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High-velocity evaporation during a flare on AT Mic

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Abstract.

We present and discuss observations of a flare event on the dM4.5e star AT Mic (Gl 799AB). These data show evidence of an energetic flare with a radiated energy of 3 10^{31} erg in the range 3600-4200Å. The Balmer emission lines display a prominent blue asymmetry which has been used to constrain the velocity of the associated bulk plasma motion. Simple models were applied to derive order of magnitude estimates for the mass and kinetic energy budget of the flare for assumed electron density, ionization fraction and temperature values. It is found that the kinetic energy of the flare plasma is two orders of magnitude less than the radiative energy release.

The chromospheric Ca II H & K lines are also observed to have a blue-shifted component which has not been observed prior to these results. We suggest that this is evidence of a very energetic particle beam penetrating to the cooler atmospheric layers where Ca II H & K is formed.

Key words: stars: flares - stars: UV ceti-type - stars: magnetic activity

1. Introduction

M-dwarfs are generally observed to be highly active objects displaying frequent enhancement of emission from chromospheric and coronal regions. The cause of the activity is now believed to be due to a magnetic dynamo effect coupled with high rotation rates and deep plasma convection. The emission resulting from the emergence of magnetic loops onto the surface of the star is observed in both the chromospheric and coronal regions. The most active of these M-dwarfs are the dMe stars.

The dMe stars are characterized by their Balmer line emission which is direct evidence for the existence of an active chromosphere, although it should be noted that the less active dM stars also have chromospheres. During flare activity both continuum and emission features become enhanced and observations have been made of very large asymmetric broadenings in the bases of chromospheric Balmer lines which are usually interpreted as mass flow events. The first evidence of flare activity is best observed in the ultra-violet continuum. The rise time is usually much sharper in the late M dwarfs, perhaps a few seconds ranging to a few minutes in the K or late M dwarfs. Emission line fluxes tend to show a more gradual rise time except in the line wings where as indicated above asymmetric broadening occurs. Multiwavelength observations are by far the best way of extracting the maximum physics from the flare, however, data are available for a limited number of events, most notably YZ CMi (Kahler et al. 1982; Doyle et al. 1988), Proxima Centauri (Haisch et al. 1983), and BY Dra (de Jager et al. 1986).

Valuable information can, however, be obtained from spectroscopic observations alone, for example, Houdebine (1993a,b) gives an analysis of a flare on AD Leo. In this paper we present and discuss the implications of an energetic mass flow event associated with a chromospheric flare observed on AT Mic. AT Mic is a dM4.5e star at 8.8 pc. Kunkel (1970) determined the flare incidence at 2.8 flares per hour. The aim of this paper is to consider the energetics associated with a particular flare event and discuss it in a general context.

2. Observations and data reduction

The observations were made in May 1992 using the SAAO 1.9m telescope equipped with the Unit Spectrograph and the Reticon Counting System (RPCS). The useful wavelength range covered was 3600 Å to 4200 Å incorporating the higher Balmer lines and Ca II H & K lines. The exposure time ranged from 120 to 360 seconds. During these observations an energetic flare was observed on AT Mic lasting several minutes.

After flat-fielding, the spectra were wavelength calibrated with reference to an argon lamp spectrum acquired 2 minutes prior to the flare. The estimated wavelength resolution was ∼0.9Å (at Hδ), which is considered adequate to resolve the line phenomena under investigation. An atmospheric extinction correction was also applied by reference to standard tables (Hayes & Latham 1975; Spencer Jones 1980) and a flux calibration accomplished with nightly observations of standard stars. By comparing the continuum flux level of quiescent spectra with the expected magnitude, we estimate the flux calibration to lie within about 30%.

The data-reduction was achieved with the FIGARO software (Shortridge & Meyerdierks 1992) and analysis carried out using the STARLINK DIPSO package (Howarth & Murray 1987).

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Fig. 1. Ca II and Hϵ lines from AT Mic during the flare (at 01:08 UT on 15 May 1992). Notice the pronounced blue asymmetry. The mean quiescent spectrum is shown for comparison.

Fig. 2. Hδ line from AT Mic during the flare (at 01:08 UT on 15 May 1992). Quiescent spectrum as above.

Table 1. Flux values (in units of 10^{-13} erg $cm^{-2}s^{-1}$) for four spectral lines observed on AT Mic. The integrated line flux is shown for the blue-shifted 'flow' component and the main spectral line. These two components account for the total line flux observed. Also shown is the percentage of the flow flux to the main component flux. Note that the Ca II H flux does not include Hϵ although Hϵ may contribute to the Ca II H flow component flux.

	Flux Hδ			Flux Ca II H			Flux Ca II K			Flux H8		
Time UT	Flow	Main	%	Flow	Main	%	Flow	Main	%	Flow	Main	%
01:08:10	1.42	5.32	27	0.90	2.67	34	1.53	7.74	20	1.31	4.90	27
01:11:34	0.67	3.36	20	4.59 $\star$	2.38	193	1.23	4.94	25	2.54	0.74	343
01:15:08	2.19	3.82	57	1.31	7.08	18	2.41	8.25	29	1.55	2.07	75
01:18:29	0.62	4.70	13	0.90	7.71	12	0.47	9.45	5	0.40	3.41	12
01:21:49	0.55	4.37	13	-	6.17	-	-	7.44	-	-	2.36	-
Non-Flare	-	2.93	-	-	4.28	-	-	5.20	-	-	1.84	-

$\star$ probably caused by the 'stationary' Hϵ component.

3. Results

The flare occurred at 1:08 UT on 15 May 1992. The first integration displayed the highest flux, while the second integration showed a considerable decrease in the line fluxes. Since the continuum level also decreases we believe that this is a double peaked event similar to that observed by Houdebine (1992). Below we discuss this flare in more detail.

3.1. Line identification

Figures 1 and 2 show the Ca II and Hδ lines respectively for the AT Mic flare. Also plotted is the typical pre-flare quiescent spectrum. The observed Balmer lines from Hδ to H11 as well as the Ca II H & K lines are visible in emission. In the preflare spectrum there is no evidence of He I lines being present but these are visible in the flare spectra at 4026.2Å and 4120.8Å. Figure 3 shows the He I flare emission at 4026.2Å averaged over five integrations with some smoothing applied. These He I lines have been observed in solar white light flares (Lites et al. 1986) as well as in other dMe flare events (Doyle et al. 1988).

The continuum flux increase in the Hδ region is about 25% in the flare spectrum and the Ca II H and Hϵ lines are strongly merged during the flare. There is also an unidentified line present in both quiescent and flare spectra at 3905Å which is visible throughout the observations. Since this line is visible in both flare and quiescent spectra we believe it may be an instrumental effect.

During the flare all the spectral lines display a prominent broadened and blue-shifted component. Such large asymmetries in the Ca II lines have not been observed previous to these results although Houdebine et al. (1993a) indicated a blue-shifted component in the Ca II K line from AD Leo, but with a somewhat smaller amplitude. Recent HST observations of the C IV line flare emission from AD Leo (Bookbinder et al. 1992) revealed a broad red-shifted wing of $\sim$ 1800 kms^{-1} although no effect was visible on the blue side of the lines. Broad components have been observed in the Mg II lines during flares on RS CVn systems (Linsky et al. 1989; Simon et al. 1980). Blue-shifted wings in the Ca XIX and Fe XXV lines during solar flares indicate upward plasma motions of up to 200-400 km s^{-1} (Fludra et al. 1993; Antonucci et al. 1990; Antonucci et al. 1982).

In Table 1 are shown values of the integrated line fluxes of the main spectral components and these 'flow' components throughout the sequence of spectra. Also shown is the percentage of the main component flux found in the flow components.

3.2. Line Fluxes

Line fluxes and widths were derived by fitting a series of gaussians to match the observed line profiles. In the majority of cases two gaussians, one for the main component and another for the asymmetric broad component, were sufficient to match the profile and account for the total line flux. In a small number of instances a further gaussian was required to account for some residual flux. Figure 4 shows an example of the gaussian components fitted to a typical broadened Hδ line as well as positions used to derive the plasma velocities (see below).

Figure 5 shows light curves for four of the spectral lines observed plus the line flux attributed to the flow component of the Hδ line and the continuum level (in the Hδ region).

3.3. Radiated energy estimate

In order to determine the importance of the kinetic energy involved in the flow we wish to compare it with the flare energy in the Johnson U-band. Since these observations cover the region 3600-4200Å a true U-band flux is not possible but measurements will give a good estimate of the radiative energy release. In fact based on results from Doyle et al. (1988) the difference is probably less than a factor of two. Since we require the energy associated with the flare only, the total flux in the quiescent spectrum was first subtracted from each flare flux and the results added. The total energy released in this wavelength range during the flare is then;

$$E_{3600-4200} = 4\pi d_\star^2 F_{tot} \Delta t \qquad (1)$$

where $d_\star$ is the stellar distance, Δt is the integration time and F_{tot} is the total flux from all flare spectra with quiescent subtracted. This total radiated energy release is $\sim$3 10^{31} erg.

Fig. 3. The He I line at 4026.2Å averaged over five spectra with some smoothing applied.

Fig. 4. An example of the fit to a typical Hδ profile. The fit (dotted line) consists of a summation of two gaussian components, one for the main component and another for the asymmetric broad component. The positions used to derive upper limits and mean values of the plasma velocity are also shown.

Table 2. Wavelength shifts and velocities for four spectral lines observed on AT Mic. The maximum wavelength is the farthest extension in the blue-shifted component and the central wavelength is that of the gaussian fit to the blue-shifted component.

	Hδ				Ca II K			
	Wavelength Å		Velocity kms^{-1}		Wavelength Å		Velocity kms^{-1}	
Time (UT)	maximum	central	maximum	mean	maximum	central	maximum	mean
01:08:10	4093.9	4097.7	574	270	3928.3	3930.9	409	210
01:11:34	4095.9	4097.8	427	265	3928.8	3931.4	371	172
01:15:08	4097.7	4100.8	296	58	3930.6	3932.0	233	127
01:18:29	4098.1	4099.5	266	144	3930.7	3931.5	226	165
01:21:49	4098.5	4099.1	237	182	3931.1	3933.5	195	-
	H8				H9			
01:08:10	3882.7	3885.4	490	282	3827.5	3833.8	617	124
01:11:34	3884.5	3887.8	351	96	3828.9	-	507	-
01:15:08	3884.9	3888.5	320	42	3831.7	3830.7	288	366
01:18:29	3886.1	-	228	-	3829.5	3834.4	460	77
01:21:49	3884.8	-	328	-	3830.9	-	350	-

3.4. Mass flow velocities

The excess blue emission seen in the wings of the spectral lines can be interpreted as a bulk motion. We have ruled out the possibility of solely turbulent broadening since the excess emission is highly asymmetric. However, the gaussian width of the flow material is larger than that of the main component so the plasma may be highly turbulent and moving at high bulk velocities. For the Hδ line the FWHM of the main component never exceeds ~64% of the flow component FWHM. For the Ca II H & K and H8 lines these values are 28%, 47% and 47% respectively. No line shows a central component of width greater than 2Åwhile the flow components often display a FWHM of 3-6Å. A similar phenomena where high-speed plasma turbulence is present in a flare-induced upflow was observed in the C IV lines during an explosive solar event by Dere et al. (1989). An alternative explanation is that we have observed a continuous distribution of upflow velocities during the integration time of 3-5 minutes. This interpretation was advanced for a solar flare observed by Fludra et al. (1993). It is therefore not possible to determine a particular dynamic scenario from data of such poor temporal resolution. During the impulsive phase the line wings extend up to approximately 8Å to the blue. This corresponds to a maximum line-of-sight Doppler velocity of approximately 600 km s^{-1} which decreases as the flare subsides. The quiescent spectrum shows no blue component in the lines. It should be noted that the spectral resolution of ~1Å gives a velocity resolution of about 80 km s^{-1} at 3600Å to 70 km s^{-1} at 4200Å.

During the gaussian fitting the central line components required a FWHM of $\sim$ 1 Å (i.e. the spectral resolution determined from arc spectra) in the pre-flare spectra which increased nominally to $\sim$ 2 Å for flare spectra. From the peak displacement of the shifted components it was also possible to estimate a mean velocity of the radiating material of $\sim$ 250 km s^{-1}. Table 2 shows the wavelength shift of the blue-shifted line components and the corresponding line-of-sight velocities as well as the velocities derived from the maximum extension in the wings. Since the Balmer lines are optically thick it is not possible to regard a velocity derived from the wings as conclusive. Optical depth effects allow the emission to originate at a lower chromospheric layer and escape to the wings of the profile. An estimate of kinetic energy using a velocity measured from an optically thick line would therefore have some degree of uncertainty.

4. Discussion

The percentage of flux in the flow components appears to be around 20-30% of the main component at the beginning of the gradual phase which drops to 5-15% by the end of the observations. It is interesting to note that during the second integration (ie. at 01:11:34 UT), the percentages of flow flux to the main component for Hδ, Hϵ and H8 were 20%, 25% and 343% respectively, indicating that the more optically thin lines have a much larger flow component flux. The light curve appears to display similar features to those observed by Houdebine (1992), a high peaked impulsive phase followed by a gradual decay phase. The flow component flux peak lags the total flux peak by at least 3 minutes for the higher Balmer lines.

One proposed model for chromospheric flare emission is that of an energetic particle beam directed down through the chromosphere from the apex of a magnetic loop (van den Oord 1988; Emslie 1978; Brown 1971). The beam interacts with lower level material, heating it and thus causing it to rise through the chromosphere in a bulk motion which can be observed as Doppler shifted spectral features (ie. evaporation).

In fact, recent spectroscopic data taken in Ly α for a flare on AU Mic has suggested the presence of such a particle beam (Woodgate et al. 1992). That data gave evidence for a proton beam carrying an energy flux of at least 10^{30} erg s^{-1} into the chromosphere giving rise to excess emission in the Ly α red wings. The thermodynamic expansion of chromospheric material giving excess blue emission could be achieved by the ejection of such a highly energetic particle beam. Significantly the Ca II lines here show clear evidence of a blue asymmetry

Fig. 5. Light curves of the Hδ, Ca II H and K, H8 line, the Hδ flow component emission and the continuum level in the Hδ region.

and such a dynamic effect has not been previously observed in dMe Ca II lines. We suggest that this signifies a very deep penetration of an energetic beam into the lower and cooler chromospheric layers where the Ca II lines are formed.

4.1. Plasma modelling

4.1.1. Plasma parameters

In order to constrain the physical properties of the flare plasma associated with this event, use has been made of escape probability methods for optically thick lines. This technique (which is appropriate for observations of low spectral resolution) allows estimates to be made of the plasma cross-section, volume, column density, mass, average emissivity and optical depth. With the mass determination and assumed flow velocity it is then possible to compare the radiative energy release with an approximate kinetic energy.

The lack of information on the plasma parameters means that complex NLTE (non local thermodynamic equilibrium) calculations are inappropriate but order of magnitude constraints can however be determined. In this method (which is discussed in detail by Houdebine et al. (1993b)) the following assumptions are made, (i) the centre to limb darkening or brightening and other surface inhomogeneities are negligible in the spectra, (ii) the plasma is homogenous and of constant thickness over its cross-section and (iii) continuum opacities and line blanketing are negligible.

The assumption of partial local thermodynamic equilibrium (PLTE) in which the relative populations of the upper atomic levels are strongly collisionally coupled to the continuum is discussed in detail by Griem (1964). It has been shown that the upper levels of hydrogen (j$\geq$8) are in PLTE for densities as low as 3 10^{10} cm^{-3} (Houdebine et al. 1989) and in this case the population of level j can be calculated from the Saha equation;

$$n_j = \frac{n_e^2 g_j h^3}{4}(2\pi m_e k T_e)^{-3/2} \exp(\chi_j / k T_e) \quad (2)$$

where χ_j is the ionization energy of level j and the other symbols take their usual meanings. The emissivity of a spectral line can be calculated with the relation,

$$\epsilon = n_j A_{j,i} h \nu_j \quad (3)$$

Since the observed flux and the emissivity infer a minimum number of atoms in the transition, it follows that the minimum plasma volume and minimum plasma mass are given by,

$$V_{min} = \frac{4\pi F_{e,j} d_\star^2}{n_j A_{j,i} h \nu_j} \quad (4)$$

$$M_{min} = \frac{4\pi F_{e,j} d_\star^2 n_e \overline{m}_s}{n_j A_{j,i} h \nu_j \alpha} \quad (5)$$

where $F_{e,j}$ is the flux from the j transition measured at Earth from a source at distance $d_\star$, n_e is the assumed electron density, α is the assumed ionization fraction, and $\overline{m}_s$ is the mean ion mass for solar abundances. A naïve estimate of the kinetic energy along the line-of-sight axis can then be made with;

$$E_k \geq \frac{1}{2} M_{min} \overline{v}^2 \quad (6)$$

where $\overline{v}$ is the mean measured line-of-sight velocity of the plasma. In this analysis any optical depth effects have been ignored and the extension in the lines used to derive the plasma velocity.

In the model calculations an escape coefficient method (Drawin 1975) is used to compute the plasma parameters on an iterative cycle until the observed flux is matched. The results are believed to be accurate to within an order of magnitude at a given optical depth. We have considered in detail the formation of the H8 line in a chromospheric region of electron temperature $T_e \sim 10^4$ K. At such a temperature the ionization fraction α lies in the range 0.75-0.85 at normal chromospheric densities (Houdebine et al. 1993b).

A determination of the electron density in chromospheric flares is difficult but characteristic values are given by Rodonò (1986) in the range $n_e \sim 10^{12}$ - 10^{14} cm^{-3}. However, to further constrain this parameter, use has been made of the relation derived by Kurochka (1967) for the variation of electron density with emission line half-widths. This assumes that the main component of the line is broadened primarily by the Stark effect so the nominal increase in central component FWHM has been used to derive an electron density. This value is however an upper limit since turbulent broadening was not included in the analysis. These calculations were done for all the hydrogen lines down to H11 for all spectra and showed a variation in this value of $\sim 10\%$. We found that the upper limit in electron density is about 10^{14} cm^{-3}.

4.1.2. Results of the modelling

Escape coefficient calculations were carried out for the above plasma parameters using the H8 line. As an indication of the variation of the results the models were run for order of magnitude changes in n_e and smaller variations in T_e and α. For the higher electron densities the model assumed local thermodynamic equillibrium and computed the required ionization fraction. Normally however we studied the variation of mass, plasma volume and kinetic energy over the temperature range 1-2 10^4 K and for a fixed ionization fraction of $\alpha = 0.75$.

It was found that a variation in the ionization fraction α of 10% led to a similar variation in the plasma parameters so our order of magnitude estimates are essentially unaffected by errors in α. In addition the assumption of LTE for higher electron densities did not significantly alter the results. The model results gave a plasma mass estimate of 10^{12} kg which did not vary by more than an order of magnitude for a large change in n_e. The estimate of plasma volume was $\sim 3\ 10^{24}$ cm^3 and varied by two orders of magnitude across the n_e range. The kinetic energy E_k, which was well defined within the n$_e$ range, was found to be $\sim 3\ 10^{29}$ erg. The kinetic energy budget derived by Houdebine et al. (1993b) for a flare on AD Leo was $E_k \sim 10^{32}$ erg. The radiative energy release on the other hand is comparable to that of the AD Leo flare ($3\ 10^{31}$ erg). Hence in this example of a dMe flare the kinetic energy is not a significant fraction of the total flare energy release, unlike the AD Leo flare modelled by Houdebine et al. (1993b). This difference is due to the derived values of electron density and plasma velocity which differ by an order of magnitude and a factor of 5 respectively. These results are therefore fully consistent with the AD Leo flare.

Large uncertainties are likely to remain in these computed values, primarily due to lack of certainty in the plasma parameters and the assumptions made in the modelling. Optical depth effects could also effect the derived plasma velocity. There is also the problem of the angle of flow direction which may have important consequences for the estimate of kinetic energy. The bulk motion itself may also consist of a very complex velocity field which would be difficult to model successfully.

5. Conclusions

We have been considering emission line spectra from the dM4.5e star AT Mic during an energetic flare event. The chromospheric Balmer and Ca II line emission displays a prominent blue-shifted component which has been used to constrain the velocity of the mass flow. Together with order of magnitude estimates of electron density and assumptions on the hydrogen line formation, our model computations indicate that the kinetic energy of the evaporation is substantially less than the radiative energy release in the 3600-4200 Å range.

This is the first time a blue asymmetry of such an amplitude has been observed in the Ca II H & K lines. The fact that the flare on AT Mic displays a prominent shift in Ca II means that we must be observing the bulk motion of this lower temperature plasma. How this heating arises so low in the chromosphere and how highly non-thermal plasma velocities are achieved is difficult to ascertain without continuous multi-wavelength observations. Since the Ca II excess emission is consistent with the same broadening/asymmetry observed in the Balmer lines it presumably has the same source.

The ratio of radiative to kinetic energy in bulk plasma motion events on dMe stars could be further constrained by observations of higher temperature lines with high time resolution. In order to fully understand the processes at work multiwavelength observations are essential. For example the evaporation of chromospheric material into the corona where the cooler matter is heated to temperatures of $\geq 10^6$ K and rapidly expands would create a soft X-ray flux. This would help to constrain the processes at work during such evaporation events.

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