QUANTITATIVE ANALYSIS OF FLARE ACCELERATED ELECTRONS QUANTITATIVE ANALYSIS OF FLARE ACCELERATED ELECTRONS THROUGH THEIR HARD X-RAYAND MICROWAVE RADIATION THROUGH THEIR HARD X-RAY AND MICROWAVE RADIATION

## K.-L. Klein and G. Trottet K.-L. Klein and G. Trottet

UA 324, Observatoire de Paris, Section d'Astrophysique de Meudon, UA 324, Observatoire de Paris, Section d'Astrophysique de Meudon, DASOP, F-92195 Meudon C\_dex, France DASOP, F-92195 Meudon Cedex, France

I. Introduction. A key question of particle acceleration during solar 1. Introduction. A key question of particle acceleration during solar flares is whether electrons and ions are accelerated by a single physi-flares is whether electrons and ions are accelerated by a single physical process, or whether a second, distinct step of acceleration must be cal process, or whether a second, distinct step of acceleration must be invoked for the high particle energies attained in some flares. Infor-invoked for the high particle energies attained in some flares. Information on the particles can be inferred from an analysis of their elec-mation on the particles can be inferred from an analysis of their electromagnetic radiation by means of model computations. As far as elec-tromagnetic radiation by means of model computations. As far as electrons are concerned, the most direct information is furnished by their trons are concerned, the most direct information is furnished by their hard x-ray ( $h\nu > 30$  keV) emission (electron-ion bremsstrahlung), which has been shown /l, 2, 3/ to vary in close temporal correlation with has been shown /1, 2, 3/ to vary in close temporal correlation with microwaves, although these are produced by a different mechanism (gyro-microwaves, although these are produced by a different mechanism (gyrosynchrotron radiation). This correlation is generally interpreted in terms of a common electron distribution  $/1$ ,  $2$ ,  $4/$  continuously injected into sources at different heights (e.g. /5/). It gives the possibility into sources at different heights (e.g. /5/). It gives the possibility to test, if the results inferred from hard x-rays are consistent. Gyro-to test, if the results inferred from hard x-rays are consistent. Gyrosynchrotron radiation does, however, not directly reflect the electron synchrotron radiation does, however, not directly reflect the electron distribution because of various processes of suppression and absorption distribution because of various processes of suppression and absorption at low frequencies /6/. Quantitative investigations of the correlation at low frequencies /6/. Quantitative investigations of the correlation have been carried out by many authors (e.g. 72, 4, 7, 8, 9/). However, on the one hand the radio radiation was often treated in a homogeneous on the one hand the radio radiation was often treated in a homogeneous configuration, whereas the gyrosynchrotron mechanism depends strongly configuration, whereas the gyrosynchrotron mechanism depends strongly on variations of the magnetic field. Furthermore, analytical simplifi-on variations of the magnetic field. Furthermore, analytical simplification has often been used, by which the low frequency effects cannot cation has often been used, by which the low frequency effects cannot be treated consistently. On the other hand, the analyses were mostly be treated consistently. On the other hand, the analyses were mostly restricted to the instant of peak flux, and no information on the temporal evolution of the injected electrons could be inferred. poral evolution of the injected electrons could be inferred.

Our purpose is to present hard x-ray and microwave modelling that takes into account the temporal evolution of the elctron spectrum that takes into account the temporal evolution of the elctron spectrum as well as the inhomogeneity of the magnetic field and the ambient medium in the radio source. We illustrate this method for the June 2g medium in the radio source. We illustrate this method for the June 29 1980 10:41UT event and discuss briefly the implication on the process 1980 10:41 UT event and discuss briefly the implication on the process of acceleration/injection. of acceleration/injection.

2. Method of analysis. The model of the x-ray source has been described 2. Method of analysis. The model of the x-ray source has been described by Trotter and Vilmer (/10/ and references therein). The radiation is by Trottet and Vilmer (/10/ and references therein). The radiation is assumed to be produced by non thermal electrons injected continuously assumed to be produced by non thermal electrons injected continuously with an injection function with an injection function

$$
q(E,t) = q_0 E^{-\gamma} f(t) \quad (0 < t \leq t_0, \quad 0 \text{ elsewhere}), \tag{1}
$$

with y being kept constant during each injection. Precipitation is con-with Y being kept constant during each injection. Precipitation is considered in the limits of weak (collisions) and strong (waves) diffusion. sidered in the limits of weak (collisions) and strong (waves) diffusion. Electrons are assumed to loose energy through collisions with ambient Electrons are assumed to loose energy through collisions with ambient electrons. From this model, the injection function, the source density electrons. From this model, the injection function, the source density

and the total number of energetic electrons are deduced. and the total number of energetic electrons are deduced.

The microwve source is represented by a collection model /11/. field lines in an ambient medium with a hydrostatic density model  $\alpha$  here  $\alpha$ The electron distribution is composed of a Maxwellian and a non thermal The electron distribution is composed of a Maxwellian and a non thermal part re**s**ulting fr**o**m the injection functi**o**n (**]**). part resulting from the injection function (1). The microwve source is represented by a collection of dipolar

3. Analysis of the 29 June 1980 **flare has been observed with the flags** flags of the flags several SMM and ground-based instruments /12, **1**3/. Its temporal evolu-several SMM and ground-based instruments /12, 13/. Its temporal evolu-3. Analysis of the 29 June 1980 flare. The flare has been observed with



Fig. 1 : Temporal evolution of the observed hard x-ray and microwave fluxes

channel and one radio frequency in fig. 1. HXRBS/SMM<br>It has been shown in /10/ that the ener-<br>1961199. It has been shown in 7107 that the energy of the event between 104130 UT <sup>10<sup>2</sup> and 1043 UT can be decomposed into five</sup>  $\left[\begin{array}{ccc} \uparrow^{103} \uparrow' & \nearrow & \end{array}\right]$  successive electron injections, whose para- $\begin{array}{c|c|c|c|c} \hline \end{array}$  successive electron injections, whose para- $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$  **Define 1** of  $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$  wave and hard x-ray sources are then not  $\frac{1}{2}$   $\left(\begin{array}{cc} \uparrow \\ \downarrow \end{array}\right)$   $\qquad$  density medium, from which most of the  $\mathfrak{m}^{\left[\frac{1}{2}\right]}$   $\bigvee$  radio frequencies cannot escape. The micro- $\frac{2}{5}$   $\frac{1}{5}$  microwave source to be identical with the <sup>2</sup>/ m42 1043 30 keV (HXIS observations, /12/). Two U<sub>T on</sub> 1980 June 29 magnetic loops of different sizes are obthe served. The geometric parameters of the<br>
served. The geometric parameters of the Fig. **!** : Temporal evolution served. The geometric parameters of the loops, the x-ray inferred density /12/ of the observed hard x-ray loops, the x-ray inferred density *i*and microwave fluxes and the assumed magnetic field strengths of the loop at the top and in the root of the tion is shown for a high-energy x-ray hard x-ray source is found to be a high cospatial. We assume the structure of the spatially resolved x-ray source below

are listed in table 1. In the following we assume the temperature to be<br>interesting the the temperature of the temperature to be



Table 1

Table 1 **Interfaces** are reported in /12/. As the event is a limb flare, we consider **Loop A Loope A** Loope A Loope in the following magnetic loops in the height  $(\text{cm})$   $\begin{bmatrix} 6 \cdot 10 & 5 \end{bmatrix}$   $\begin{bmatrix} 5 \cdot 10 & 0 \end{bmatrix}$  plane of the sky. They are supposed 8 homogeneous along the line of sight. volume  $\begin{bmatrix} \text{cm} \\ \text{cm} \end{bmatrix}$  1.1-10 2.1 10 homogeneous along the hypothesis of  $/12/$ , we temp.  $(K)$   $5.10^{5.10}$   $5.10^{7}$  suppose that a quarter of the electron number inferred from hard x-rays is dens. (cm) 7.10 2.10 mumber inferred from hard x-rays injected into each of the two arches.  $\begin{array}{c|cc}\n\text{top} & \text{G} & 240 \\
\hline\nB_{\text{scat}} & \text{G}\n\end{array}$  240 240 a simplified form of (1), considering First (Fig. 24) 240 241 240 240  $\mu$  240  $\mu$  a parabolic f(t) (t =2 t<sub>onsid</sub>). Furth identical in both loops, although slight We compute the microwave spectrum from a parabolic f(t)  $(t_0 = 2 t_{max})$ . Further-

d to be perfectly trapped <sup>max</sup>during  $\epsilon$ more, the electrons are assumed to be perfections are retained injection, but no particles from previous injections are retained. injection, but no particles from previous injections are retained. more, the electrons are assumed to be perfectly trapped  $\frac{max}{a}$  during each

4. Results. Fig. 2 shows gyrosynchrotron spectra computed at two 4. Results. Fig. 2 shows gyro synchrotron spectra computed at two Instants during the injection where the fluxes are greater (5.2 GHz, with microwave observations at four discrete frequencies (5.2 GHz) 8.4 GHz, I**1**.8 GHz, **1**9.6 GHz; Bern University, courtesy A.Magun), inte-8.4 GHz, 11.8 GHz, 19.6 GHz; Bern University, courtesy A.Magun), integrated over 2 s. Because of absorption in the terrestrial and the terrestrial atmosphere terms of the terms of the measured 19.6 GHz flux represents a lower limit.Both the low and the measured 19.6 GHz flux represents a lower limit.Both the low and instants during the injection where the fluxes are greatest, together grated over 2 s. Because of absorption in the terrestrial atmosphere



the high frequency parts of the spectrum radiated by electrons with the injection function inferred from hard x-rays account for the observations. Emission at the high frequency end is dominated by the small loop A. Its emission is weak at low frequencies because of self absorption by the energetic electrons and a small amount of gyroresonant absorption by the Maxwellian electrons.

SH 1.2-7

This part of the spectrum comes predominantly from loop B.

The temporal evolution of the microwave flux during injection 4 is plotted for two discrete frequencies in fig. 3. Up to the end of



Time (s after 10 42 00 UT)

Fig. 3 : Computed (full line) and observed (crosses) evolution of microwave fluxes at a low and a high frequency during injection 4.

he injection the computed curve fits the observations. Afterwards electhe injection the computed curve five the convenience of the observed flux de-<br>tron losses through precipitation are revealed by the observed flux detron losses through precipitation are revealing to perfectly trapped particles. The cre**as**ing fa**s**ter than that comput**e**d for perf**e**ctly trapp**e**d particle**s**. The low frequency peak lags that at high frequencies by several seconds both low frequency peak lags that at high frequencies by several second den-<br>in the model and in observations. This is because growing electron denin t**he** model and in **o**b**s**er**v**ations. **Th**i**s** i**s b**e**c**au**s**e growing electron den-sity during the injection increases emission and self absorption. While sity during the injection increases emission and self absorption.<br>the latter does not affect high frequencies, it diminishes the low frethe latter wes not affect high the lots phase of the injection, where  $\epsilon$ qu**e**ncy flux, which **p**eaks only in the lat**e** phase of the injection, when quency flux, which peaks only in the late phase of the injection, when the instantaneous num**b**er density ha**s** gone down**.** the instantaneous number density has gone down.

At the very beginning of the every, the start is not computed for the computible with the observated spectrum, which peaks at higher frequencompatible with the observated spectrum, which provides at higher cies than afterwards when the flux has grown. This microwave phase might  $\frac{1}{2}$  the dominated by thermal electrons, but then a temperature of some  $10^{\circ}$ be dominated by thermal ele**c**tron**s**, but then a temperature of some IO**-** K be dominated by thermal electrons, but then a temperature of some 10 K i**s** required /14/. is required /14/. At the very beginning of the event, the computed flux is not

5. Discussion. The analysis of the 29 June 1980 flate have the most energetic part the hard x-ray inferred injection function and the most energetic part the hard in ray inferred in the most energy intervals. controversy existed, because various authors had claimed the number of controversy existed, because various assumed the number of magnitude smaller than that producing hard x-rays (review in /2/, recent discussion in /9/). than that producing hard x-rays (r**e**vi**e**w in /21, recent discussion in /9/)**.** Account for suppression and absorption, source inhomogeneity and for Account fo**r s**uppression and ab**s**orption, source inhomogeneity and for energy losses during a continuous injection of particles solves this energy losses during a continuous and topporter and topping of radiation of particle di**s**crepancy and expl**a**ins **s**p**e**ctra and te**m**poral evolution of radiations. discrepancy and explains spectra and temporal evolution of radiations. 5. Discussion. The analysis of the 29 June 1980 flare has shown that in

The discussed event i**s c**ompati**b**le with several electron injections, during ea**c**h of which the spe**c**tr**a**l in**d**ex remains con**s**tant. This jections, during each of which the spectral index remains constant. This lends strong support to a single st**e**p acceleration process. lends strong support to a single step acceleration process. The discussed event is compatible with several electron in-

ACKNOWLEDGEMENTS. We wish to accurate the accuracy of the definition of the same of the definition of the same of B. Dennis (NASA) for kindly providing microwave and hard x-ray data. K.-L.K. acknowledges support by an ESA fellow**s**hip. K.-L.K. acknowledges support by an ESA fellowship. Acknowledgements. We wish to acknowledge Drs. A. Magun (Bern) and

References

References<br>1. Peterson,L.E., and Winckler,J.R.: 1959, J.Geophys.Res. 64, 697

I. Peterson, 20076, <sup>19</sup>50 and Winches **Planes**, D.Reidel Publ., Dordrecht 2. Sv**e**stka,Z.: **]**976, "Solar Flare**s**", D.Reidel Publ., Dordrec**h**t 2. Svestka,Z.: 1976, "Solar Flares", D.Reide1 Pub!', Dordrecht

- 3. Corne1l,M.E., et a1.: 1984, Astrophys.J. 279, 875
- 3. C**o**rnell,M.E., et al.: 1984, Astrophy**s**.**J**. 279, 875 4. Ho1t,S.S., and Ramaty,R.: 1969, Solar PhyS:-8, 119
- 4. Holt,S.S., and Ramaty,R.: 1983, Solar Phys. 84, 295<sup>-</sup>
- 5. Klein,L., et al.: 1**9**83, **S**ol**a**r Phy**s**. 84, **2**95 6. **R**amaty,R.**: 19**6**9**, **Ast**ro**ph**y**s**.J. 1**5**3, 7\_ 6. Ramaty,R.: 1969, Astrophys.J. 153, 753
	- 7. Takakura, T.: 1972, Solar Phys. 26, 151

7. Takakura, 1.: 1972, Solar Phys. 53, 139

8. Bohme,A., et diversity, **Secure 8.** 1984, submitted to Astrophys.J.

**9**. Gary,D.E.: 1**98**4, submitt**e**d t**o** Astrophys.J. 10. Trottet,G., and Vi1mer,N.: 1984, Adv.Space Res. 4, 153

- 10. **The U.S. Company of Trottet,G.**, 1984, Astron,Astrophys 11. Klein,K.-L., and Trottet,G.: 1984, Astron.Astrophys. 141, 67
	- 12. Hernandez,A.M.: 1985, in preparation
- 1**2**. Hernandez,A.M.: 1985, in prep**a**ration 13. Kundu,M.R.: 1982, Adv.Space Res. 2, 159
- 13. Kundu, **Kundu, Karling, Resp. 2002**, Adv. DbD, thesis NA **1**4. Batchelor,D.A.: **1**984, Ph**D** thesis, **N**ASA Tech.Memorandum 86102 14. Batche1or,D.A.: 1984, PhD thesis,-NASA Tech.Memorandum 86102