# A gas-dynamic model for a flare on YZ CMi: Interpretation of spectroscopic observations with high temporal resolution

M.M. Katsova[1], M.A. Livshits[2], C.J. Butler[3] and J.G. Doyle[3]

[1] *Sternberg State Astronomical Institute, University of Moscow, 119899 Moscow, USSR*

[2] *Institute of Terrestial Magnetism, Ionosphere and Radio Wave Propagation, Academy of Sciences, Troitsk, 142092 Moscow Region, USSR*

[3] *Armagh Observatory, College Hill, Armagh, N. Ireland*

**Abstract:** The spectra of a flare on YZ CMi, obtained with a temporal resolution of 60 seconds on March 4 1985 and over the range 3600-4400 A, are analysed using a gas-dynamic model. In this model, the optical radiation in the U-band, outside of flare maximum, is produced by a condensation formed during the gas-dynamic process. With the optical continuum described by a Planck function for a temperature of $T \approx 10^4 K$, the emitting source area $S \geq 5\ 10^{17} cm^2$. The hydrogen plasma kinetics of an "8 levels plus continuum" model atom are calculated, and it is shown that the low slope of the Balmer decrement, just after the flare maximum, is connected with a large population in the second level of the hydrogen atom.

## 1 Introduction

Simultaneous observations in different spectral ranges allow substantial advances in our understanding of the nature of solar and stellar flares. One of the areas where improvements in instrument design have benefited these studies recently is the ability to obtain stellar flare spectra with a convenient time resolution ($\Delta t < 60s$). This paper presents an interpretation of spectroscopic data for a flare on YZ CMi based on a gas-dynamic model of stellar flares.

## 2 Observations

The observations of YZ CMi, discussed here, were obtained during a coordinated run between telescopes at the South African Astronomical Observatory, and the ESA X-ray satellite, EXOSAT, on 4 March 1985. The photometric observations consisted of UBVRI photometry with the 0.75m telescope with integration times of 10, 3, 1, 1 and 1 second respectively in the five passbands. Details have been published by Doyle et al. (1988). We show in figure 1 the U and B band flux for the flare at 19:55 UT, which has a peak amplitude of 1.2 magnitude in U and a duration of about 6 minutes. It is easy to see, on the U-band light curve, three maxima: the first (I) at 19.917 UT, the second (II) at 19.935 UT and the third (III) at 19.97-19.99 UT.

The spectroscopic observations were obtained with the 1.9m telescope at SAAO equipped with the RGO Unit Spectrograph and a reticon photon counting system. The wavelength range covered was 3600-4600 A with a spectral resolution of approximately 1.5 A at $H\delta$. Spectra were taken approximately every 60 seconds with a 60 second exposure time. Figure 2 shows the integrated fluxes for the $H\gamma$, $H\delta$, $H\zeta$ and $H\eta$ and Ca II K lines, as well as a 30 A continuum region, centred at 4084 A, and a 150 A continuum region, centred at 3650 A.



https://doi.org/10.1017/S0252921100153874 Published online by Cambridge University Press

The intense continuum emission at 19.917 UT (I) is observed mainly at $\lambda < 4000A$ (see figure 2, and also figure 10 in Doyle et al. 1988). The higher Balmer line radiation reaches its maximum as the blue continuum decreases. The intensities of $H\delta$, $H\zeta$, $H\eta$ relative to $H\gamma$ do not vary significantly during flare epoch I; a changing slope for the Balmer decrement has been noticed earlier for a flare on UV Ceti (Rodono, 1987, Butler et al. 1988).

# 3 The gas-dynamic model

The primary energy release in a flare takes place above the chromosphere and initiates a number of secondary effects. Kostyuk and Pikel'ner (1974) first showed that a consideration of gas-dynamic motions is of vital importance for the analysis of secondary processes in solar flares. This gas-dynamic model has been further developed for solar and stellar flares (Katsova et al. 1981); see also reviews of Fisher (1986) and Katsova and Livshits (1988).

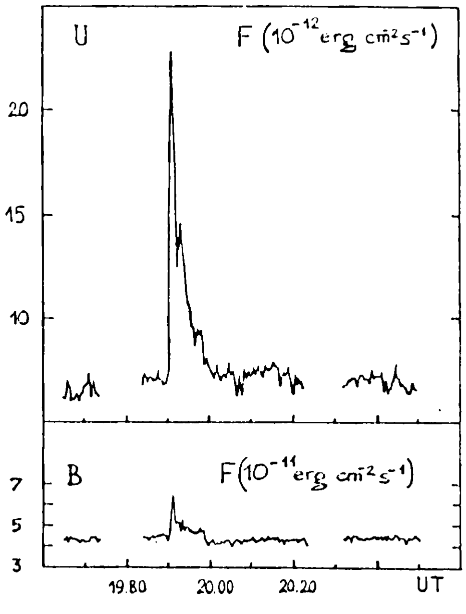


figure 1. The U and B band light curves for the YZ CMi flare on 4 March 1985. The time resolution is 20 seconds.

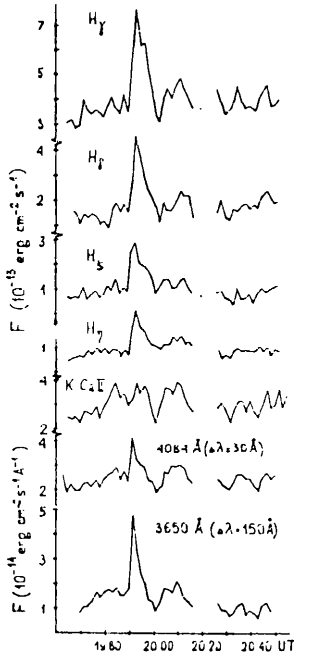


figure 2. The variation of the fluxes in the $H\gamma$, $H\delta$, $H\zeta$, $H\eta$ and $Ca\ II\ K$ lines, and in the continuum regions centred at 4084 A and 3650 A, during the flare on YZ CMi.

A description of some of the characteristics of the model, follows. A high pressure region forms in the upper chromosphere under the combined impulsive effect of the heat flux and of the accelerated particles. Two disturbances propagate from that region, one upwards, and one downwards. A second shock wave is expected to form in red-dwarf chromospheres in a time of 0.3 to 1 second and will be accompanied by a burst in the EUV lines. The downward-directed shock wave propagates down to the photosphere in 1 to 2 minutes and, between its front and the temperature jump region, (from $10^4K$ *to* $2\ 10^7K$), produces a gas condensation with a temperature $T \approx 10^4K$ and a density of hydrogen nuclei $n \geq 10^{15}cm^{-3}$. Thus sharp, non-stationary, phenomena are expected to occur during the primary energy release in flares, in addition to the appearance of radiation from the downwards-directed condensation, which occurs over several minutes.

# 4 Optical emission

The downwards-moving gas condensation is responsible for the optical emission at 19.935 UT (II). We consider the two components of this emission; namely the optical continuum and the Balmer emission.

**(a) Optical continuum.** The intensity of the optical continuum at 3600-4600 A is relatively small, and practically independent of wavelength. In the first approximation, the optical continuum may described by a black-body radiation curve for $T \approx 10^4$. That is in good agreement with the theoretical estimate. The numerical simulation of the flare gas-dynamic process (Livshits et al. 1981; Katsova et al, 1981) shows that even for a relatively weak stellar flare the optical depth of a gas condensation approaches unity. This allows us to estimate the flare area, S from:

$$2\pi D^2 F = S\pi B_\lambda(T)(1 - e^{-\tau}) \tag{1}$$

where F is the flux at the earth in $erg\ cm^{-2}\ s^{-1}$, and $B_\lambda(T)$ is the Planck function. For the flare on YZ CMi the flux is 2.5 $10^{-14}$ $erg\ cm^{-2} s^{-1}$ at 4000 A, which for a distance $D = 6.05\ pc$, $T \approx 10^4 K$, and $\tau > 1$, corresponds to a flare area $S \approx 5\ 10^{17} cm^2$. The lack of a corresponding X-ray event in the EXOSAT data could be explained by a small area for this flare.

**(b) The Balmer decrement.** There are two observational facts which require explanation, (i) the behaviour of the Balmer decrement (see Butler et. al. 1988), and (ii) the disappearance of the higher Balmer lines (see Doyle et al. 1988).

Hydrogen radiation in solar and stellar flares arises in layers where the electron density $10^{13} cm^{-3}$. Here, firstly, the intensities of the $H\gamma - H\eta$ lines must sharply decrease due to highly effective electron collisions. However, a gently sloping Balmer decrement is observed. Such a form of the Balmer decrement arises, for example, if the population of a higher level is due to recombination. This paper presents another explanation for the slope of the Balmer decrement connected with variations of optical depth. Secondly, from the Inglease-Teller formula, the high Balmer lines, up to $H_{17}$, should be observed for $n_e \leq 10^{14}\ cm^{-3}$, however they are observed to disappear earlier, beginning with $H_{10} - H_{11}$. The absence of the $H_{12} - H_{17}$ lines in flare spectra could also be caused by decreasing optical depth for the corresponding transitions.

We have carried out new calculations of the kinetics of the hydrogen atom to predict the radiation in the higher Balmer lines from gas condensations. The results of Gershberg and Schnoll (1974) were generalized to the case of a stationary layer, e.g., we consider that the medium is made more transparent, not due to the velocity gradient, but due to a variation in the photon frequency by collisions, repeated many times.

We use a common presentation of the escape probability of a photon from a medium, $\beta_{ik}$, introduced by Sobolev (1960). The averaged value over the emitting layer $\beta_{ik} = NRB$ (net radiative bracket) was calculated for the absorption coefficient given by Vidal et al. (1973). Then the statistical equilibrium equations for the "8 level plus continuum" model of the hydrogen atom were solved. The results given in

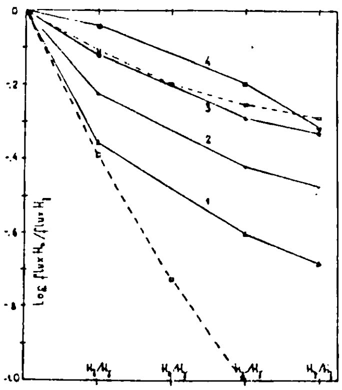


figure 3. The Balmer decrement relative to $H\gamma$: (i) before the flare on YZ CMi, (ii) for the flare plus star at time II, (iii) for the YZ CMi flare only, and (iv), for the UV Ceti flare, (Rodono, 1987b; Butler et al. 1988). The dashed lines show the theoretical calculation for a gas condensation with $\tau(L\alpha) = 10^6$, (lower line), and $\tau(L\alpha) = 10^8$, (upper line), for $n_e = 10^{13}\ cm^{-3}$ and $T = 10^4 K$.

figure 3 suggest that the downwards directed gas condensation has a very large optical depth in the $Ly\alpha$ line



https://doi.org/10.1017/S0252921100153874 Published online by Cambridge University Press

centre. Multiple scattering of the $Ly\alpha$ photons maintains a large population in the second level, $n_2$ which is responsible for the fact that $\tau(H\alpha)$ is much greater than 100. The flux of the higher Balmer lines disappears when the optical depth is small. The evolution of the Balmer decrement is connected with decreasing $n_2$ when the gas condensation moves down, i.e. with decreasing temperature. We also find that the $H\delta$ profiles calculated for the flare epoch II are in good agreement with the observations.

The detailed calculations of the kinetics of the hydrogen plasma and a more complete version of this paper will be published elsewhere.

**References:**


Butler, C.J., Doyle, J.G., Foing, B.H. and Rodono, M.: 1988, *'Activity in cool star envelopes' Havnes, O., Pettersen, B.R., Schmitt, J.H.M.M., Solheim, J.E. (eds), Kluwer, p 167*

Doyle, J.G., Butler, C.J., Byrne, P.B. and Van den Oord, G.H.J.: 1988, *Astron. and Astrophys. 193, 329*

Fisher G.H.: 1986, *'Radiative Hydrodynamics' Springer-Verlag, p 53*

Gershberg, R.E., Schnoll, E.E.: 1974, *Izv. Krymsk. Astrophys. Observ. 50, p 122*

Katsova, M.M., Kosovichev, A.G., Livshits, M.A.: 1981,*Astrofizika, 17, p 285*

Katsova, M.M., Livshits, M.A.:1988, *'Activity in cool star envelopes' Havnes, O., Pettersen, B.R., Schmitt, J.H.M.M., Solheim, J.E. (eds) Kluwer, p 143*

Kostyuk, N.D., Pikel'ner, S.B.: 1974, *Astron. J. of USSR, 51, p 1002*

Livshits, M.A., Badalyan, O.G., Kosovichev, A.G., Katsova, M.M.: 1981, *Solar Phys. 73, p 269*

Rodono, M.: 1987, *private comm.*

Sobolev, V.V.: 1960, *'Moving envelopes of stars' Harvard Univ. Press*