any one time of 0.013 and a flare rate of $0.022 \pm 0.010\,\mathrm{hr}^{-1}$ for field M2–M9 dwarfs. Although the observation time per object is limited (less than 14 hours per object, except for the follow up observations of 2M1707+64), we conclude that flare activity is not rare in old (field) mid to late M dwarfs and might even be present in most of these objects.

We discovered a massive flare on the M9 dwarf 2M1707+64 with a UV amplitude of more than 6 mag. This object, which is either a very low mass star or brown dwarf, shows a repeat of flare activity at a rate of $0.090 \pm 0.063\,\mathrm{hr}^{-1}$ (probability of flaring 0.049). With both this and another flare on the same object we found deviations of the flares' 4-band emission from that expected for a blackbody. In particular, the R-band always fit poorly, which is consistent with the presence of strong H_α line emission.

We also improved the determination of the rotation period of 2M1707+64, deriving a value of 3.619 ± 0.015 hr, under the assumption that the observed spot was stable over 16 days of observations.

We found three further flares on the late M dwarfs 2M1344+77, 2M1546+37 and 2M1714+30. Their amplitudes and energy release were much smaller than in the case of 2M1707+64 and their emission closer resemble that of a

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[1] Mathematically the uncertainty derived from the sinewave-fitting is $\frac{1}{2}\frac{P}{T} \times P$, identical to the theoretical expression for the periodogram. However, the derivation of the periodogram expression depends on the (invalid) assumption of uniform sampling. With the fitting method, in contrast, we explicitly determine the quality of fit of the data to the model at individual epochs for arbitrary phase shifts.

Table 2. Properties of the detected flares: spectral type, quiescent H_α equivalent widths, the flares' amplitudes in the four bands, an estimate to their duration and the number of recorded data points (samples) for each flare. H_α EWs are taken from Gizis et al. (2000).

object	year	SpT	H_α EW [Å]	$\Delta_{\rm UV}$	$\Delta_{\rm G}$	$\Delta_{\rm R}$	$\Delta_{\rm I}$	duration [hr]	samples
2M1707+64	2002	M9	9.8	> 6	2.9	2.7	1.0	> 1.0	4
2M1707+64	2005			> 3.7	0.94	0.77	0.16	> 0.1	1
2M1344+77	2002	M7	2.7	> 1.6	0.094	0.047	0.007	< 0.5	1
2M1546+37	2003	M7.5	10.9	> 1.7	0.155	0.121	0.022	< 0.75	1
2M1714+30	2003	M6.5	5.4	> 1.4	0.075	0.031	0.007	< 0.5	1

blackbody. The occurrence of flares and cool surface spots strongly suggests the existence of magnetic fields in UCDs, even though the exact creation mechanism remains enigmatic.

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