Electron temperatures of flare plasmas from emission line fluxes

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Summary: We present spectral diagnostics for the fluxes of emission lines, in the spectral range 3600-4400 Å, during the cooling phase of stellar flares on dMe stars. Using these diagnostics, electron temperatures have been computed for flares on AD Leonis, Proxima Centauri and UV Ceti. This preliminary model assumes a single flare loop containing a homogeneous, stationary optically-thin flare plasma.

.1 Introduction

To explain the observed spectral line fluxes during stellar flares, we have studied the main atomic processes for a few lines which were first discussed by G.A. Gurzadyan (1984). In several flares for which time-resolved spectroscopy is available, a distinct difference in the behaviour of the Ca II K, He II 4026 Åand Balmer lines has been noted; both in the time of maximum emission and the evolution of emission during the later phases. The observations we present and discuss here are explained using a simple model which involves cooling of the plasma without expansion. Furthermore, this method shows that the flux evolution in a quasi-optically-thin line, such as the higher members of the Balmer series, can be a good electron temperature diagnostic provided the line reaches its maximum emission efficiency at some stage during the flare.

.2 The modelling of the line fluxes

a) The Cooling Phase Assumptions

Because of the rapid damping of the UV and optical continuum and hard X-rays during a flare, we assumed that radiative processes are negligible compared to the collisional processes, for electron densities in the range $10^{12} - 10^{14} cm^{-3}$. To estimate the electron density (Ne), we have assumed that the ionization balance is collisionally dominated and that the electron contribution from heavy elements is low (less than10%) for 6400< Te <50000K. Therefore we compute the degree of ionization using collisional ionization from the ground state and radiative recombination to levels 1-18.

These results are not too far removed from those given by the more complete Collisional-Radiative model of Drawin (1971). The flare plasma is assumed to be stationary and of constant density; an unlikely situation because of probable large velocity fields, but nevertheless one we assume would not appreciably affect the integrated Balmer line fluxes. According to Drawin (1971), for a pure collisionally dominated hydrogen plasma, the degree of ionization varies only slightly over the density range $10^{12} - 10^{15} cm^{-3}$ and over the entire temperature range. This implies that the collisionally dominated populations decrease as Ne decreases, however the total number of emitters over the more rarified plasma would be constant, and consequently the integrated fluxes in the lines would be unaffected.

The flares that have been studied are assumed to be single events, where the period of energy release, as well as the time taken for the thermalisation of high energy particles, is assumed to be short compared to the cooling time of the plasma. Finally, the most important assumption is to neglect the optical depth in the lines. This is discussed later.

b) Emission Efficiency Curves

For an optically thin plasma, the flux emitted in a given line depends only on the collisional rates which populate or depopulate the upper level. Thus it is possible to estimate the atomic populations of the levels and the ionization fractions for a given range of electron temperature and density.

Hydrogen : The Balmer lines : There are two sets of simplifying assumptions to consider for the higher levels of hydrogen;

(i) At low densities and high temperatures it is possible to assume that it is mainly radiative recombination that populates the upper levels followed by spontaneous de-excitation to the lower levels. This is the coronal approximation used by Gurzadyan (1984).

(ii) The other possibility is to assume Partial Local Thermodynamic Equilibrium (PLTE) for the levels in which the relative populations of the upper atomic levels are strongly collisionally coupled to the continuum and their populations are given by the Boltzman or Saha equations.

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In the present study, for the levels ≥ 5 which correspond to $H\gamma$, we make the second assumption. The PLTE criteria (Hans.R.Griem 1964) for hydrogen, given in table 1, clearly show that for Te $\leq$ 50000 K, levels ≥ 5 are in PLTE for an electron density of $10^{13} cm^{-3}$. Furthermore, it is interesting to point out that the population of level 8 agrees with the PLTE population better than 10% for Ne=5.10^{10} cm^{-3} and Te=15000 K and that level 1 needs for the same temperature Ne=2.10^{18} cm^{-3}. From this we can compute the "emission efficiency curves" for the higher Balmer lines which are proportional to the populations of the upper levels. Then;

$$E_H(T_e) \propto N_e g_i h^3 exp(I_i/kT_e)/(2\pi m_e kT_e)^{3/2}$$

where $Ne = D/N_{tot}$, with D the ionization degree of hydrogen, and I_i is the energy of ionization of level i. These curves are plotted in fig. 1 for the levels 2,5,6 and 8.

The CaII K line :

The formula of the PLTE criterion for the Ca II level $2P^0_{3/2}$ gives N_e $7.10^{16} cm^{-3}$ for Te=15000 K, so that for densities in the range 10^{12}-10^{13} cm^{-3}, the sum of the collisional excitation probability to the upper levels is 10-100 times less than the sum of the spontaneous de-excitation probability to the lower levels. Now, except in a few cases, collisional de-excitation cross sections are always less than the corresponding collisional excitation cross section. This then allows us to consider this level collisionally dominated by excitation from the lower states. On the other hand, assuming a weak radiation field implies that the ionization fractions are collisionally dominated and are well described by the computations of Shull and Van Steenberg (1982). The ground state level of the CaII ion is assumed to follow, qualitatively, the evolution of the ionization fraction $\alpha = N_{CaII}/(N_{CaI} + N_{CaII} + N_{CaIII})$ in the temperature range 12000-17000 K, with the qualitative correction factor $1/P_{CaII}$, where P_{CaII} is the partition function.

The emission efficiency function then becomes;

$$E_{CaII}(N_e, T_e) \propto N_e(T_e)\alpha T_e^{0.18} exp(-E_4/kT_e)/P_{CaII}(T_e) \text{ with } P_{CaII}(T_e) = \sum g_i exp(-E_i/kT_e)$$

TABLE 1

Partial local thermodynamic equilibrium criteria for hydrogen levels. (Lower limit for Ne in cm^{-3})

Ne	Te 5. 10^3	1.5 10^4	5. 10^4	1. 10^6
Level				
1	1.3 10^{18}	2.2 10^{18}	4.0 10^{18}	1.8 10^{19}
2	3.5 10^{15}	6.1 10^{15}	1.1 10^{16}	5.0 10^{16}
3	1.1 10^{14}	1.9 10^{14}	3.5 10^{14}	1.6 10^{15}
4	9.7 10^{13}	1.7 10^{13}	3.1 10^{13}	1.4 10^{14}
5	1.5 10^{12}	2.5 10^{12}	4.6 10^{12}	2.1 10^{13}
6	3.1 10^{11}	5.3 10^{11}	9.8 10^{11}	4.4 10^{12}
7	8.3 10^{10}	1.4 10^{11}	2.6 10^{11}	1.2 10^{12}
8	2.7 10^{10}	4.6 10^{10}	8.4 10^{10}	3.4 10^{11}

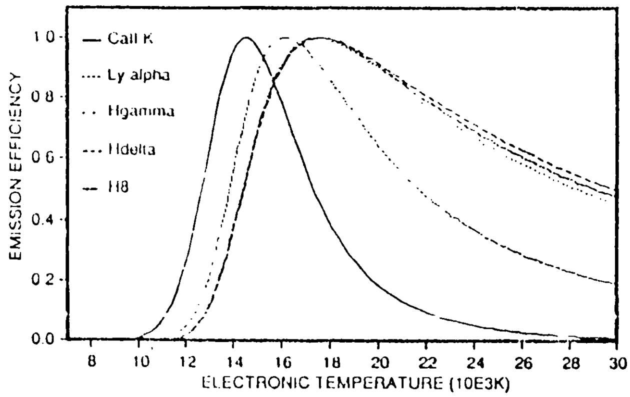

fig. 1; Emission efficiency curves for the lines Ly α H_γ, H_δ, H_8 and CaII K.

Comments :

It is important to note the differences between these emission efficiency curves, viz. their shapes and temperature maxima, because they are directly related to the behaviour of the observed lines. We notice that our results are in good agreement with those from S. Kelma (1967). Using these curves, we are now able to compute electron temperatures from the observed fluxes in the lines relative to their maxima and discuss the validity of the previous assumptions.

.3 Cooling curves of flares and their interpretation

We studied four flares from which we have calculated cooling curves during the gradual phase. These are plotted in figs. 2 to 5. The fluxes in the lines have been fitted in order to reduce the noise without losing information on the general shapes of the relative fluxes.

Flare (1); AD Leonis, 3.40 UT 28 March 1984

Flare (2); Proxima Centauri, 8 37 UT 24 March 1984

Flare (3); UV Ceti, 2.47 UT 8 Dec. 1984

Flare (4); UV Ceti, 3.49 UT 8 Dec. 1984

Flare (1) is important for the application of this model, because it shows a very fast increase (<1 min) in the continuum and in the HeI 4026 Åline followed by a rapid decline. This requires a high energy, strong, X-UV radiation field and/or a very high plasma temperature during the very first minutes of the flare. This behaviour is closely followed by the hydrogen lines but not the CaII K line which increases very slowly. After the first 4 minutes, the fluxes in the hydrogen lines increase again up to the value of the previous maximum, though no other

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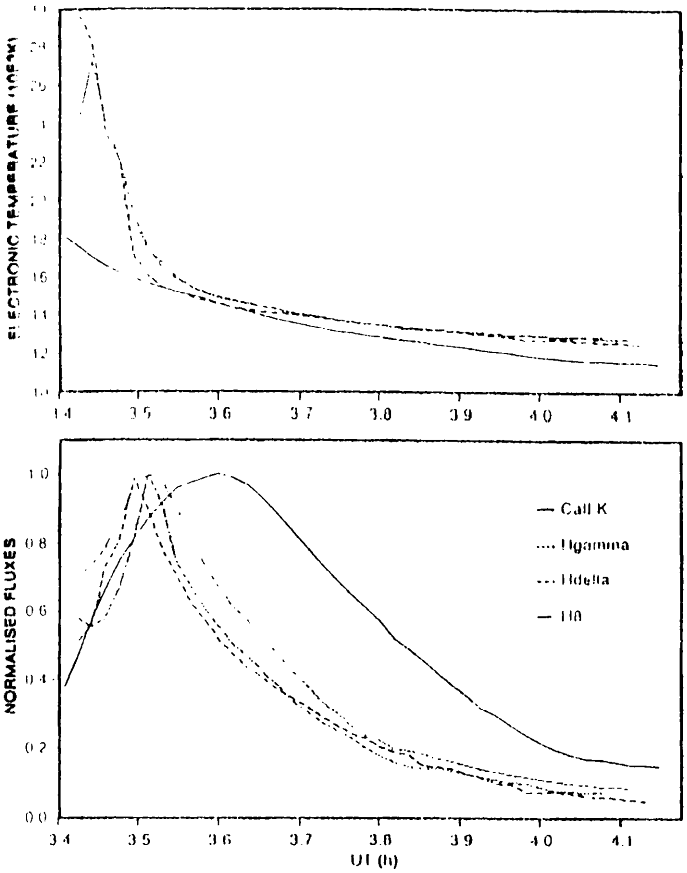

fig 2: Normalised fluxes in the lines and computed cooling curves during AD LEO flare(1) 3.2h UT, 28 MARCH 1984.

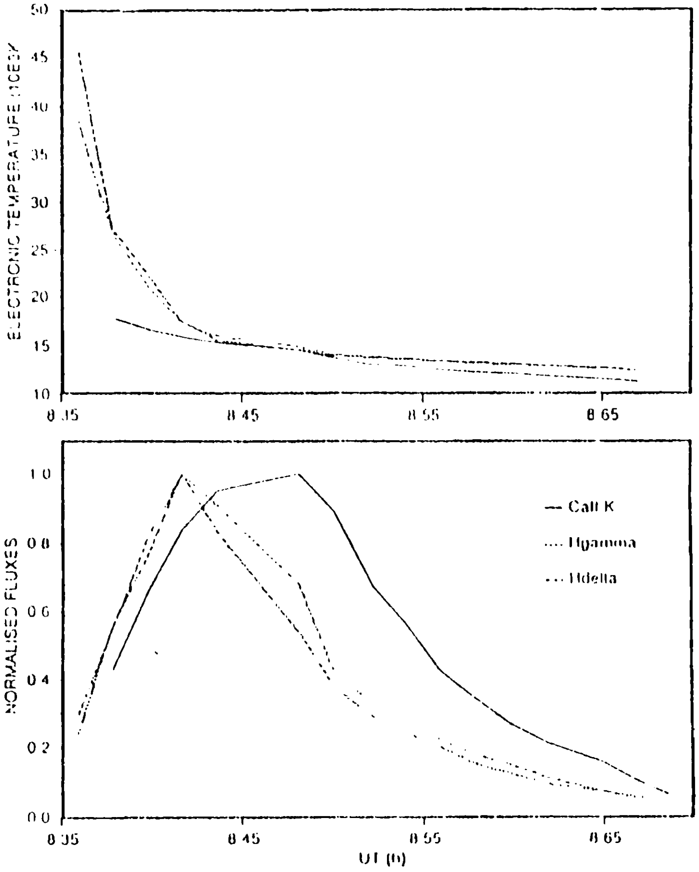

fig.3: Normalised fluxes in the lines and computed cooling curves during Proxima Centauri flare(2) 8.37h UT, 24 MARCH 1984

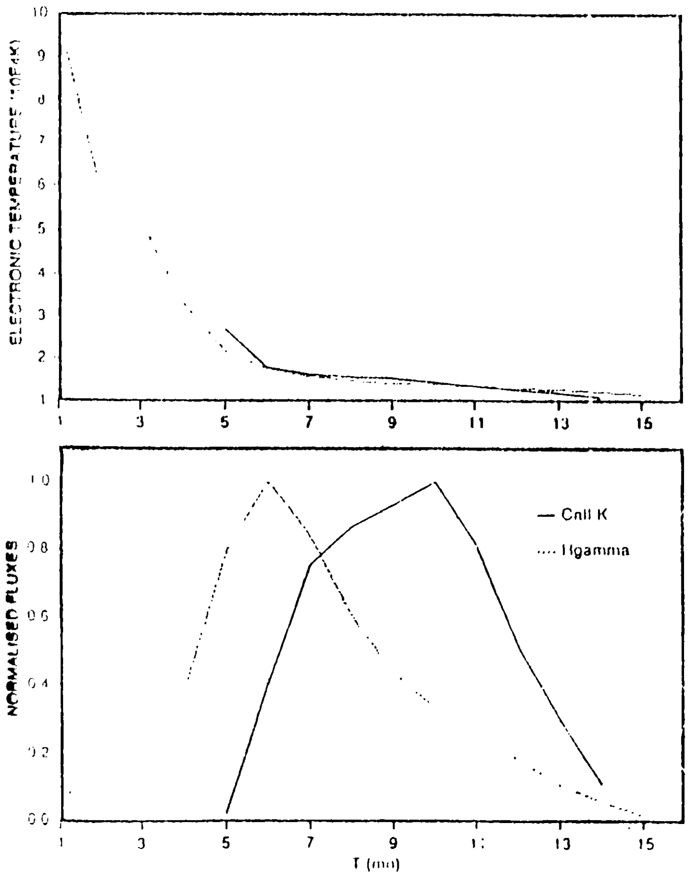

fig 4: Normalised fluxes in the lines and computed cooling curves during UV Ceti flare(3) 2.47h UT, 8 Dec. 1984.

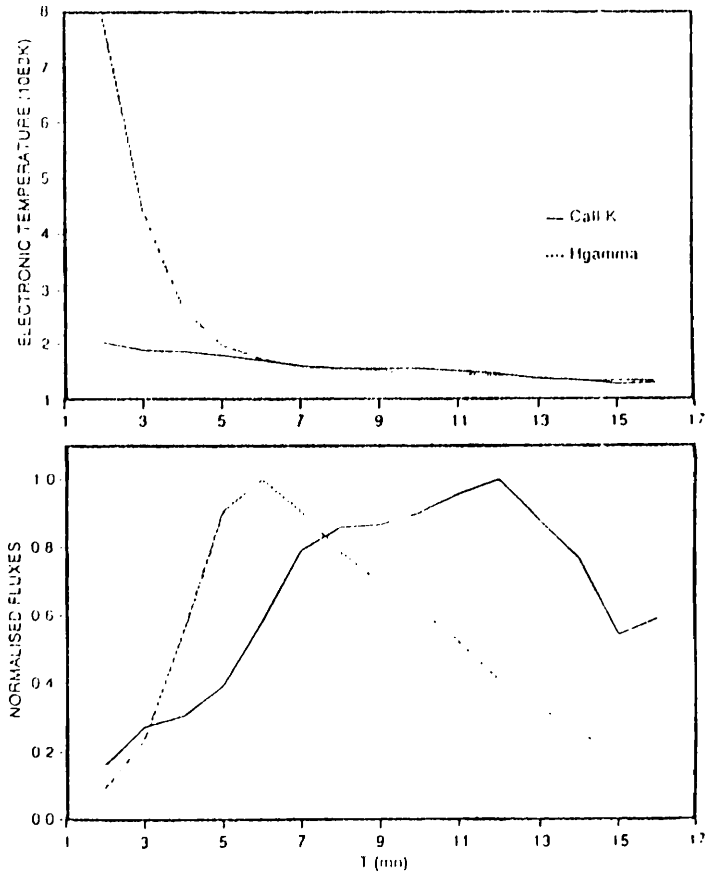

fig.5: Normalised fluxes in the lines and computed cooling curves during UV Ceti flare(4) 3.49h UT, 8 Dec. 1984

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physical parameters, like the FWHM of the lines, the continuum or the HeI line, show evidence of another energy release. However, the CaII K line still increases slowly to a maximum, reached 5 min after the 2^{nd} maximum in the Balmer lines. We see a secondary event located at 3h30 UT, but it is too small to explain these phenomena.

On the one hand, the observed fluxes in the Balmer lines can be explained using only temperature variations and the curves in figure 1. Indeed, if Te increases after the initial energy release to a higher value than 17500 K, then the emissivity first increases and then decreases (see figure 1), and if Te later decreases, then the flux should increase again to the same maximum, and finally decrease. In that case the maximum temperature should be located at 3.425 UT. On the other hand the flux in the CaII K line shows, simultaneously, a continuous increase, corresponding to a simple decrease of Te. Furthermore the Balmer line fluxes are very well correlated with the continuum flux and with the higher lines which are most probably in PLTE with the free electrons. This means that during the first four minutes, the continuum flux is so intense that it might be the dominant cause of ionization in the plasma, increasing significantly the degree of ionisation D and all the radiative rates. In that case the cooling phase would really only begin 1 min after the flare release. The CaII K line behaviour is more difficult to explain because the radiative processes involved are more complex. Also the Te effect might damp the increase of F_{CaII}(Ne,Te) due to Ne because it scales only as Ne, and because this line is sensitive to the expansion of the plasma. More generally it is not possible to conclude when radiative phenomena are important without a more complete and detailed study.

The other flares do not display such a complex evolution. Nevertheless they all have in common an earlier, and sharper, increase in the Balmer lines compared to the CaII K line. The results display a great disparity at higher temperatures and this is explained by, a not unexpected, opacity effect. The opacity of the medium in a line is proportional to the lower level density and tends to slightly decrease the extrapolated temperature at maximum emission efficiency and to significantly reduce the flux at maximum. This opacity effect on the computed Te is greater before the maximum due to the shape of the emission efficiency curve. On the other hand, the LTE departure increases as $\sqrt{Te}$ and with the inverse of the principal quantum number. This underpopulates the lower intermediate levels and strengthens the previously noted effect.

It is interesting to point out the agreement of the lower temperatures ($<$ 15000K), and the slight discrepancy for the CaII K line which can be explained simply by a non-isothermal plasma.

.4 Conclusions

This short note points to the possible existence of two main phases in the gradual stage of flares: (i) the radiative phase for which many radiative processes such as photoionisation can be dominant, and (ii) a collisional phase which appears later, when nearly all the atomic transitions are collisionally dominated. These two phases could be completely blended (as for the UV Ceti flares because the flare plasma does not reach a high enough Te to distinguish them. Alternatively, the radiative phase could be completely non-existent, as for the Proxima Centauri flare, where only a very weak continuum enhancement was observed. Furthermore, the maximum of Te could be so low that the hydrogen lines never reach their maximum emission efficiency.

We can also notice the good agreement of the derived temperature behaviour during the later phases of the flares, as derived from different spectral lines. This is in spite of the rough assumptions used to compute the emission efficiency curve of CaII K. In this context we show that H8 is a good Te diagnostic, even in a plasma significantly in expansion. The accuracy of the computed Te for this line, after the radiative phase, is only limited by the poor signal to noise ratio of the observations.

Nevertheless, to confirm the true role of Te on the observed behaviour, it is important to study other possible effects such as soft X-ray photoionisation which is often very well correlated with the Balmer lines,(see Butler et al. 1988), and to compute emission efficiency curves for other lines with significantly different opacities and different temperatures of maximum emmission, and using more complete collisional-radiative models.

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