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On the origin of solar white-light flares

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Abstract. Using the Hα line intensity as a constraint, we study the role of a chromospheric condensation and the role of non-thermal effects in producing the continuum enhancement of white-light flares. Within an acceptable range of Hα line intensities and electron energy flux, it is shown that neither a chromospheric condensation nor non-thermal effects alone can directly explain the observed continuum enhancement. The hybrid role of both chromospheric condensation and non-thermal effects can only lead to a Balmer jump, but still not to a significant continuum intensity increase between 4000 and 7000 Å. A possible picture is discussed, that is, the Balmer jump is directly produced by the association of a chromospheric condensation and of non-thermal effects, while the continuum enhancement between 4000 and 7000 Å is indirectly produced by the condensation and the non-thermal effects via radiative heating to the deeper photospheric layers.

Key words: Sun: flares – Sun: chromosphere – Sun: photosphere – Sun: X-rays, gamma rays

1. Introduction

Great progresses have been made in recent years on the researches on solar white-light flares. The white-light patches usually correspond to the brightest portion of Hα kernels (Sakurai et al. 1992), but sometimes such a correspondence has not been observed, that is, a white-light patch may correspond to a relatively weak Hα emission (e.g., Mauas et al. 1990; Hiei et al. 1992). Hudson et al. (1992) analysed some white-light flares observed by Yohkoh and presented both impulsive and gradual components. The temporal relations between the hard X-rays and white-light emissions have been shown by Neidig & Kane (1992) and Rieger et al. (1996). They found that there is a general coincidence between these two emissions, which means that the white-light emission is in some way related to the injection of non-thermal electron beams. However, Neidig et al. (1993), who studied in detail the white-light flare of March 7, 1989, showed that there are numerous impulsive features of the hard X-ray time profile, but the peak temporally matching to the white-light emission is neither with the largest flux nor with the hardest spectrum. Rieger & Gan (1993) summarized the white-light flares observed by SMM. They concluded that not every white-light flare has a strong hard X-ray emission and that not every strong hard X-ray flare is a white-light flare.

For the intensity of white-light emissions, the observations made by filter give that the relative increase of the intensity $\Delta I/I_0$ (where I_0 is the intensity of the quiet-Sun) may vary from 50% (4000–7000 Å) to 300% or more (Balmer jump) (e.g., Hudson et al. 1992; Neidig et al. 1993, 1994); while $\Delta I/I_0$ derived from spectroscopic observations remains to be around 10% (e.g., Mauas et al. 1990; Ding et al. 1994; Fang et al. 1995). The differences between filter and spectroscopic observations are well known and have been discussed by Neidig (1989). In order to explain $\sim$10% of $\Delta I/I_0$, semiempirical models of solar white-light flares require some temperature increase in the upper photospheric layer (e.g., Gan & Fang 1988; Mauas et al. 1990; Ding et al. 1994; Fang & Ding 1995; Ding & Fang 1996).

Under the standard paradigms of solar flares, that is, the initial source of energy release lies in the upper corona, three kinds of explanations on the origin of solar white-light flares have so far been proposed (Gan 1997): chromospheric condensation; non-thermal effects, including non-thermal excitation and ionization; extremely strong chromospheric heating. As concerns the possibility of photospheric origin of white-light flares (e.g., Li et al. 1997; Ding et al. 1999), we do not discuss it in this paper.

Gan et al. (1992) studied the role of chromospheric condensations in the continuum emission of white-light flares. They found that chromospheric condensation could produce continuum enhancement only when it is rather strong and with a higher temperature (typically 9000$\sim$10000 K). The resultant enhanced continuum exhibits usually a reddish distribution with a Balmer jump. By use of the PANDORA program (Vernazza et al. 1981), Gan & Mauas (1994) showed further that with some conditions a chromospheric condensation can heat radiatively photospheric layers, resulting in an enhancement of the continuum emission from H^- ions. These authors studied the continuum emission isolately but did not evaluate the amplitude of the associated chromospheric lines like Hα. Although a chromospheric condensation seems to be able to explain many features of white-light flares, so far we have not seen any semiempirical models with a chromospheric condensation to explain a real white-light

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flare. From existing semiempirical models with a chromospheric condensation for two non-white-light flares (Gan et al. 1993), we notice that the parameters describing the condensation are much different from those required by producing the continuum enhancement. This reminds us a question: can the chromospheric condensation explain both continuum enhancement and the Hα line emission of a white-light flare?

For quite a number of white-light flares, a good time correlation between white-light and hard X-ray emission has been observed. The energy carried by non-thermal electrons seems to be large enough to produce the continuum enhancement. But how this process is working is a problem, since the direct energy deposition of non-thermal electrons into the deeper layer of the photosphere is obviously not large enough. Therefore, the non-thermal collisional excitation and ionization of hydrogen by electron beams provide an alternative way. Aboudarham & Hénoux (1986b, 1987) showed that, with inclusion of non-thermal effects, the upper photosphere can be radiatively heated, resulting in an increase of the white-light emission both at chromospheric and photospheric levels. Hénoux et al. (1993) calculated the continuum enhancement by adding the contribution of non-thermal collisional processes to the thermal emission expected in an atmosphere represented by the F2 model (Machado et al. 1980). Then, the influence of non-thermal effects on the spectral line profiles was extensively studied (e.g, Fang et al. 1993; Hénoux et al. 1995; Ding & Fang 1997). However, there are still some difficulties in explaining white-light flare by using non-thermal effects alone. First, the black-light flare expected by non-thermal effects (Aboudarham et al. 1990; Hénoux et al. 1990) has not been observed so far (van Driel-Gesztelyi et al. 1994). Second, in showing the radiative heating to the deep layer of photosphere, F_{20} (the flux of non-thermal electrons above 20 keV) taken as 10^{12} ergs cm^{-2}s^{-1} seems to be too large in comparison with the usual observations. Moreover, even for this large value of F_{20}, the predicted continuum enhancement between 4000 and 7000 Å is still not high enough to explain the observations (Ding & Fang 1996). Third, the non-thermal effects alone cannot explain the usual line asymmetries appearing during the impulsive phase in a majority of solar flares. Besides, from the semiempirical model of the white-light flare on October 24, 1991 (Fang et al. 1995), we notice that although F_{20} was taken as large as 10^{11} ergs cm^{-2}s^{-1}, the Balmer jump is still very weak. The role of non-thermal effects in producing continuum emission of white-light flares should be studied in more detail.

Avrett et al. (1986) once proposed the so-called F3 model (strong chromospheric heating) and F1* model (strong photospheric heating) to explain the Type I and II white-light flares (about the definition of Type I and II, see Machado et al. 1986; Fang & Ding 1995), respectively. Machado et al. (1989) combined F3 and F1* together and proposed the so-called F4 model, that is, they thought that the strong chromospheric heating may lead to a radiative backwarming of the deep photospheric layers (Aboudarham & Hénoux 1986a). The F3 or F4 models imply an extremely strong chromospheric heating; and the column mass of the transition region (m_{top}) must be as large as 6 10^{-3} g cm^{-2}. The residual intensity of the Hα line expected from F4 model is then greater than 10, which is too large in comparison with usual observations.

It seems that the origin of solar white-light flare continuum emission is still an open question. In fact, the existence of chromospheric condensations in solar flares has been confirmed (e.g., Gan & Rieger 1996), while the impulsive hard X-ray emission observed in solar flares is the direct evidence for the existence of non-thermal effects. In this paper, we first check the limitations of both chromospheric condensation and non-thermal effects in producing the continuum enhancement of white-light flares. Then we consider an hybrid role of the condensation and the non-thermal effects. At last, a possible explanation on the continuum emission of solar white-light flares via radiative heating of the lower atmospheric layers is suggested.

2. Results

The method used in this paper is the same as that used by Fang et al. (1993) and Hénoux et al. (1995). The code was originally developed from the work of Fang & Hénoux (1983), Gan & Fang (1987), and Gan et al. (1992). The relevant formulations of non-thermal collisional excitation and ionization of hydrogen by electron beams can be found in Aboudarham & Hénoux (1986b, 1987) and Fang et al. (1993). The method of how to describe a chromospheric condensation can be found in Gan et al. (1992). Briefly, for a given model atmosphere (base model), we may introduce a chromospheric condensation (characterized by its thickness ΔZ, temperature T, and pressure ratio P_0) into the top of the chromosphere, or introduce a non-thermal electron beam (characterized by F_{20} and the spectral index δ) injected into the atmosphere. Then the equations of rediative transfer, statistical equilibrium, and the particle conservation are solved simultaneously. The model atmosphere with a condensation or/and a non-thermal effect is therefore obtained. The continuum emission and Hα line profile can then be calculated. In calculations, a four levels plus a continuum atomic model of hydrogen is assumed. The other upper levels are treated in LTE. The continuum mechanisms include bound-free and free-free transitions of both hydrogen and negative hydrogen ions, as well as Thomson scattering. The broadening of Hα line includes all the important mechanisms, such as Doppler, radiation damping, van der Waals resonance, and Stark effects. Further details can be found in Gan & Fang (1987), Gan et al. (1992), and Fang et al. (1993).

Three base models are used. The first two, named G1 and G2, are taken from Gan et al. (1993), who showed that a condensation overlapping on G1 and G2 could reproduce Hα line profiles observed for two flares. The other base model is F2 (Machado et al. 1980), that represents a big flare. Fig. 1 shows these three base models.

2.1. The role of a chromospheric condensation alone

Like Gan et al. (1992), we study the role of chromospheric condensations in the continuum emission. But beside calculating

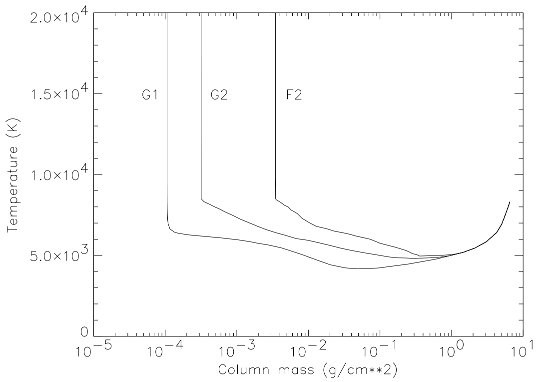

Fig. 1. Temperature versus column mass distribution of the three base models G1, G2, and F2.

the continuum, we also calculate the Hα line profile. We compare the calculated Hα line profile with the observed ones. If the calculated line profile is obviously unreasonable, e.g., the intensity is too strong or the Doppler shift is too far, it means that the condensation introduced is not reasonable. Then we try with other parameters of condensation. The aim is to find such cases that the condensation can directly produce a continuum enhancement between 4000 and 7000 Å while the Hα line emission is within the scope of usual observations.

Using model G1, we have made a series of calculations with different parameters of condensations. The results show that, within an acceptable range of Hα line emission, we could not find a condensation which can emit directly enhanced white-light emission. This result is consistent with that of Gan et al. (1992), who claimed that the chromospheric condensation could produce the continuum enhancement only when the transition region moves downward below to $m_{top} > 10^{-4}\,\mathrm{g\,cm^{-2}}$, while in the base model of G1, m_{top} is just equal to $10^{-4}\,\mathrm{g\,cm^{-2}}$. So even ignoring the constraint imposed by the observed Hα line intensity, a significant continuum enhancement is hard to be produced by introducing a condensation into G1.

Calculations based on G2 show, without exception, that, when the condensation can directly emit some continuum between 4000 and 7000 Å, the Hα line emission is always too strong. In Fig. 2 we give one example, in which P_0=50, ΔZ=80 km, and T=10600 K. It can be seen in this figure that the Hα line emission is much stronger than the one generally observed in solar flares. Whether or not the Hα line is extremely strong in white-light flares is now hard to say. But, from the present observations (e.g., Fang & Ding 1995; Li & Zhong 1997), this does not seem to be the case. The results obtained here constrain the universality of the conclusions reached by Gan et al. (1992). In fact, De La Beaujardiere et al. (1994) have found for a white-light flare that the velocity deduced from Hα line is inconsistent with that a chromospheric condensation would produce.

Further calculations based on F2 confirm the results obtained for G2. Fig. 3 presents another example, in which P_0=30, ΔZ=14 km, and T=9240 K. We see that the Hα line emission is still too strong, although the continuum enhancement is rather limited in amplitude.

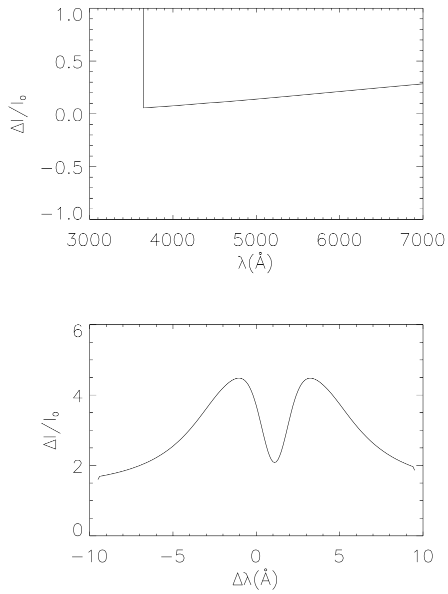

Fig. 2. Continuum emission and Hα line profile generated by a condensation (P_0=50, ΔZ=80 km, and T=10600 K) in an atmosphere represented by the model G2. km, and T=10600 K) in an atmosphere represented by the model G2.

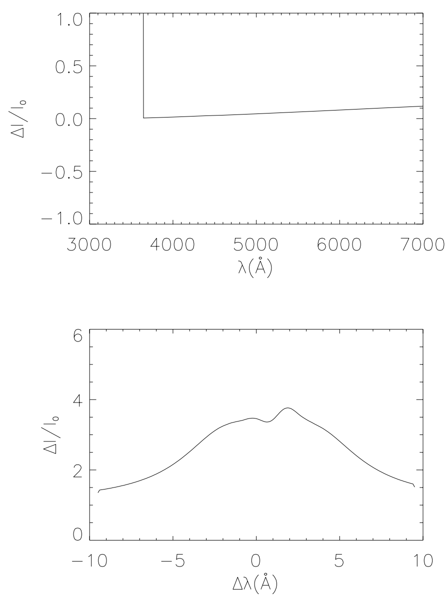

Fig. 3. Continuum emission and Hα line profile generated by a condensation (P_0=50, ΔZ=80 km, and T=10600 K) in an atmosphere represented by the model F2.

As a conclusion, when the observed intensity of the Hα line is taken into account, it becomes doubtful that a chromospheric condensation could directly explain the observed white-light continuum enhancement between 4000 and 7000 Å.

2.2. The role of non-thermal effects alone

According to Aboudarham & Hénoux (1986b, 1987), non-thermal collisional excitation and ionization of hydrogen by

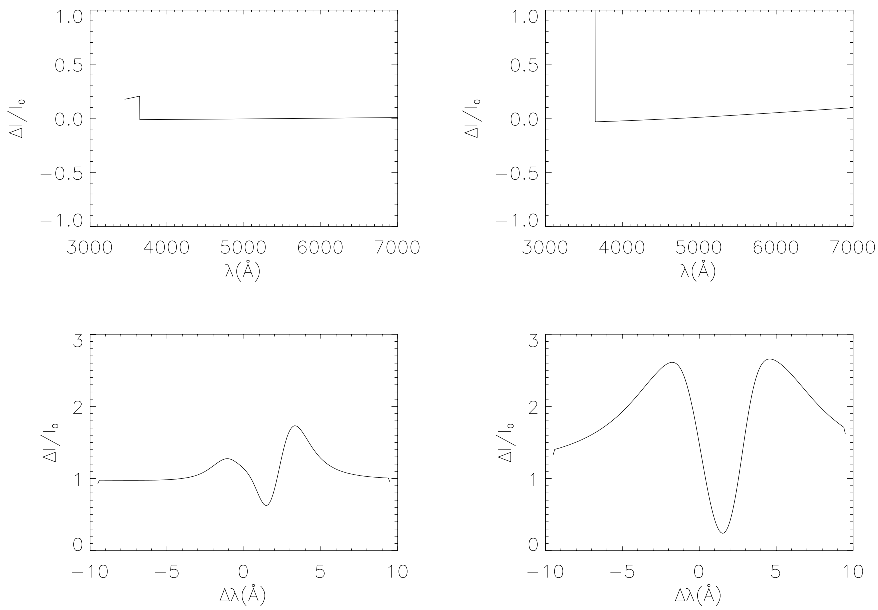

Fig. 4. In an atmosphere represented by the model G2, continuum emission and Hα line profile generated by a chromospheric condensation (P_0=100, ΔZ=80 km, and T=10600 K) alone (left panel) or complemented by non-thermal effects with F_{20}=10^{11} ergs cm^{-2}s^{-1} and δ=3 (right panel).

electron beams not only lead to a direct enhancement of the chromospheric hydrogen continuum emission, but also lead to an increase of the H^- population and to enhanced absorption of photospheric and chromospheric continuum radiation. Consequently the photosphere is radiatively heated. Here we do not take into account the contribution of the radiative backwarming since it requires very high values of the beam energy flux, which may lead to drift velocity of the return current close to or higher than that of the thermal speed; we just consider the possibility of non-thermal effects to directly produce continuum enhancement.

For given sets of F_{20} and δ, we first calculate the model atmosphere with a non-thermal effect based on G1. It is found that within F_{20}=$10^{10} - 10^{11}$ ergs cm^{-2}s^{-1}, the continuum enhancement between 4000 and 7000 Å is negligible. When we take F_{20} as high as 10^{12} ergs cm^{-2}s^{-1}, the continuum emission shows to be decreased. This situation corresponds to the black-light flare expected by Aboudarham et al. (1990) and Hénoux et al. (1990). But F_{20}=10^{12} ergs cm^{-2}s^{-1} is too big in comparison to general observations. In fact, G1 is usual, and F_{20}=$10^9 - 10^{11}$ ergs cm^{-2}s^{-1} are also usual. With these usual values, it is very normal if no continuum enhancement appears; otherwise the white-light flares would be more frequent. The unusualness of white-light flares demonstrates that some special requirements must be satisfied.

The results based on G2 are similar to those based on G1. If we take too strong flux of electrons, the continuum enhancement between 4000 and 7000 Å may become negative. For the F2 model, our calculations confirm the conclusions made by Fang et al. (1993) that non-thermal effects have a great influence on Hα line profiles. But the continuum enhancement $\Delta I/I_0$ does not exceed 4%, which is consistent with Aboudarham & Hénoux (1987) and Hénoux et al. (1993).

As a conclusion, near the disk center, with F_{20}=10^9–10^{11} ergs cm^{-2}s^{-1}, despite which base model is used and which δ is taken, the continuum enhancement resulting directly from purely non-thermal effects is not significant.

2.3. Association of a chromospheric condensation and of non-thermal effects

Since neither a chromospheric condensation alone nor non-thermal effects alone can directly produce a significant continuum enhancement, we consider here whether it is possible for white-light flares to result from both effects acting together. In order to find such cases in which the Hα line emission is acceptable while there is an increase of continnum between 4000 and 7000 Å, a series of calculations was made for a varity of combinations of these effects. The computations showed that the predicted emission spectrum could not fulfil such conditions. In Fig. 4 we show one example based on G2. The left side of the figure shows the continuum enhancement and the Hα line profile generated by a chromospheric condensation with P_0=100, ΔZ=58 km, and T=8160 K. It can be seen that the intensity enhancement between 4000 and 7000 Å is negligible, while the Balmer jump is around 20%. When the non-thermal effects contribution, generated by an electron beam of F_{20}=10^{11} ergs cm^{-2}s^{-1} and δ=3, are added, the Balmer jump increases from 20% to 130%, and there is also an enhancement of continuum between 4000 and 7000 Å, but the Hα line intensity is too strong to match to the usual observations. Also, the deep central reversal is not in agreement with observations.

However, we may expect an increase of the Balmer jump, to be obtained by an appropriate combination of a chromospheric condensation and non-thermal effects, that would keep the Hα line intensity acceptable. Fig. 5 illustrates this situation for G2. The left side of the figure corresponds to a chromospheric condensation with P_0=30, ΔZ=58 km, T=8160 K. The relative intensity of the Balmer jump is about 2%. When the non-thermal effects (F_{20}=5 10^{10} ergs cm^{-2}s^{-1} and δ=4) are introduced, the

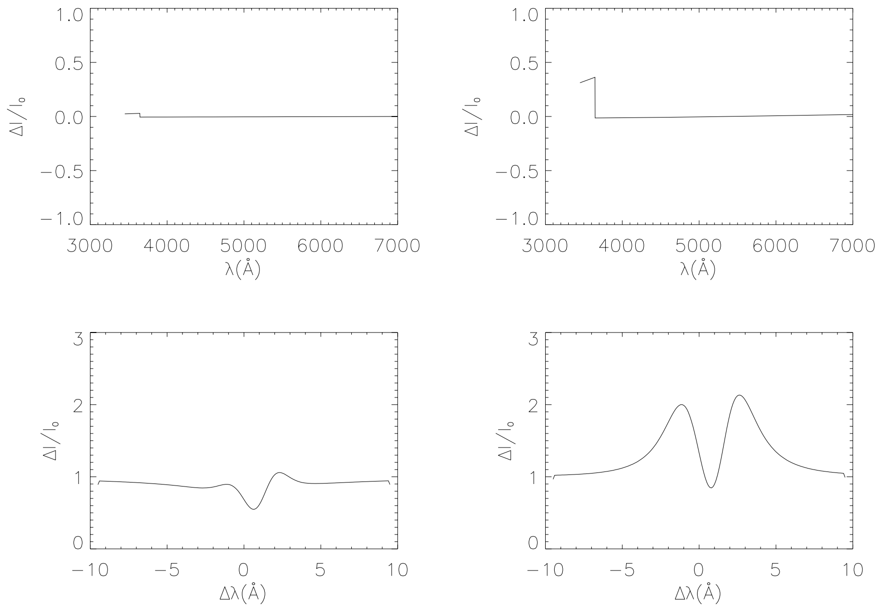

Fig. 5. In an atmosphere represented by the model G2, continuum emission and Hα line profile generated by a chromospheric condensation (P_0=30, ΔZ=58 km, and T=8160 K) alone (left panel) or complemented by non-thermal effects with F_{20}=5 10^{10} ergs $cm^{-2}s^{-1}$ and δ=4 (right panel).

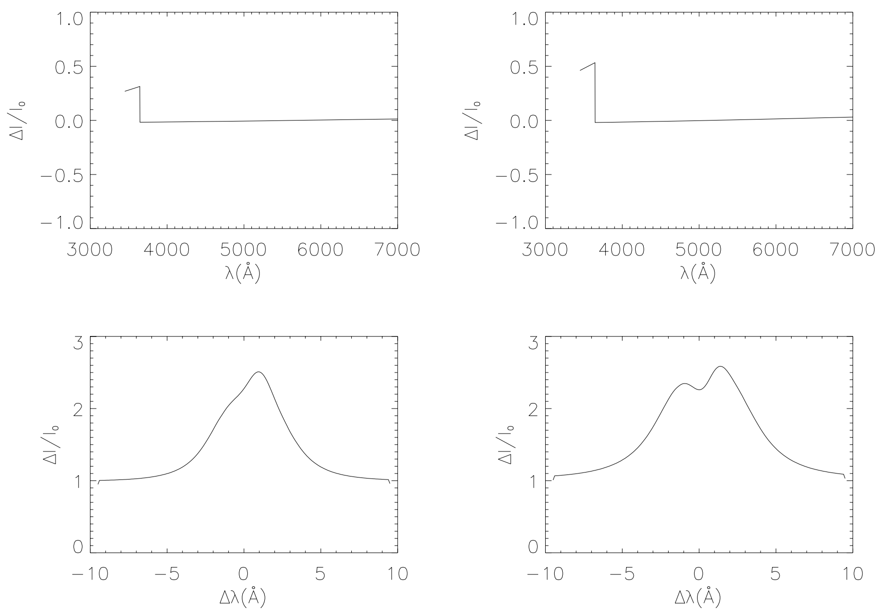

Fig. 6. In an atmosphere represented by the model F2, continuum emission and Hα line profile generated by a chromospheric condensation (P_0=10, ΔZ=69 km, and T=8100 K) alone (left panel) or complemented by non-thermal effects with F_{20}=5 10^{10} ergs $cm^{-2}s^{-1}$ and δ=4 (right panel).

relative intensity of the Balmer jump increases to 40% (right side of Fig. 5), while the Hα line intensity is still in an acceptable range, although there is a central reversal in the Hα line profile. Fig. 6 gives another example for F2 model. The left side of the figure corresponds to a chromospheric condensation with P_0=10, ΔZ=69 km, T=8100 K. When the non-thermal effects (F_{20}=5 10^{10} ergs $cm^{-2}s^{-1}$, δ=4) are introduced, the intensity of the Balmer jump increses from 35% to around 60%.

3. Discussion and summary

In the above section, we have seen that a chromospheric condensation itself cannot directly produce a significant enhancement of the continuum emission between 4000 and 7000 Å if the intensity of Hα line is taken into account, except for the case where spectral observations would show that the Hα line is exceptionally strong in the white-light flares. This result limits the universality of the work of Gan et al. (1992), who did not consider the spectral lines. For reasonable values of the electron energy flux, such as F_{20} is lower than or equal to 10^{11} ergs $cm^{-2}s^{-1}$, non-thermal effects alone cannot directly produce any increase of continuum emission either. The combined roles of a condensation and non-thermal effects are still very limited. Altogether they can only produce an increase of the Balmer jump, but cannot lead to a significant increase of the continuum emission between 4000 and 7000 Å.

However, the preceding conclusion does not take into account the backwarming of the upper photosphere. Aboudarham & Hénoux (1987) showed that non-thermal effects lead to a radiative heating of the deep atmosphere. Gan & Mauas (1994) also found that a chromospheric condensation may affect the whole distribution of the atmospheric cooling rate and may result in a radiative heating to the deep layer of photosphere. All these authors calculated the consequence of the backwarming and showed that an increase of the continuum emission resulted from the photospheric heating. However, they consider only one effect and did not estimate, as a way to check the limits of validity of their models, the associated resulting Hα line intensity.

Therefore, if a chromospheric condensation and non-thermal effects may be responsible for the white-light flares, one possible picture is that, as shown in this paper, the Balmer jump is produced directly by both roles of a condensation and non-thermal effects, while the continuum enhancement between 4000 and 7000 Å originates in the photosphere which may be radiatively heated due to the existence of a chromospheric condensation and non-thermal effects. Obviously, in such case a detailed study of the resulting energy balance in the upper photosphere remains to be done.

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