SEMI-EMPIRICAL MODELS OF THE WHITE-LIGHT FLARE ON
OCTOBER 24, 1991

C. FANG
Department of Astronomy, Nanjing University, China; and Observatoire de Paris, DASOP-URA326
(CNRS), 92195 Meudon Cedex, France

J. C. HÉNOUX
Observatoire de Paris, DASOP-URA326 (CNRS), 92195 Meudon Cedex, France

HU JU, XUE YIN-ZHANG and GAO XIU-FA
Department of Astronomy, Nanjing University, China

and

FU QI-JUN
Beijing Astronomical Observatory, Academia Sinica, Beijing, China

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Abstract. On October 24, 1991, a white-light flare was observed both from space and from the
ground. A multi-waveband spectral analysis shows that the peak time of the continuum emission
coincides well with that of a radio burst at 2840 MHz and with the hard X-ray emission. Three
semi-empirical models, corresponding to the pre-flare condition and to the peak time of continuum
emission both with and without non-thermal excitation and ionization of hydrogen by an electron
beam, have been obtained. The results indicate that there is fast heating both in the chromosphere
and the photosphere. Some evidence is given that this WLF is very likely a result of bombardment
by an electron beam. By taking into account non-thermal effects, the chromospheric temperature of
the semi-empirical model is significantly reduced.

1. Introduction

It is known that white-light flares (WLFs) are rare events. Up to now, less than
90 WLFs have been recorded (Neidig, 1992). Among them, only about ten WLFs
have been observed with spectral instruments. The number of those with high-
temporal-resolution spectra is still lower. Thus, the spectral characteristics of WLF
are still not well known. Moreover, the mechanism of continuum emission and the
sources of energy are still unexplained.

Two extreme cases of WLFs exist (Machado, 1986): the first has a Balmer jump
and its continuum emission is produced mainly by hydrogen free-bound transitions;
the second has no Balmer jump and its continuum emission results from negative
hydrogen (H⁻) free-bound and free-free transitions. Indeed there are also WLFs
were both H and H⁻ emission are present.

The simplest way to model the WLF’s atmosphere is to assume that the radiation
is emitted in a uniform layer. This method reproduces the continuum emission, but
the enhancement in both lines and continua are then difficult to explain correctly.
Semi-empirical modelling by detailed non-LTE calculations has also been used.


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Avrett, Machado, and Kurucz (1986) discussed the continuum emission from several semi-empirical flare models. However, they did not give WLF models for specific events. Recently, Mauas, Machado, and Avrett (1991) presented a semi-empirical model of the WLF on June 15, 1982. Fang et al. (1992) gave a semi-empirical model of the WLF on September 19, 1979. These latter two WLFs belong to the second kind of WLF (i.e., those without a Balmer jump), and no pre-flare models were produced, making it difficult to know precisely the change of the atmosphere during the flares.

Aboudarham and Hénoux (1986, 1987), Hénoux and Aboudarham (1992), Fang, Hénoux, and Gan (1993), and Hénoux, Fang, and Gan (1993) investigated the role of non-thermal excitation and ionization of hydrogen by particle beams in the formation of continuum emission. The importance of nonthermal effects and the role of photospheric backwarming in WLF emission were pointed out, leading to the conclusion that electron beams can produce WLFs. These investigations also indicated that semi-empirical models where non-thermal effects are not taken into account would overestimate the temperature in the lower atmosphere of flares. Recently from a detailed analysis of multiwavelength observations, Neidig et al. (1993) concluded that the observed time correlation of the hard X-ray and WLF optical emissions is consistent with chromospheric heating by nonthermal electrons. Hudson et al. (1992) showed the first space observations of four flares, including the flare of October 24, 1991, and pointed out also that there is a good coincidence between the hard X-ray and the continuum emissions of WLFs.

The optical data presented herein are of special interest in some respects. The spectra were obtained in five wavelength bands, having a width of 50–60 Å, obtained simultaneously and with a high time resolution (5 s). One of the three bright kernels of the flare, along the slit of the spectrograph, was observed before it began flaring, so the preflare conditions can be well determined. Besides these data, radio and X-ray bursts are also observed for this flare. All data are presented in Section 2. The resulting non-LTE semi-empirical models are given in detail in Section 3, followed by a discussion and conclusions in Section 4.

2. Observations

On October 24, 1991, a 2N/X.2.1 flare occurred at S14 E59 on the solar disk. Due to its fast development and its obvious white-light emission, it was a very interesting event. With the solar tower telescope (STT) of Nanjing University (Fang and Huang, 1983), we observed its spectra simultaneously in five wavelength bands, including Hα, Hβ, Hγ, Na I D, and Ca II K lines, with a temporal resolution of 5 s. The width of each wavelength band was about 50–60 Å with a dispersion of approximately 0.85 Å mm⁻¹–1.08 Å mm⁻¹. The observations began just at the onset of the flare. The radio burst of this flare was observed by the Beijing
Astronomical Observatory, and the hard X-ray and the soft X-ray emissions were observed from space by Yohkoh (Hudson et al., 1992).

Figure 1 shows a Hα slit-jaw picture taken at 02:38:30 UT, just after the time of the peak of continuum emission. Figure 2 shows part of the spectra obtained by the STT. From Figure 2 it can be seen that there are three main bright kernels along the slit. One of them was not flaring at the starting time of observations (02:37:55 UT). Therefore, since we can entirely follow its time development, the spectra of this kernel was analysed in detail.

By using a PDS microdensitometer, the spectra taken on films were scanned at the flare kernel as well as at the nearby undisturbed quiet region of the Sun. For each wavelength band, continuum intensities were measured in several continuum windows taken in spectral regions of maximum emission between the absorption lines with a similar spectral dependence both in the flare and in the quiet-Sun spectra. The absolute intensity in each window was obtained from

$$I_f(\lambda) = I_{LN}^c(\lambda)L_D(\lambda)\frac{I_f^c(\lambda)}{I_q^c(\lambda)},$$  

where $I_{LN}^c(\lambda)$ is the absolute intensity at the solar disk center given by Labs and Neckel (1968) and $L_D(\lambda)$ is the limb-darkening coefficient calculated according to the formula given by Pierce and Slaughter (1977). $I_f^c(\lambda)$ and $I_q^c(\lambda)$ are the relative intensities in the continuum windows for the flare and the undisturbed quiet region respectively. Equation (1) is based on the assumption that the ratio of the window intensities for the flare and the undisturbed quiet region is the true ratio of their continuum intensities. Since the line blanketing effect was taken into account in the computation of $I_{LN}^c(\lambda)$, the computed values of $I_f(\lambda)$ can be regarded as the
absolute intensities of the true continuum. The mean value of the computed absolute intensities in all windows of each wavelength band was accepted as the absolute continuum intensity in this wavelength band.

Line intensities were obtained by using the relation

$$I(\lambda) = R(\lambda)I_f^c$$

where $R(\lambda)$ is the ratio of the intensities in the line and in the nearby flare continuum. Figure 3 gives the temporal variations of the continuum intensities in different wavelength bands and at the center of the Hα line. The variation of the radio flux at 2840 MHz is also plotted. It can be seen that the duration of the continuum emission is only 1–2 min, and especially that there is a good coincidence between the time of the optical continuum emissions (02:38:20 UT) and the
time of the peak of the radio flux (02:38:17 UT). Yohkoh observations indicated that the hard X-ray flux also peaks at this time, though the peak time can not be measured precisely due to the saturation of the data (Hudson et al., 1992; Watanabe, 1993).

As explained in Section 3.2.1, three semi-empirical models, shown in Figure 4, were built in order to represent the observations, and comparison between various computed and observed parameters are presented in subsequent figures. The observed continuum spectra before the kernel flaring (at 02:37:55 UT) and at the peak time (02:38:20 UT) are given in Figure 5, in which the error bars indicate the mean square deviations of the measurement. The observed profiles of the Hα and the Ca II K lines are given before flaring in Figure 6 and at the peak time in Figures 7 and 8 (solid lines). The most obvious characteristics of hydrogen lines are that they are extremely broad and show a strong central reversal. The half-width of the Hα line at the peak time of continuum emission also reached a maximum with a value as high as 10 Å! The duration of this strong broadening and central...
reversal is only 1–2 min, showing clearly the impulsive property of the observed flare.


3.1. Method of Computation

In order to derive the atmospheric structure of the WLF, and especially to investigate the change in the atmospheric conditions during the flare process, we constructed semi-empirical models corresponding to the preflare conditions and to the peak time of continuum emission. The method and the computation code are similar to that given by Fang et al. (1986) and by Gan and Fang (1987). In brief, the statistical equilibrium equations and the transfer equations for hydrogen and ionized calcium, coupled with hydrostatic equilibrium and the particle conservation equations, were solved iteratively. A four-level-plus-continuum atomic model of hydrogen and a five-level-plus-continuum atomic model of ionized calcium were used. Five broadening mechanisms – Doppler broadening, radiative damping, Van de Waals forces, linear and quadratic Stark effect – have been included in the calculation of the line profiles. All the bound-free and the free-free transitions of the hydrogen atom and negative hydrogen (H⁻) are included. By trial and error, a final semi-
Fig. 5. Comparison between the observed continuum intensities, with error bars giving the mean square deviations of the measurements, and the theoretical intensities computed with the semi-empirical models FQ (upper panel), FT (middle panel), and FNT (lower panel).

empirical model for each case was obtained, which can well reproduce not only the continuum emission but also the observed intensities of the H\(\alpha\) and Ca II K lines. These two lines are formed in a wide range of the atmosphere, from the upper chromosphere for the line centers to the upper photosphere for the line wings. So the two lines, together with the emission in continua, give strict constraints on
Fig. 6. Hα and Ca II K line profiles as observed (solid lines) and as computed (line with three dots per dash) with the semi-empirical model FQ (preflare conditions). The theoretical profiles convolved with a macroturbulence velocity of 10 km s⁻¹ for both lines are shown by dotted lines.

Fig. 7. Observed and computed profiles as in Figure 6. The computations are made for the semi-empirical model FT, corresponding to the peak time of the continuum emission. The theoretical profiles convolved with a macroturbulence velocity of 100 km s⁻¹ and 30 km s⁻¹ for the Hα line and the Ca II K line, respectively, are shown by dotted lines.

the atmospheric structure model. This makes the semi-empirical models obtained fairly well determined.

3.2. NON-THERMAL EXCITATION AND IONIZATION OF HYDROGEN

As indicated by Fang, Hénoux, and Gan (1993) and by Aboudarham and Hénoux (1986, 1987), non-thermal excitation and ionization of hydrogen by electron beams greatly influence the line profiles as well as the continuum emission. If bombardment by a beam of particles occurs during the flare, any semi-empirical model that
does not include these nonthermal effects would overestimate the chromospheric temperature. Taking into account the timing and the characteristics of the observed hydrogen line profiles described in Section 2, which are typical of the spectra of an atmosphere bombarded by an electron beam (Fang, Hénoux, and Gan, 1993; Hénoux, Fang, and Gan, 1993), the flare of October 24, 1991 is very likely a result of electron beam bombardment. Thus we have computed a semi-empirical model with nonthermal effects included. The nonthermal collisional ionization and excitation rates (Fang, Hénoux, and Gan, 1993) are given by the following relations:

for hydrogen:

\[ C_{1c}^B = 1.73 \times 10^{10} \frac{1}{n_1} \frac{dE^H}{dt}, \quad C_{12}^B \sim 2.94 \times 10^{10} \frac{1}{n_1} \frac{dE^H}{dt}, \]
\[ C_{13}^B \sim 5.35 \times 10^9 \frac{1}{n_1} \frac{dE^H}{dt}, \quad \text{and} \quad C_{14}^B \sim 1.91 \times 10^9 \frac{1}{n_1} \frac{dE^H}{dt}; \]  

(3)

for Ca II:

\[ C_{14}^B(Ca) \sim 2.38 \times 10^{10} \frac{1}{n_1} \frac{dE^H}{dt}, \quad C_{15}^B(Ca) \sim 4.25 \times 10^{10} \frac{1}{n_1} \frac{dE^H}{dt}, \]
\[ C_{1c}^B(Ca) \sim 4.69 \times 10^{10} \frac{1}{n_1} \frac{dE^H}{dt}, \]  

(4)

where \( dE^H/dt \) is the energy deposition rate of the electron beam, which is given by Emslie (1978) and Chambe and Hénoux (1979):

\[ \frac{dE^H}{dt} = \frac{1}{2} (1 - x)n_H \Lambda' K F_1 \left( \frac{N}{N_1} \right)^{-\delta/2} (\delta - 2) \int_0^{u_1} \frac{u^{(\delta/2) - 1}}{(1 - u)^{(2+\beta)/(4+\beta)}}. \]  

(5)
The electron flux is assumed to be proportional to $E^{-\delta}$, with a low energy cut-off $E_1$. $F_1$ is the total energy flux above $E_1$. A given column density, $N$, can only be reached by electrons of energy greater than $E_N$, and $N_1$ is the deepest column depth reached by the electrons of energy $E_N$. $E_N$ is given by

$$E_N = \left[ \left( 2 + \frac{\beta}{2} \right) \frac{\gamma K N}{\mu_0} \right]^{1/2},$$

where $\mu_0$ is the cosine of the angle between the initial velocity vector and the solar vertical; $K = 2\pi e^4$; $\beta$ and $\gamma$ are the mean values along the electron trajectory with $\beta$ and $\gamma$ defined in Emslie (1978). Finally,

$$u = \left( \frac{E_N}{E} \right)^2; \quad u_1 = 1 \quad \text{for} \quad N > N_1 \quad \text{and}$$

$$u_1 = \frac{N}{N_1} \quad \text{for} \quad N \leq N_1.$$

$\Lambda' \sim 9$ is expected for an electron beam with an energy of several tens of keV. Consequently, $\beta \sim 2$ and $\gamma \sim 15$ were adopted.

The non-thermal collisional rates were included in the statistical equilibrium equations. A white-light flare must be associated with specific hard X-ray energy fluxes and power-spectrum indexes. No statistical study of the association between white-light flare occurrence and hard X-ray characteristics exists yet. As the hard X-ray observations of Yohkoh are saturated, we cannot get precise values of the total energy flux, $F_1$, and of the power index, $\delta$. As an estimate, considering the fact that the flare is a moderate one (importance 2N/X2.1), we adopted $F_1 = 1 \times 10^{11}$ ergs cm$^{-2}$ s$^{-1}$ and $\delta = 3$. A power index of 4 would have required a total energy flux higher by nearly one order of magnitude, and the use of a still higher power index would lead to unrealistic energy flux requirements.

### 3.2.1. Three Semi-Empirical Models

Three semi-empirical models, corresponding to the pre-flare conditions and to the peak time of continuum emission, without and with the non-thermal effects included, have been computed. Their temperature distributions are shown in Figure 4, marked by FQ, FT and FNT respectively. For comparison, the semi-empirical models of normal flares, named $F_1$ and $F_2$ and given by Machado et al. (1980), are also plotted in the figure. The continuum emission and the profiles of the H$\alpha$ and Ca II K lines reproduced by the three semi-empirical models are shown in Figures 5–8. Good agreement is obtained between the computed and observed continuum intensities plotted in Figure 5. The theoretical profiles of the H$\alpha$ and Ca II K lines have been obtained by convolving the profiles with a macro turbulence velocity field of 100 km s$^{-1}$ (FWHM). A reasonable agreement between the observed and convolved theoretical profiles is obtained in the wings. However, the computed profiles
(dashed lines) are still narrower than the observed ones and the central reversals disappear, which is not consistent with the observations. Including non-thermal effects does not remove the discrepancy. Considering that the macroturbulence has no clear physical meaning, a real turbulent velocity field, such as meso-turbulence (Magnan, 1985; Fang and Ding, 1992), may account for the discrepancy. This problem needs further study. The observed Ca II K and Hα line profiles show also an enhancement of the red wing, presumably due to downward motions that are not reproduced.

4. Discussion and Conclusions

By using multi-wavelength spectral data of the flare of October 24, 1991, we have obtained semi-empirical models, corresponding to the pre-flare time and to the time of the maximum of continuum emission. It is shown that there is a significant heating both in the chromosphere and the upper photosphere. The increase of temperature in the chromosphere is about 1000–1500 K, while in the photosphere the temperature increase at a column mass $m = 1 \text{ g cm}^{-2}$ attained 300 K. Besides, the transition region rapidly moves from $m = 2.6 \times 10^{-4} \text{ g cm}^{-2}$ down to $m = 3.2 \times 10^{-3} \text{ g cm}^{-2}$. All these changes happened within about 25 s (from 02:37:55 UT to 02:38:20 UT). This shows clearly the impulsive property of this WLF. Moreover, the peak time of the continuum emissions coincides well with that of the radio burst (with a delay not higher than 2 to 3 s) and of the hard X-ray burst. The hydrogen line profiles were greatly broadened and showed a strong central reversal. All these facts imply that the WLF was probably a result of particle bombardment. It is consistent with the arguments given by Hudson et al. (1992) and Neidig et al. (1993) and can be understood by non-LTE computations including non-thermal effects (Aboudarham and Hénoux, 1986, 1987; Fang, Hénoux, and Gan, 1993; Hénoux, Fang, and Gan, 1993).

If a particle beam bombardment took place in the observed WLF, then the semi-empirical model (FT) which does not include non-thermal effects would overestimate the temperature increase in the chromosphere. Thus, we computed a semi-empirical model (FNT) by including the non-thermal excitation and ionization of hydrogen caused by an electron beam. The result shows that the temperature in the chromosphere can then be reduced by about 300 K. However, the temperature in the photosphere must remain nearly the same in order to correctly reproduce the continuum emission, which mainly comes from the photosphere. As required mainly for reproducing Ca II K line profiles, the position of the transition region in the model FNT is not so different from that in the model FT. However, another point should be mentioned, which is that the FNT model predicts a more obvious Balmer jump than the model FT, as is shown in Figure 5. This is one of the typical signatures of electron beam bombardment (Fang, Hénoux, and Gan, 1993).
Unfortunately, there is no Balmer limit observation available for this flare. Such observations must be done for future WLFs.

The WLF of October 24, 1991 is very likely produced by an electron beam bombardment. By the use of semi-empirical models, deduced from such observations, one can study the energetics of WLFs and explore the energy source in detail. A more detailed study of the energetics in the observed flare is not fully possible since the hard X-ray data are saturated, making it impossible to estimate the characteristics of the electron beam. However, we can notice that the 300 K temperature increase at a column mass of 1 g cm$^{-2}$ in the photosphere puts severe constraints on the energy deposit mechanism. For reasonable values of the energy flux and power index, electron beams cannot deposit directly the required energy in these photospheric layers. Either some local in-situ energy release must take place or some other energy transport than beams must be acting. Aboudarham and Hénoux (1987) suggested that radiative heating due the local enhancement of the absorption of radiation coming mainly from the deep photosphere, was at the origin of the observed heating. The increase of opacity in the high photosphere is due to the enhancement of the H$^-$ number density that results from non-thermal ionization of hydrogen by the electron beam. At these depths the electron number flux is not high enough to deposit directly a significant amount of energy, but it is sufficient to increase substantially the hydrogen ionization degree and consequently the H$^-$ number density and atmospheric opacity. Aboudarham and Hénoux predicted a temperature increase close to the observed one (240 K) for an energy flux in the electron beam as high as $10^{12}$ ergs s$^{-1}$ cm$^{-2}$. A power index $\delta = 4$ was required to produce such heating. This is the upper limit of the energy flux possible before the start of return current instabilities in a dense flaring atmosphere. This makes the observed photospheric heating at the limit of what can be produced by electron bombardment.

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