INVESTIGATION OF FLARE HEATING BASED ON X-RAY OBSERVATIONS

J. Jakimiec[1], B. Sylwester[2], J. Sylwester[2], R. Mewe[3],
G. Peres[4], S. Serio[4], J. Schrijver[3]

[1]Astronomical Institute, Wroclaw University, Poland

[2]Space Research Centre, Polish Academy of Sciences, Wroclaw, Poland

[3]Laboratory for Space Research, Utrecht, The Netherlands

[4]Astronomical Observatory, Palermo, Italy

ABSTRACT. Using X-ray date recorded by the Solar Maximum Mission Hard X-ray Imaging Spectrometer we have investigated flare evolution in a (T_m, N)-diagram, where T_m is the maximum temperature and N is the mean density in the flare volume. It is important that the behaviour of a flare in such a diagram does not depend significantly on details of the flare geometry and therefore can be effectively compared with simplified model calculations of flare loops.

This flare diagnostics allows us to show that most large flares achieve a quasi-steady-state during their decay, which means that the cooling is then so slow that a flare evolves along the line of steady-state loops in the (T_m, N)-diagram. The diagnostics allows us to determine the time evolution of the flare heating function, $E_H(t)$, which gives the rate of thermal energy release, per unit volume. For the flares which achieve the quasi-steady-state branch it gives a new valuable method of estimation of the electron density in the flare loops.

ИССЛЕДОВАНИЕ НАГРЕВА СОЛНЕЧНЫХ ВСПЫШЕК ПО НАБЛЮДЕНИЯМ РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ: Используя рентгеновские наблюдения полученные при помощи спектрометра HXIS со спутника **Solar Maximum Mission**,мы исследовали эволюцию солнечных вспышек на диаграмме (T_m,N), где T_m обозначает максимальную температуру, а N - среднюю плотность во вспышке. Важно, что поведение вспышки на этой диаграмме слабо зависит от деталей геометрии вспышки и поэтому его можно сравнивать с упрощенными теоретическими моделями вспышечных петель. Эта диагностика показала, что большинство больших вспышек достигает квазистационарное состояние на фазе затухания вспышки. Это означает, что охлаждение вспышечной плазмы происходит тогда настолько медленно, что вспышка передвигается вдоль линии представляющей стационарные петли на диаграмме (T_m,N). Предложенная методика позволяет определять функцию нагрева вспышечной плазмы, $E_H(t)$, которая дает скорость выделения тепловой энергии, рассчитанную на единицу объема. Для тех вспышек, которые достигают квазистационарной ветви, эта методика дает новый, ценный способ определения плотности горячей вспышечной плазмы.

VÝSKUM OHREVU SLNEČNÝCH ERUPCIÍ NA ZÁKLADE POZOROVANÍ ICH RÖNTGENOVÉHO ŽIARENIA. Vývoj erupcií bol skúmaný metódou (T_m, N) diagramu, zostrojeného z röntgenových meraní spektrometra HXIS, umiestneného na družici Solar Maximum Mission. T_m označuje maximálnu teplotu a N strednú hustotu v objeme erupcie. Pre metódu je dôležitá tá skutočnosť, že chovanie erupcie v diagrame (T_m, N) slabo závisí na geometrických detailoch erupcie. Touto metódou môžu byť preto efektívne porovnané erupcie rôznych geometrických tvarov so zjednodušenými modelmi erupčných slučiek. Táto diagnostika umožnila zistiť, že väčšina silných erupcií dosahuje tzv. kvazistacionárny pokles. Znamená to, že objem erupcie chladne tak pomaly, že v diagrame (T_m, N) jej vývoj prebieha pozdĺž krivky stacionárnych erupčných slučiek. Metóda ďalej umožňuje určiť časovú zmenu funkcie ohrevu erupčnej plazmy $E_H(t)$, a tiež rýchlosť uvoľnenia tepelnej energie z jednotkového objemu erupcie. Pre erupcie, ktoré dosiahnu oblasť kvazistacionárneho stavu, okrem toho, plynie možnosť vypracovania novej cennej metódy určovania koncentrácie elektrónov v erupčných slučkách.

1. INTRODUCTION

In a provious paper (Jakimiec et al., 1985) a method of investigation of flare heating process using X-ray observations, has been proposed. The main idea consists in displaying flare evolution in a (T_m, N)-diagram, where T_m is the maximum temperature and N is the mean (electron) density in the hot flare plasma volume. Here we briefly summarize the method of flare investigation and use it to discuss time evolution of the rate of the thermal energy release for some flares.

An example of the temperature-density (T_m, N) diagram is shown in Fig. 1. The thin straight line represents the relation:

$$T_m = 6.9 \times 10^{-4} (NL)^{1/2} , \qquad (1)$$

which is valid for steady-state coronal loops (cf. Rosner et al. 1978, Withbroe 1981). Here L is the loop half-length (the distance from the loop top to its footpoint).

Moreover, for the steady-state loops the following relation between the maximum temperature T_m, the loop length L and the heating function E_H is fulfilled:

$$E_H = 1.0 \times 10^{-6} \, T_m^{3.5} \, L^{-2} \text{ erg cm}^{-3}\text{s}^{-1} \qquad (2)$$

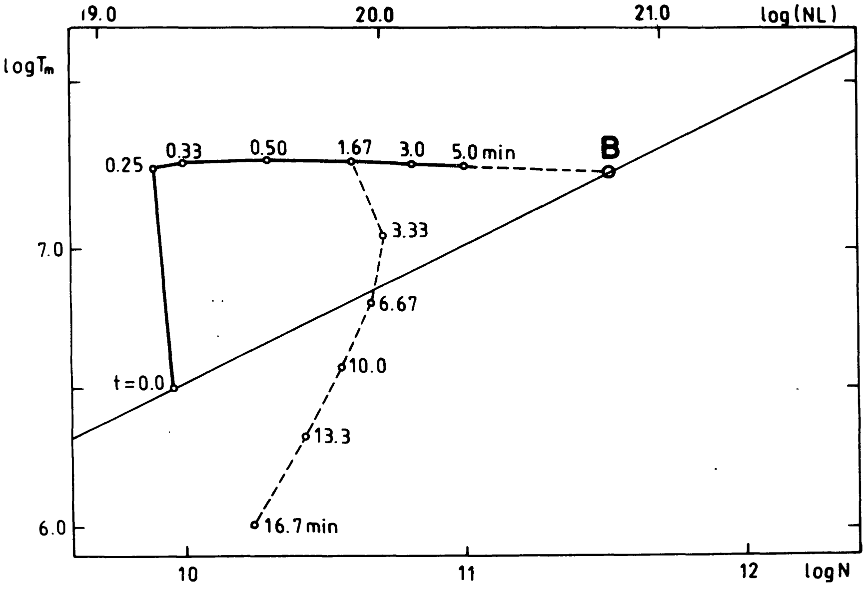

Fig. 1: The evolution of a calculated model of the flare loop in the temperature-density diagram. See the text for details. The numbers give time in minutes.

The heating function E_H gives the rate of thermal energy release, per unit volume.

The thick line in Fig. 1 shows the evolution of a theoretical model or a flaring loop calculated under assumption of a constant heating $E_H = 10$ erg $cm^{-3}s^{-1}$, beginning at time $t = 0$ (Pallavicini et al. 1983). The model calculations were terminated at $t = 5$ min. But the point B represents the steady state for the investigated loop ($E_H = 10$ erg $cm^{-3}s^{-1}$, $L = 2 \times 10^9$ cm), which should be reached by the model if the constant heating is continued further on.

The broken line in Fig. 1 shows the evolution of the model after abrupt switch-off of the heating at $t = 1.67$ min. A quick cooling of the flare loop then occures.

From Fig. 1 we see that:

1. During the flare growth under constant heating the temperature T_m very quickly assumes the same value as it would have in the steady state. This means that the formula 2. is valid during the flare growth phase, except the very beginning of it.
   This is understandeble, because the maximum temperature T_m is controlled mainly by the processes of plasma heating and thermal conductivity as well during the flare growth as in the steady state.
2. The value of T_m very quickly ($\Delta_t \sim 10$ s) adjusts to an actual value of the

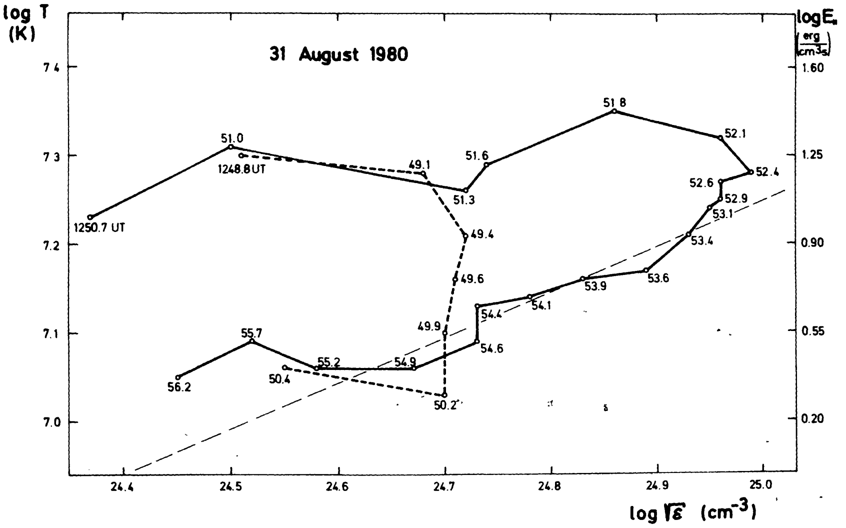

Fig. 2: The empirical diagnostic diagram for a pair of flares of 31 August 1980. The numbers give time (UT). The long-dashed line is the line of steady-state loops drawn to fit the decay phase of the second flare. See the text for details.

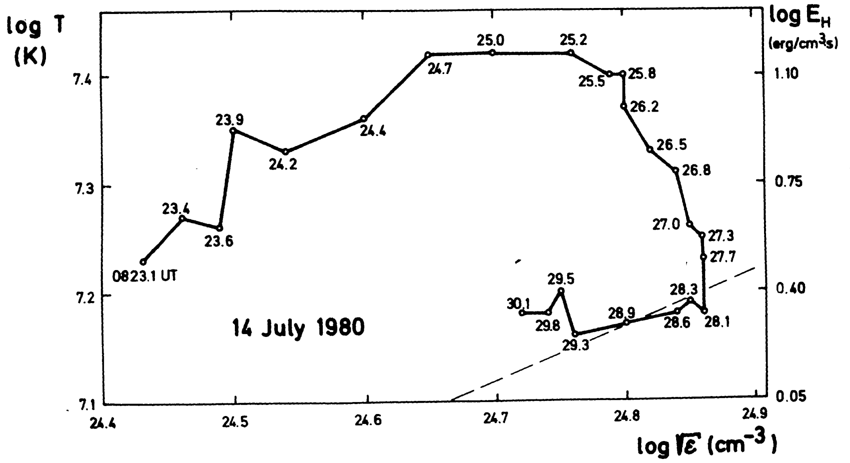

Fig. 3: The same diagram as in Figure 2 for a flare of 14 July 1980

heating function. This means that $T_m(t)$ will closely reflect time variations of $E_H(t)$. This very close relation between T_m and E_H provides sensitive diagnostic tool of E_H variations during flare evolution.

3. If the flare heating lasts long enough the flare may achieve the steady-state regim.

In Figure 2 and 3 are shown examples of empirical diagrams analogous to Fig. 1. The temperature T_m was estimated from SMM HXIS observations. Assuming that the hot plasma volume did not change very much during the investigated time interval of the flare development, we used $\log\sqrt{\mathcal{E}}$ as an abscissa of the diagrams ($\mathcal{E}$ is the emission measure, $N \propto \sqrt{\mathcal{E}}$ for $V \approx \mathrm{const}$).

2. TIME EVOLUTION OF FLARE HEATING

Now we are going to estimate the values of the heating function E_H from formula 2. The values of T_m are determined with a high accuracy from X-ray observations, but the values of L can be determined with much lower accuracy. The point is that L in formula 2 has its precise physical meaning. This is the length of the magnetic lines of force, along which occurs an effective transfer of the heat from the hot flare volume to the dense layers of the transition region and the chromosphere. It is difficult to determine the value of this parameter with high accuracy from available observations. In X-ray pictures (HXIS, FCS) we usually see a hot flare core surrounded by a somewhat cooler matter, so that the size of the source increases with decreasing temperature. Consequently, at present the estimated values of L significantly depend on the assumed topology of the magnetic lines of force in a flare under investigation. The present accuracy of the L-values is not better than within the factor of 2.

For the larger flare of 31 August 1980 we have taken $L \approx 1.4 \times 10^9$ cm as estimated from the FCS Mg XI isophotes (cf. Strong et al. 1985) and for the 14 July 1980 flare we put $L \approx 2.5 \times 10^9$ cm as estimated from the HXIS isophotes of the main flare region (cf. Machado et al. 1985). This gives the E_H-values indicated by the scales on the right-hand side of Figs. 2 and 3.

For the small flare on 31 August (broken line in Fig. 2) an abrupt termination or significant decrease of the heating clearly occurred at 1249.1 UT. The evolution of the larger flare (solid line in Fig. 2) suggests that a gradual decrease of the heating occurred after 1252 UT, which allowed it to reach a quasi-steady state, i.e. slow cooling along the line of steady-state equilibria.

At the beginning of the 14 July flare the heating rate E_H gradually increased with the increasing emission measure (inflow of the matter into the hot flare volume). For about 1 minute it became stabilized at its maximum value $E_H \approx 15$ erg $\mathrm{cm}^{-3}\mathrm{s}^{-1}$ and then quickly decreased to the value of about $E_H \approx$ 2 erg $\mathrm{cm}^{-3}\mathrm{s}^{-1}$, which allowed the flare to follow the quasi-steady-state evolution.

Let us stress once more that the relative variations of E_H are determined with a much higher accuracy than their absolute values, which include the factor L^{-2}.

3. DISCUSION OF THE QUASI-STEADY-STATE (QSS) EVOLUTION

Flare evolution along the steady-state branch means that $E_H \neq 0$ and it decreases so slowly that the outflow of the matter from the flare allows it to evolve quasi-stationary.

On the steady-state branch formula (1) is valid, so we can determine the values of (NL) with a high accuracy. If we apply the above estimates for L, we obtain values of the density N with accuracy of about factor of two. This gives us a very useful new method of evaluation of the density in the flare loops. It is important that it does not use the plasma volume estimates from X-ray pictures, which may contain large errors (e.g. the filling factor problems).

For the middle of the QSS branch of the 14 July flare we obtain $N \approx 2 \times 10^{11} cm^{-3}$. For the larger flare of 31 August the density changes from $N \approx 4 \times 10^{11} cm^{-3}$ to $N \approx 2 \times 10^{11} cm^{-3}$ during the QSS evolution. The heating function decreased from 9 to 3 erg $cm^{-3}s^{-1}$, during this phase.

These estimates of the density give the following scaling of the $\sqrt{\mathcal{E}}$ -values into N-values:

$\log N = \log\sqrt{\mathcal{E}} - 13.5$ for the 14 July flare,
$\log N = \log\sqrt{\mathcal{E}} - 13.3$ for the 31 August flare.

Assuming that the plasma volume does not change very much during the whole investigated flare evolution, we can apply these scaling formulae also for the phase of flare growth. At the beginning of a flare the volume may be somewhat smaller and then the scaling will give too small values of N.

4. DISCUSSION OF THE HEATING FUNCTION VALUES FOR VARIOUS FLARES

It is interesting that for most of big flares observed by the Solar Maximum Mission we obtain similar maximum values of T_m (20 MK $< T_m <$ 30 MK). This may suggest that:

1. For the big flares the heating rate E_H achieves its maximum value determined by the process of the magnetic energy dissipation in the flare loops,
2. The length L of the magnetic lines as discussed in Section 2, is similar for different flares, being determined mostly by typical height of the hot flare volume in the solar atmosphere.

We hope to be able to investigate this important problem of flare energetics more comprehensively.

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REFERENCES

Jakimiec, J., Sylwester, B., Sylwester, J., Leman, J.R., Mewe, R., Bentley, R.D., Peres, G., Serio, S., Schrijver, J.: 1985, Paper presented to the Solar Maximum Analysis Workshop, Irkutsk, USSR, to appear in the Workshop Proceedings.

Machado, M.E., Rovira, M.G., Sneibrun, C.V.: 1985, Solar Physics 99, 189.

Pallavicini, R., Peres, G., Serio, S., Vaiana G., Acton, L., Leibacher, J., Rosner, L.: 1983, Astrophysics J. 270, 270.

Rosner, R., Tucker, W.H., Vaiana, G.S.: 1978, Astrophys. J. 220, 643.

Strong, K.T., Benz, A.O., Dennis, B.R., Leibacher, J.W., Mewe, R., Poland, A., Schrijver, J., Simnett, G., Smith, J.B., Jr., Sylwester, J.: 1985, Solar Physics 91, 325.

Withbroe, G.L.: 1981, in Solar Active Regions (ed. F.Q. Orrall), Colorado University Press, Boulder, 199.