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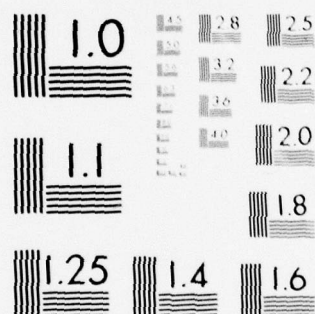
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H α PROFILES FROM ELECTRON-HEATED SOLAR FLARES

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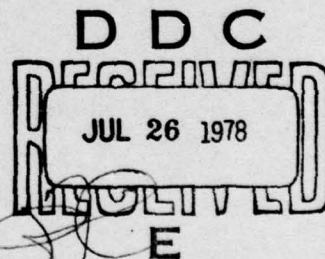
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21. ABSTRACT (Continue on reverse side if necessary and identify by block number) We briefly review the status of models of optical flare heating by electron bombardment. We recompute Brown's (1973a) flare model atmospheres using considerably revised radiative loss rates, based on Canfield's, (1974b) method applied to H α , Lyman- α , and H γ . Profiles of H α are computed and compared with observation. The computed profiles agree satisfactorily with those observed during the large 1972 August 7 flare, if spatial and velocity inhomogeneities are assumed. The electron H-alpha		

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injection rate inferred from $H\alpha$ is one order of magnitude less than that inferred from hard X-rays, for this event. This may be due to either (1) the neglect of a mechanism that reduces the thick-target electron injection rate or (2) failure to incorporate important radiative loss terms.

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1. PREVIOUS WORK

Over the last decade or so there has been considerable enthusiasm for the idea that energetic electrons (in the 10-100 keV range) may be a primary product of the energy release in many solar flares, their collisional degradation in the atmosphere resulting in the various flash phase thermal phenomena (optical, UV and soft X-ray emission and the onset of mass motions) as secondary products. The evidence for this suggestion in terms of the total energy of the electrons and the synchronism between the various thermal and non-thermal emissions has been reviewed by several authors (e.g. Brown 1973a, 1975, 1976; Hudson 1973; Kane 1974; Lin 1975). Detailed theoretical models have been developed (see these reviews for references) to predict the structure of various regimes in the solar atmosphere where the electron input appears in the energy equation together with thermal conduction and radiative losses. In the high temperature regime conduction is dominant and Shmeleva and Syrovatskii (1973) have obtained a steady state description of its temperature structure, and also of that in the UV flare where radiation is also important. Recently some quantitative work has begun (Craig and McClymont 1977; Kostyuk and Pikel'ner 1975; Kostyuk 1975, 1976) on the role of mass motions.

In the low temperature (chromospheric) flare mass motions undoubtedly also play an important role. However, optical depth effects also become significant there, adding to the complexity of numerical modeling. Brown (1973a) calculated steady state chromospheric models with a simplified Lyman-continuum radiative-loss method. There are two areas in which Brown's (1973a) calculations obviously could be improved: (1) convection and conduction; (2) radiative losses. Kostyuk and Pikel'ner (1975) and

Kostyuk (1975) did only the former; here, we do only the latter.

In this paper we amend Brown's (1973a) models, maintaining the steady-state, constant-pressure, electron-input, radiative-output approximation for the optical flare, but taking into account Canfield's (1974a) criticisms of Brown's radiative losses. We are thus assuming that heating increases gradually enough to permit a steady state radiative solution but still on a time scale shorter than that for arrival of heat flux conducted from the corona (cf. next section). Canfield (1974a) computed the $H\alpha$ profiles expected from Brown's (1973a) models and found major discrepancies with observations. Pursuing this, Canfield (1974a) then found that Brown had overestimated the hydrogen radiative losses by up to two orders of magnitude. Brown omitted the radiative input of the Balmer continuum from the photosphere in his energy equation, though including it in his ionization equation, thus overestimating the radiative loss rate. The Lyman continuum radiative output was obtained by reducing the optically thin output by $\exp(-\tau_{Ly\ c})$, which we now view as overly simplified. Methods were then developed by Canfield (1974b,c) to allow a relatively simple method for radiative losses in lines. Subsequent work (in progress) has shown that the situation is more complex than originally stated by Canfield (1974a). Due to a numerical error, Canfield (1974a) found that hydrogen continuum radiative losses were much less than hydrogen line losses. In fact, these subsequent calculations show hydrogen continuum cooling to be sometimes comparable to line cooling, and sometimes greater. Interestingly, they also show regions dominated by continuum heating. Because of these findings, we view the present models as an evolutionary improvement upon previous work, but consider it likely that further improvements will result from

still more complete treatments of radiative aspects of the problem.

2. SOLUTION OF THE ENERGY EQUATION

Hard X-ray burst observations are consistent with a flare electron spectrum of approximately power-law form above about 20 keV. If such electrons are injected downward into the chromosphere (thick target model) the injection rate $F(\text{electrons s}^{-1})$ and spectral index are given from the hard X-ray observations by the expressions in Brown (1975). When the electron energy flux above 20 keV is $\mathcal{F}_{20}$ the rate of collisional energy deposition at a total hydrogen (atoms plus ions) column depth $N \text{ cm}^{-2}$ into the atmosphere is (cf Brown 1973a)

$$Q(N) = 1.7 \times 10^3 \mathcal{F}_{20} B_x(\delta/2, \frac{1}{3}) \left(\frac{6 \times 10^{19}}{N} \right)^{\delta/2} \text{erg gm}^{-1} \text{s}^{-1} \quad (1)$$

where δ is the electron injection spectral index and

$$x = 1 \quad N \geq 1.5 \times 10^{17} E_c^2 \\ = \frac{N}{1.5 \times 10^{17} E_c^2} \cdot N < 1.5 \times 10^{17} E_c^2 \quad (2)$$

$E_c(\text{keV})$ is the low energy cutoff (if any) in the electron spectrum and B_x is the partial beta function (total if $x = 1$). Equation (1) corrects some algebraic errors in Brown's (1973a) expression (cf. Lin and Hudson, 1976).

As many authors have pointed out, the flare atmosphere is divided into a high and a low temperature region by the radiative instability of cosmic plasma above $T \approx 5 \times 10^4 \text{ K}$ (at constant pressure; cf. Cox and

Tucker, 1969). Material above this transition zone rapidly becomes too hot to participate in forming the optical flare spectrum so we only consider the atmospheric structure below $T = 5 \times 10^4$ K. In this region three radiative loss contributions are important: heavy element lines and continua; H-negative continuum; and the hydrogen Lyman and Balmer lines and continua.

Heavy element lines and continua are assumed to be optically thin. They are somewhat problematic in that their loss contribution has only been computed down to around 2×10^4 K. Below this temperature their behavior becomes model dependent because of the effect of decreasing hydrogen ionization on the collisional ionization equilibrium and because some of the important lines may become optically thick. The best that seems possible at present is an empirical fit to the solar radiative loss curve (McWhirter et al. 1976) extrapolated to lower temperatures (similar to Brown 1973a).

The H-negative and $H\alpha$ and Lyman- α losses here have been based on Canfield's (1974b,c) probabilistic radiative loss technique. This complicates the practical handling of the problem considerably over Brown's original (1973a) treatment.

For a quasi-steady state throughout the heated region, the energy balance equation can still be written as

$$Q(N) = R \quad (3)$$

at all N but R , the rate of radiative energy loss, is no longer just a local function of N (through n , T) as in Brown's (1973a) treatment.

Instead R depends on the entire structure of the atmosphere model, $T(N')$, $n(N')$ for all N' , through radiative transport effects. Consequently (3) had to be solved by an iterative scheme using some starting model flare atmosphere and adjusting T at each level N' in the model grid (at constant pressure) until a model converging on condition (3) was obtained. In this iteration scheme we used Canfield's (1974c) program to approximate the radiative losses but confirmed previous estimates of the accuracy of the method by comparison with a detailed calculation for the converged model (see below). We have neglected any effect of direct non-thermal ionization or excitation by beam collisions, the importance of which is still disputed (cf. Hudson 1972, Brown 1973b, Lin and Hudson 1976).

In this approach it was found that the deeper layers were very slow (iteratively) to approach a steady state. This is because the radiative response time to the small input is long (due to radiative transport effects) so that in practice a steady state would only be reached slowly in real time also - in fact in a time long compared to typical beam durations (10-100 s). We therefore refined our procedure somewhat by estimating the real elapsed time up to any iterated stage in the model - i.e. we performed the iteration in quasi-real time steps. (The elapsed time was approximated by $(kT/m_H)/(Q-R)$). The final model adopted was that reached after an estimated real elapsed time equal to a beam input duration τ_B as parameter. (Here we use only $\tau_B \approx 60$ s). The deepest layers of the atmosphere were thus not yet in a steady state when heating was terminated. Note that this procedure does not incorporate time dependent radiative transfer but is a first approximation in avoiding the overestimate of the temperatures of deep layers incurred by assuming a steady state throughout.

It is appropriate at this point to consider the various time scales involved (cf. Brown 1973a,b, 1974). First, the radiative response time τ_R is of order $(kT/m_H)/Q$ which rises rapidly with depth due to the N dependence in (3). Thus a fair approximation is

$$\tau_R \sim \left(\frac{10^9}{\bar{x}_{20}}\right) \times \left(\frac{N}{6 \times 10^{19}}\right)^2 \geq \left(\frac{10^9}{\bar{x}_{20}}\right) \left(\frac{n}{10^{12}}\right)^2 \quad (4)$$

and we see that for the $\bar{x}_{20}$ values we require (Section 4), $\tau_R \leq \tau_B$ except in the deepest layers (as noted above) so that a quasi-steady radiative treatment is not unreasonable, though not perfect either. The importance of conduction is harder to estimate since it may differ drastically according to whether transient steep conduction fronts are involved, or the atmosphere is quasi-steady. We can at least check the self-consistency of our model atmosphere using the simple estimate

$$\tau_{\text{COND}} \approx nkT / \{ \kappa(T) T / L^2 \} \quad (5)$$

for the conduction time. Using $n \geq 10^{13} \text{ cm}^{-3}$, $T \approx 10^4 \text{ K}$ in the $H\alpha$ region, Coulomb conductivity $\kappa(T)$ and adopting the shortest possible temperature scale length L from our Figure 1 in this region we find $\tau_{\text{COND}} \geq 10^5 \text{ s}$. (The chief uncertainty in this estimate rests on the possibility that our temperature structure at $T \approx 10^4 \text{ K}$ could be substantially modified when linked conductively to the hot region above $5 \times 10^4 \text{ K}$ which we ignore). Our calculation is thus at least self-consistent.

3. MODEL ATMOSPHERES

Here we present only results for the typical parameters $\delta = 4$, $E_c = 10$ keV, $\tau_B = 60$ s for flux values, $\mathcal{F}_{20} = 10^8, 10^9, 10^{10}$ and 10^{11} erg $\text{cm}^{-2} \text{s}^{-1}$. The resulting model atmospheres are shown in Figures 1 and 2 in terms of respectively $T(z)$ and $n(z)$ (total hydrogen density) as functions of height z above the photosphere. In general the results differ from Brown (1973a) in deeper penetration of the heating (due to reduced radiative losses) and in local features on the $T(z)$ profiles due to the hydrogen line losses. The plateau at $T = 10^4$ K is due to the manner in which the optically-thin radiative losses were cut off and so may be spurious. Particularly interesting in view of the ATM observations of EUV continua of neutral and singly-ionized elements is the heating between 500 and 1000 km. It is cut off at the lower end by reduced penetration of heating and increased effectiveness of radiative cooling, primarily due to H^- .

4. COMPUTED AND OBSERVED $\text{H}\alpha$ PROFILES

Although the present models are based on very limiting assumptions concerning the dynamical and radiative effects, a preliminary comparison with the observations is nevertheless interesting. $\text{H}\alpha$ line profiles were computed as before (Canfield 1974a). Figure 3 shows the computed $\text{H}\alpha$ profiles (dashed lines) for the four atmospheres, together with observed profiles (dash-dot lines) of the flare of August 7, 1972 (Zirin and Tanaka, 1973; Tanaka 1977). We will compare our computations with these data because we also have hard X-ray data (Hoyng *et al.* 1976, Lin and Hudson 1976) for the August 7 flare.

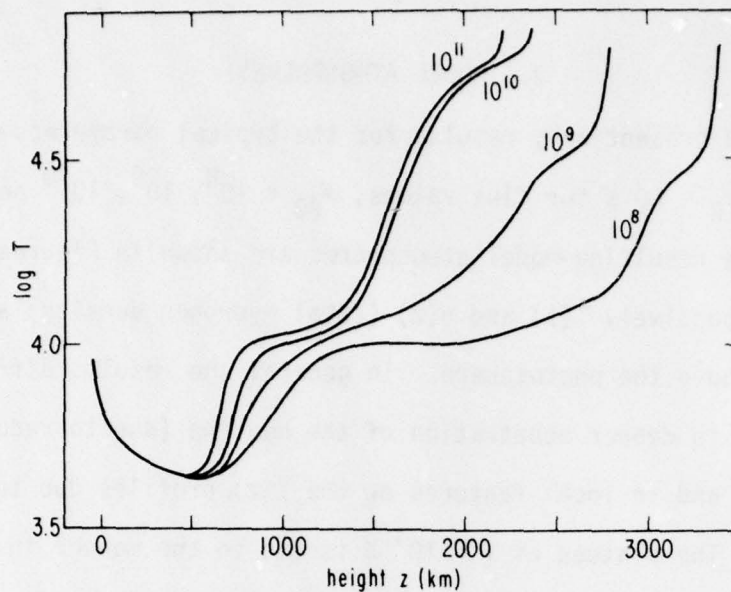


Figure 1. The computed temperature distributions for $\mathcal{F}_{20} = 10^8, 10^9, 10^{10}$ and 10^{11} erg cm⁻² s⁻¹.

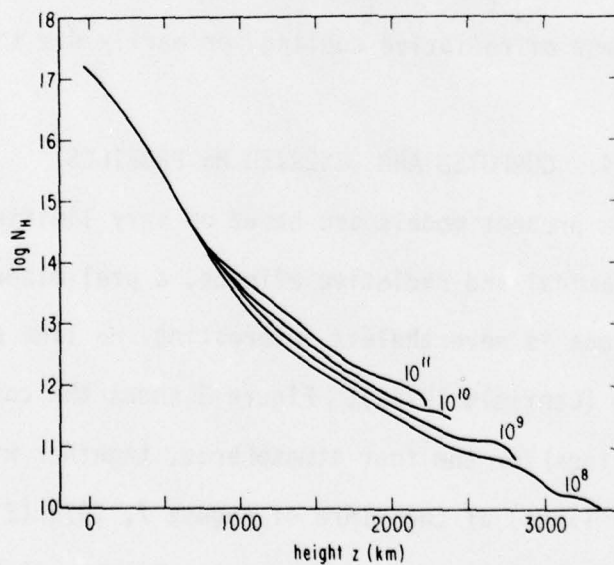


Figure 2. The computed hydrogen (atoms and ions) number density distributions for $\mathcal{F}_{20} = 10^8, 10^9, 10^{10}$ and 10^{11} erg cm⁻² s⁻¹.

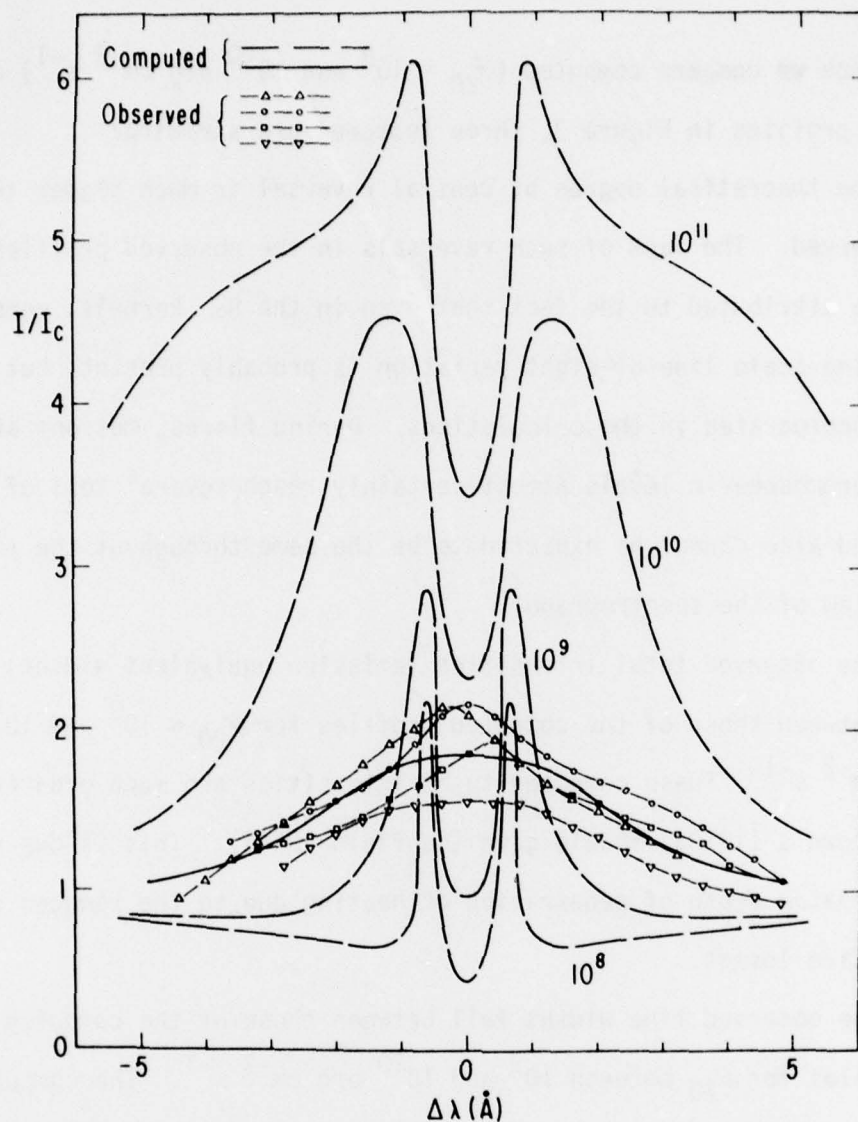


Figure 3. Computed and observed $H\alpha$ line profiles. Dashed: computed from the models for given $\mathcal{F}_{20}$ values. Dot-dashed: two observed 1972 August 7 flare kernels each at 1518 and 1521 UT (Tanaka 1977). Solid: combination of computed profiles with $\mathcal{F}_{20} = 10^9$ and 10^{10} , after smoothing with 60 km/s random velocities.

When we compare computed ($\mathcal{F}_{20} = 10^9$ and 10^{10} erg cm⁻² s⁻¹) and observed profiles in Figure 3, three features are striking:

- (i) The theoretical degree of central reversal is much higher than observed. The lack of such reversals in the observed profiles can be attributed to the fact that even in the H α kernels, considerable fine-scale line-of-sight variation is probably present, but not incorporated in the calculations. During flares, motions at chromospheric levels almost certainly reach several tens of km s⁻¹ and also cannot be expected to be the same throughout the field of view of the spectrograph.
- (ii) The observed total intensities (emission equivalent widths) fall between those of the computed profiles for $\mathcal{F}_{20} = 10^9$ and 10^{10} erg cm⁻² s⁻¹. These computed total intensities are much greater than Brown's (1973a) models gave (Canfield 1974a). This is due to the greater depth of penetration of heating due to the reduced radiative losses.
- (iii) The observed line widths fall between those of the computed profiles for $\mathcal{F}_{20}$ between 10^9 and 10^{10} erg cm⁻² s⁻¹. The computed line widths are much greater than those for Brown's (1973a) models, in better agreement with the observations. This is a combination of the effects of greater optical thickness of the H α -forming region and Stark broadening due to higher values of N_e for a given value of $\mathcal{F}_{20}$. The major difference between these profiles and those from the earlier models is a measure of the importance of the method used for computing radiative losses.

An elaborate comparison of computed and observed profiles is premature at this point. Briefly speaking, we find that the half-widths and equivalent widths of the computed profiles and the observed profiles can be made to agree within the observational uncertainty by incorporating effects of spatial inhomogeneity in $\mathcal{F}_{20}$ and in radial velocity.

We represent the radial velocity inhomogeneities by convoluting the computed profiles with a Gaussian profile of half-width 60 km s^{-1} (macro-turbulence), comparable to velocities observed in the June 15, 1973 flare by Doscheck *et al.* (1977). This is just sufficient to remove the central reversal from the model profile. Once this has been done we find that although the observed half widths and equivalent widths both fall in the range of theoretical profiles for $\mathcal{F}_{20} = 10^9 - 10^{10}$, the ratios of the two widths still do not fall anywhere along the theoretical curve for this ratio. However they may be made to do so by assuming that the heated region (electron impact area) occupies only a fraction α of the observed kernel area. The appropriate model $H\alpha$ profiles are then a combination of α times the electron heated model profile for any chosen electron flux plus $(1-\alpha)$ times the quiet sun (or preflare) profile, α being the "filling factor". We find that the best match to the data obtains for $\alpha \approx 1/3$ and that for this value the best fit value of $\mathcal{F}_{20}$, averaged over the whole kernel area, is about $3 \times 10^9 \text{ erg cm}^{-2} \text{ s}^{-1}$, implying local values $\approx 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ on the impact areas. Had we adopted a macroturbulent velocity as high as 100 km s^{-1} we could obtain a fit to the data with rather less horizontal beam inhomogeneity in the kernels but then the necessary $\mathcal{F}_{20}$ would also have been less, and merely emphasized our conclusions in the following discussion.

Since we have profiles and models only for discrete $\mathcal{F}_{20}$ values, some idea of how the combined profile discussed above would compare with the observations is shown by the solid curve in Figure 3. This profile is an arbitrarily scaled average of the $\mathcal{F}_{20} = 10^9$ and 10^{10} profiles, after convolution with a gaussian (Doppler) profile of width 60 km s^{-1} .

From the observed hard X-ray fluxes for this same August 7 event Hoyng et al. (1976) infer an energy input rate in electrons of $E > 20 \text{ keV}$ of $3 \times 10^{29} \text{ erg s}^{-1}$, while Lin and Hudson (1976) obtain $2 \times 10^{29} \text{ erg s}^{-1}$. If, as with the $\text{H}\alpha$ profiles, we adopt an impact area $1/3$ of $6 \times 10^{18} \text{ cm}^2$, the $\text{H}\alpha$ kernel area given by Zirin and Tanaka, a value of $\mathcal{F}_{20} \approx 1\text{--}1.5 \times 10^{11} \text{ erg cm}^{-2} \text{ s}^{-1}$ is thus implied by the hard X-rays. This is approximately one order of magnitude greater than the injection rate inferred from the $\text{H}\alpha$ profiles computed from the models. This discrepancy cannot be reduced, but rather is increased, by supposing that the bulk of the thick target electrons impact not in the kernels alone, but over the area of the entire $\text{H}\alpha$ flare. According to Zirin and Tanaka, this latter area is $2.5 \times 10^{19} \text{ cm}^2$, which corresponds to an injection of all the thick target electrons with a flux of $\mathcal{F}_{20} \approx 1 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$. For this value of $\mathcal{F}_{20}$ we compute an emission equivalent width of about $25 \text{ \AA}$, if the flux is homogeneous over the entire flare area. The observed value of the equivalent width given by Zirin and Tanaka for the flare outside the kernels is about $1 \text{ \AA}$. This large discrepancy also cannot be explained by inhomogeneities in the energy flux. Only imaging of the hard X-ray emission will enable us to incorporate inhomogeneities properly and provide a more stringent constraint on the electron heating model. Roy (1976) has argued that hard X-ray spikes (in the flare of August 2, 1972 - c.f. Hoyng et al. 1976) are not

in fact coincident with optical ($3835 \text{ \AA}^0$) flashes (Zirin and Tanaka 1973). However Zirin (1977) has found an exact correspondence and pointed out that Roy (1976) used incomplete optical data.

The discrepancy between fluxes inferred from $H\alpha$ profiles versus hard X-rays may be attributed to the following:

- (i) The electron injection rate into the chromosphere is considerably less than inferred above for a purely thick target model. For instance the thick target may be fed by collisional precipitation from a trapped source, in which case $\dot{N}_{20}$ would take 1/3 of the above value (Melrose and Brown 1976). Further reduction may be involved if electrons are confined by turbulent scattering or if the hard X-rays are significantly thermal.
- (ii) Important sources of radiative cooling may have been omitted, e.g. bound-free hydrogen emission. As mentioned above, our preliminary calculations show this to be a complex, model-dependent radiative heating and cooling mechanism whose effects will be the subject of later work.

Support for the former explanation comes from the low EUV output of flares found by Emslie, Brown and Donnelly (1978).

There are also a few factors that must be mentioned that would increase the discrepancy: (1) use of an active region model instead of a quiet-sun model as the unperturbed atmosphere; (2) added heating terms such as heat conduction and soft X-ray heating; (3) any additional line broadening mechanism such as Stark effect from plasma waves (Spicer and Davis, 1975). The only effects which could reduce the discrepancy are thus radiative losses higher than our estimates or a net conductive loss from the $H\alpha$ region. Such improvements are appropriate for further work.

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