II. X AND γ RADIATION : THE SUN

SOLAR X RADIATION

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RÉSUMÉ. — *On définit les sursauts de Rayons X comme une radiation électromagnétique provenant des transitions électroniques affectant les couches électroniques les plus profondes. Les rayons γ sont d'origine nucléaire. Les émissions solaires de rayons γ n'ont pas encore été découvertes.*

D'après leur origine, on peut diviser ces émissions de la façon suivante :

1) *Rayons X quasi-thermiques émis par* a) *la couronne calme,* b) *les centres actifs sans éruption et* c) *les éruptions de rayons X.*

2) *Sursauts de rayons X non thermiques qui sont toujours associés à des éruptions.*

On suggère de classer les sursauts liés à des éruptions de la façon suivante :

TYPE	NOM OU DESCRIPTION	RÉGION SPECTRALE	ÉMIS PAR
—	—	—	—
Classe I	Sursauts de rayons X non impulsionnels.	$\lambda \gtrsim 0{,}5$ Å	Plasma chaud (éruptions de rayons X).
Classe II	Sursauts impulsionnels ou à faible durée de vie.	$\lambda \lesssim$ quelques Å	Jets d'électrons.
II*a*	Coïncident avec les sursauts radio impulsionnels ou éruptions.		Électrons piégés de grande énergie.
II*b*	Coïncident avec type III.		Jets d'électrons en mouvement centrifuge.
II*c*	Sans phénomène optique ou radio de type impulsionnel.		Inconnu.

ABSTRACT. — *X-ray bursts are defined as electromagnetic radiation originating from electronic transitions involving the lowest electron shells ; gamma rays are of nuclear origin. Solar gamma rays have not yet been discovered.*

According to the origin *we have* :

1. Quasi thermal X-rays, *emitted by* (a) *the quiet corona,* (b) *the activity centers without flares, and* (c) *the X-ray flares.*
2. Non-thermal X-ray bursts ; *these are always associated with flares.*

The following subdivision is suggested for flare-associated bursts :

TYPE	NAME OR DESCRIPTION	PREFERRED WAVELENGTH REGION	EMITTED BY
—	—	—	—
Class I	Non-impulsive X-ray bursts.	$\lambda \gtrsim 0.5$ Å	Hot plasma (« X-ray flare »).
Class II	Impulsive and short-lived bursts.	$\lambda \lesssim$ some Å	Electron jets.
II*a*	Coinciding with impulsive radio bursts or explosive flares.		Trapped energetic electrons.
II*b*	Coinciding with type III bursts.		Upward moving electron jets.
II*c*	Without impulsive optical or radio phenomena.		Unclear.

Резюме. — Всплески лучей X определены как електромагнитное излучение происходящее от электронных переходов затрагивающих самые глубокие электронные слои. Лучи γ ядерного происхождения. Еще не были обнаружены излучения солнечных лучей γ.

По их происхождению, эти излучения могут быть разделены следующим образом :

1) Квазитепловые луичи X, излучаемые : *a*) спокойной короной, *b*) активными центрами без вспышки и *c*) вспышками лучей.

2) Всплески нетепловых лучей X, всегда связанные со вспышками.

Выдвинута мысль классифицировать всллески связанные со вспышками следующим образом :

Тип класс I	Наименование или описание	Спектральная область	Источник излучения
—	—	—	—
	неимпульсные всплески лучей X	$\lambda \gtrsim 0{,}5$ Å	горячая плазма (вспышки лучей X)
Класс II........	импульсные всплески или с небольшой продолжительностью жизни	$\lambda \lesssim$ нескольких Å	Электронные струи
II*a*.......	совчадают с импульсными радиовсплесками или вспышкой		захваченные электроны с большой енергией
II*b*.......	совпадают с типом III		Электронные струи в центробежним движении
II*c*.......	без оптического или радиоявления импульсного типа.		незнакомый

1. Introduction ; Nomenclature.

Quite a number of review papers dealing with the Sun's X-ray radiation has appeared in the last few years. Here we refer only to a paper by the present author (De Jager, 1964) which is, as far as we know, the latest review, and which contains references to the literature published before the second half of 1963. It also gives a list of other review papers which appeared after 1960.

In the astrophysical or cosmic ray literature a clear distinction has not always been made between X and gamma rays. Physicists use to define X-rays as electromagnetic radiation originating from electronic transitions involving the lowest electron shells ; gamma rays are of nuclear origin. Mostly gamma rays are harder than X-rays.

This distinction has not rigorously been followed in the astronomical literature, and in fact, it has sometimes only been the *energy* of the solar quanta that was used to classify them. However, one had better avoid confusion and keep to the physical definition. Hence solar energetic radiation will only be called gamma radiation if it is certain that the radiation is of nuclear origin. Since such radiation has not yet been observed the conclusion must be that all energetic solar radiation observed so far must be classified as X radiation. But in this class of radiation a certain distinction can certainly be made. In this paper we suggest the following subdivision :

Soft X rays : $\lambda > 1$ Å or $E < 10$ keV,
Hard X rays : $\lambda < 1$ Å $E > 10$ keV.

In the latter region we might, if desired have a finer subdivision as follows :

0.1 Å $< \lambda < 1$ Å (10 keV $< E < 100$ keV) : deci-Angstrom region,

0.01 Å $< \lambda < 0.1$ Å (100 keV $< E < 1$ MeV) : centi-Angstrom region,

0.001 Å $< \lambda < 0.01$ Å (1 Mev $< E < 10$ MeV) : milli-Angstrom region.

It is further important to discriminate the X-ray bursts of the Sun according to their mechanism of origin (we realize, of course, that such a distinction is often only possible after a theoretical discussion of the event). In that case one may distinguish between *quasi-thermal X-ray events*, and *non-thermal X-ray bursts.*

The quasi-thermal X-ray radiation is the radiation emitted by a hot stationary plasma. Knowledge of the temperature and the density is sufficient to find the source function of the plasma. The non-thermal bursts are presumably due to the interaction of guided energetic streams of particles with an ambient gas (e.g. Bremsstrahlung-bursts) or with a magnetic field (e.g. synchroton radiation). For non-thermal X bursts the notion " kinetic temperature of the gas " has hardly any sense ; it is only the energy and density of the particle stream that matters.

Obviously, if defined in this way, there is no sharply defined limiting wavelength between non-thermal and quasi-thermal X radiation, and there is a range of energies where the two kinds of radiation can both occur. Furthermore, since the distinction between them is based on theoretical inferences, it will not always be possible immediately to classify a burst of energetic solar radiation. However, as a rule the life time of the event will be a useful parameter for classification : non-thermal bursts usually live fairly short.

2. Solar quasi-thermal X-rays.

This subject which has been treated in quite a number of recent review papers will be dealt with quite briefly. We may distinguish between solar quasi-thermal X-rays emitted by :

a) the quiet corona,

q) the activity centers without flares,

c) X-ray flares.

All components of the radiation, whether due to free-free emission or free-bound emission or to line emission are proportional to N_eN_i, and because in this highly ionized plasma the number of ions N_i is proportional to the number of electrons N_e, the intensity of the coronal emission is proportional to N_e^2. As in the corona N_e decreases outward with a scale height of about 5×10^4 km, the X-ray emission intensity should decrease outward with a scale height of about 2.5×10^4 km ; i.e. the intensity would decrease to 0.01 of the limb value over a distance of a little more than 10^5 km. Theoretical predictions of the solar X radiation were made by Elwert and Kawabata for temperatures between 7×10^5 and 10^8 °K. From these Elwert predicted an integrated X-ray flux of 0.03 Q erg cm^{-2}s^{-1} during sunspot minimum, and 0.4 Q erg cm^{-2} s^{-1} during sunspot maximum (Q is an uncertainty factor of the order 2 to 4). These values are roughly in agreement with observations : during sunspot minimum Friedman observed 0.13 erg cm^{-2} s^{-1} ; during maximum he found values ranging from 0.4 to 1 erg cm^{-2} s^{-1} (cf. Elwert 1963).

The most recent achievements concerning the spectrum of the quiet corona is the observation of the detailed spectrum, both by the photographic technique down to 33 Å (see Tousey's review in this symposium) and by the photoelectric scanning technique (see a description of Hinteregger's observations in Tousey's review). In the wavelength region above 33 Å the photographic observations of Tousey and the photoelectric observations of Hinteregger confirmed Elwert's prediction that the spectrum is virtually a line spectrum, with no appreciable contribution of a continuous emission. Not in agreement with Elwert's prediction seem the observations in the shorter wavelength region made by the Hulbert Space Flight Center (N. R. L.). These observations, made with a plane crystal spectrometer in the shorter wavelength region, (14 — 25 Å ; see Chubb's paper in the proceedings of this Symposium) show that also in this spectral range the main contribution to the emission is from spectral lines : Friedman (discussion remark at this Symposium) announced that the ratio between the integrated line inten-

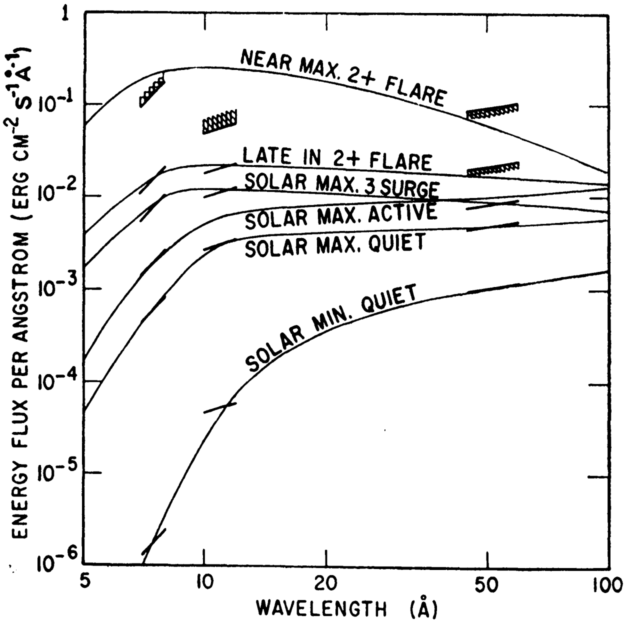

Fig. 1. — Solar X-ray emission for various solar conditions. The curves drawn are based on measurements in three wavelength bands, as indicated by the heavy bar segments. The slopes of the bar segments are the slopes of the assumed X-ray emission functions used to reduce the photometer responses to the plotted energy fluxes. The energy fluxes refer to values observed at the earth above the atmosphere. (After Friedman, 1963, Figure 14.)

sity and the — not yet detected — continuum intensity is at least *six*. On the other hand, ELWERT's theory for the quiet Sun predicts a continuous spectrum with only a few weak lines.

The difference between ELWERT's prediction and the observations may, however, be due to the fact that the Sun was not wholly quiet during the observations. The spectral lines observed by the N. R. L. group were all emitted by an *activity region*, and ELWERT's computations show that such regions, with their higher temperatures, will emit mainly a line spectrum in the relevant region.

As to the *activity centres* the best information on this region is given by monochromatic X-ray images of the Sun. These show that the average electron density of the coronal activity regions should exceed the density of the quiet corona by a factor of the order of 8 (see a further discussion in DE JAGER, 1964).

The only *spectral line observations* of coronal activity regions made so far are the plane crystal spectrometer observations of the Naval Research Laboratory mentioned above and discussed in CHUBB's contribution to this symposium. Further observations going into that direction are the broad band spectral observations made by the Ariel satellite, where photon discrimination by means of proportional counters enabled the determination of the shape of the spectrum in the short wavelength region between 3 and 15 Å. Since the quiet corona hardly emits any radiation in the wavelength region below 10 Å (see Figure 1) this emission is virtually due to the coronal activity regions. A comparison of the observed shape and intensity of the spectrum with theoretical computations by ELWERT enables the observer to determine the electron temperature of these activity regions. The Ariel observers obtained values of the order of 2×10^6 °K, thus confirming optical observations of the enhanced temperature of the coronal activity regions.

The conclusion is that X-ray observations of the emission of coronal activity regions lead to an average density increase by a factor 8 and a temperature of the order of 2×10^6 °K.

3. X-RAYS EMITTED BY SOLAR FLARES.

A solar flare has three different aspects :

The *optical flare* is produced by a relatively cool and dense plasma ($T \approx 10^4$ °K ; $\log N \approx 13.5$), and emits a line spectrum of relatively low excitation emission lines.

The *X-ray* or *radio flare* is the hot counterpart of the optical flare. It consists of a plasma of very high temperature (T up to 10^7 °K or even higher) which emits quasi-thermal solar X-ray radiation of relatively short wavelengths (down to 1 or 0.1 Å) and which may produce at the same time a strong enhancement of radio radiation, mainly in the centimeter region, partly also on decimeter waves.

The flares are often related to the *acceleration of energetic jets of charged particles.* When such jets interact with the ambient gas or are forced to move in a magnetic field they lose energy in the form of radiation ; this is what we define as a non-thermal X-ray burst. Of course, it is impossible to decide on observational grounds alone whether a burst belongs to the quasi-thermal or non-thermal X-ray phenomena as defined in this paper. However, in the main one may define a burst as a non-thermal burst if it lasts not longer than a few seconds to a few minutes, or in any case if it lives much shorter than the optical or radio flare ; quasi-thermal bursts may last longer, and may have a life time comparable to the optical or radio flares.

The ground for these assertions is the fact that fast single jets of electrons are known to last rather short or they occur in clusters which themselves do not last longer than one or two minutes (a result, mainly based on radio observations of type III bursts). Also magnetically trapped electrons may last only for a relatively short time in the magnetic field, as was shown by computations of SCHATZMAN (1964). On the other hand the hot plasma, which is thought responsible for the quasi-thermal X-ray bursts may last for at least a few minutes, usually as long as the main phase of the related solar flare.

Quasi-thermal X-ray emissions associated with flares have been observed in the whole region below 100 Å by quite a number of observers: the N. R. L. observers recorded the short wavelength tail spectrum (20-60 keV) of flare associated emission on 31 August 1959 and found it describable by a colour temperature of 1.2×10^8 °K. The emission was observable for at least six minutes (two rockets ascends). The N. R. L. observers thought this burst, with its rather long duration and its unique colour temperature, to be due to quasi-thermal emission by a hot plasma. However, KAWABATA who re-examined the observations of this burst, and who compared them with simultaneous X-ray emissions in the 2 to 8 Å region and with cm and dm radio observations, concluded that the best description of the observations would be to assume the emission to be composed of two parts : a quasi-thermal component caused by a gas with a temperature of 2 × 10^7 °K and a non-thermal burst in the energy region above 20 keV. Finally we remark that other observations sometimes also show a combination of a longer lasting quasi-thermal burst, on which a short-lived non-thermal burst may be superimposed, often at shorter wavelengths.

Other observations were made by Yefremev *et al.* by the N. R. L. series of Solar Radiation satellites, the U. K. Ariel satellite and by the OSO-A satellite. All these observations confirm that together with solar flares the Sun may emit enhanced quasi-thermal X-ray radiation in the whole wavelength region < 100 Å, with particular enhancement below about 10 Å, where normally hardly any solar radiation is emitted. The colour temperature of the emitted radiation may be well above 10^6 °K. The general character of the bursts, as observed in particular and in detail in the 3-18 Å band by the U. K. Ariel satellite is that of a gradual hardening and intensification of the spectrum during the growth phase of the flare (see Figure 2).

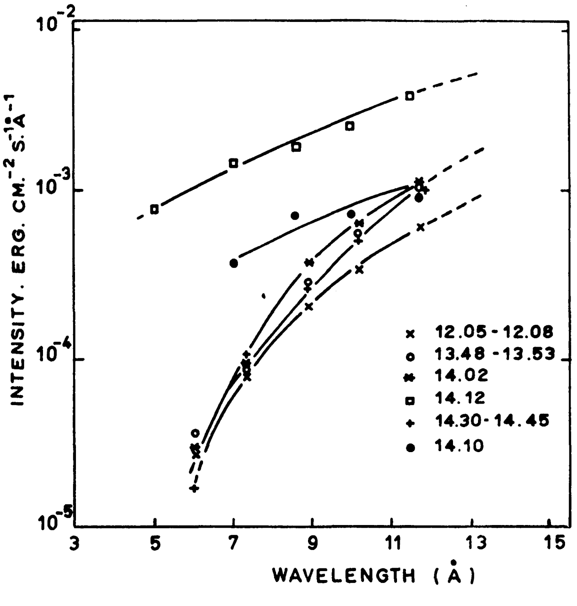

Fig. 2. — **Flare spectrum of April 27, 1962 recorded by the Ariel satellite. The recordings show an intensification and hardening of the radiation during the occurrence of the flare. (Courtesy Dr. Pounds, Leicester.)**

These observations confirm a result for the first time brought forward by radio observers, that solar flares may quite often be accompanied by a hot component : the radio or X-ray flare. The location and structure of this component is still unknown. The temperature seems to be well above 10^6 °K and may rise up to above 10^7 °K. Theoretically one may expect a gas cloud with a temperature of several 10^6 °K to expand and nearly explosively leave the Sun, shooting a blast wave into interplanetary space, unless being held near the Sun by a magnetic field.

We next describe the *non-thermal radiation bursts* from flares. Shortlived bursts of hard radiation (10^4 to 10^6 eV) with durations ranging from some seconds to one or some minutes at maximum have been observed on several occasions. They show the following properties.

1. They occur mostly during the flash phases or the rising phases of flares. We recall that the acceleration of particles to high speeds occurs often in the beginning phases of flares (Radio bursts of type III, the start of type II radio bursts, other optical phenomena showing the emission of high velocity gas clouds).

2. The hard X-ray bursts correlate also with centimeter radio bursts. Such radio bursts tend to occur in large activity centres in particular in those where the flare " touches " or partly covers the penumbras of sunspots.

3. The energies of these bursts are of the order 10^4 to 10^6 eV so that they may be due either to Bremsstrahlung by electrons moving with velocities of 60 000 to 280 000 km/s or to synchroton radiation of magnetically trapped electrons.

4. Some peculiar non-thermal X-ray bursts.

On August 25, 1958 a short-lived burst of photons of at least 0.4 Mev energy has been recorded by the satellite 1958 epsilon between 17.54 and 17.55 UT. The origin of this burst has been obscure for quite some time. However, recently Křivský (1964) could attribute it to the very beginning phase of a solar flare of importance 1+. This flare was visible on H alpha filtergrams taken by the McMath and Sacramento Peak Observatories. It started before 17.58 UT and ended 18.44 UT. Later it started again and pulsated between 19.04 UT till later than 20.01 UT. The flare occurred in a rather complicated E type spot group on the western hemisphere of the Sun. No radio emission concurrently with the flare has been observed ; however, the next day, August 26, an extraordinarily intense flux of radio emission was observed on decimeter waves, originating from the same activity region. During the occurrence of the hard X-ray burst a SEA effect occurred which started as early as 17.00 UT on August 25.

The peculiarity of this apparently non-thermal burst is that it occurred with a flare without the simultaneous occurrence of phenomena that indicate the existence of a X or radio flare. This means that the existence of a hot plasma is not a necessary condition for the occurrence of an acceleration process which produces energetic jets of electrons. Neither should the optical flare always be of the rapidly developing or of the explosive type : the relevant flare had its maximum at about 18.18 UT, i.e. 25 minutes after the hard X-ray burst and did not show any explosive phenomena. Apparently the burst occurred at the very beginning of the flare so that this observation shows that impulsive acceleration processes may occur in the very first phase of rather unimportant optical flares without the simultaneous occurrence of the hot plasma which manifests itself sometimes in the radio or X-ray flares.

A similar cases is the X-ray burst of September 18, 1963. It was observed by means of Geiger counters on a French balloon flying above Kiruna and launched by the Laboratoire de Physique Cosmique of Meudon (see Figure 3). The burst lasted from 13.54 to 14.01 UT with its top intensity at 13.56. The energy of the photons was 60 keV or 500 keV. At the same time a small flare of importance I+ started (beginning at about 13.54). The flare was of the non-impulsive type ; the intensity gradually rose to a maximum at about 14.16 UT. Then it gradually decreased in intensity. There were no associated radio phenomena at meterwaves. At decimeter and centimeter waves a small increase of intensity was noted (Figure 4). It started at 14.55, showed a small peak around 13.56, reached a maximum at 14.16 at which time a slightly intenser flash occurred. It had decreased to zero again at 16.00 UT. There were no ionospheric phenomena concurrent with the X-ray burst ; however, there was a SID at 14.16 occuring simultaneously with the peak in radio intensity. This burst is in some respects similar to the one described above and studied by the Japanese and Czech astrophysicists.

Summarizing we may conclude that the solar X-ray bursts, in their connection with solar flares and radio phenomena may be divided into two large classes ; the second class may be further subdivided.

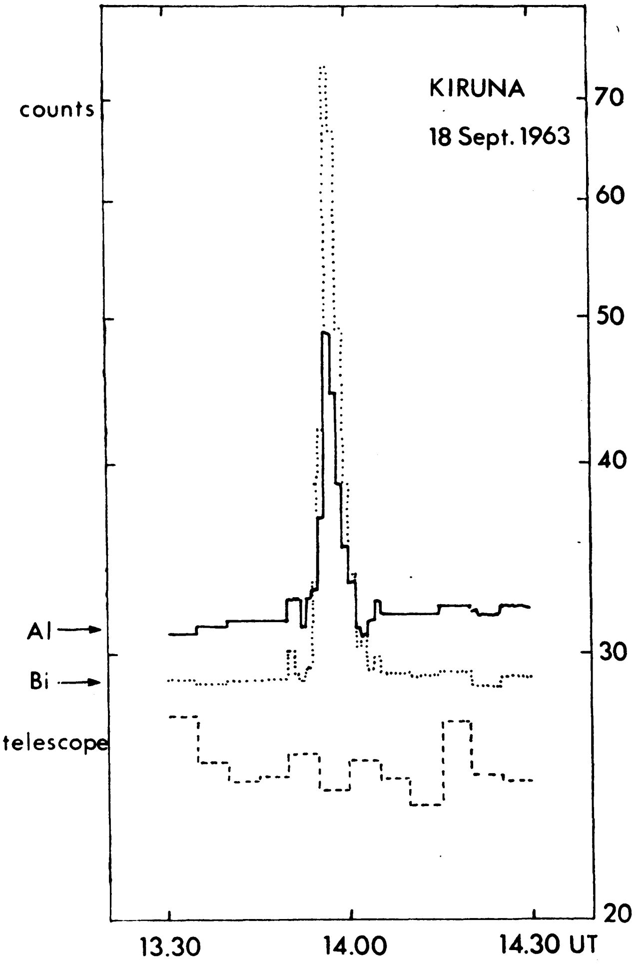

FIG. 3. — Hard X-ray burst of solar origin observed at th start of the class 1+ flare of September 18, 1963, by means of a balloon launched by the Institut de Physique Cosmique (Meudon) at Kiruna. The lines labelled Al and Bi give counts per *second* in Al and Bi counters. The telescope records particle counts per *minute*.
(Courtesy Dr. J. P. LEGRAND, Meudon).

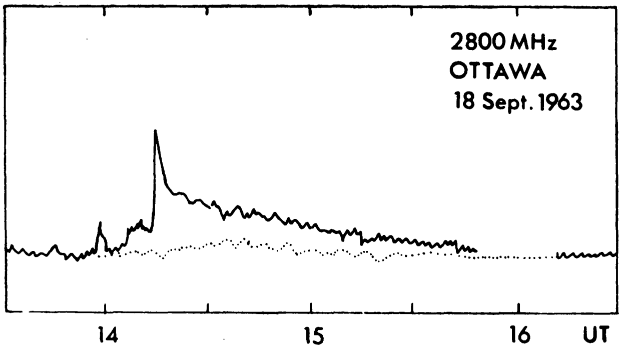

FIG. 4. — Radio intensity at 10.7 cm concurrent with the flare of September 18, 1963. Note the small peak at 13.58 UT, coinciding with the X-ray burst shown in Figure 3.
(Courtesy Dr. A. E. COVINGTON, Ottawa.)

Class I : Non-impulsive X-ray bursts.

Life time comparable with that of the associated optical flare and of the associated radio burst at cm or dm waves. These radio bursts are mostly characterized by sharp rise times, a short impulsive phase, and a slower decline. The X-ray bursts of class I show no *very* impulsive phenomena. The X-ray bursts of class I occur mostly in the spectral region above 0.5 or 1 Å. It is these very soft bursts, that produce S. I. D.'s ; the harder bursts, to which most class II events belong do not produce S. I. D.'s.

Interpretation : Quasi-thermal radiation emitted by the radio or X-ray flare, which consists of a hot plasma (T $\approx$ several times 10^6 °K), perhaps, but not certainly confined by a magnetic field (in view of the relatively long life time), and with a still unknown density.

Class II : Impulsive and short-lived bursts of X-rays.

The life time is considerably shorter than that of the optical flare or of the radio flare, and ranges between some seconds and a few minutes. These bursts occur for the greater part in the region of hard X-rays ($\lambda <$ some Å), and do not show a clear relationship to S. I. D.'s.

Interpretation : Non-thermal bursts. These bursts indicate the existence of magnetically guided or non-guided jets of electrons which radiate through the mechanism of Bremsstrahlung or synchroton radiation. The Bremsstrahlung must be due to braking of the electrons in the photosphere or in the dense part of the flare. Braking in the corona is impossible since the corona is transparent for these energetic electrons.

The impulsive X-ray bursts may be further subdivided into three classes :

Class IIa : Bursts coinciding with important impulsive radio bursts at cm or short dm waves, and with important optical flares showing a flash or other explosive phenomena. To this class belongs the greater part, perhaps 80 % of the class II X-ray bursts. The bursts do not occur in the flare's maximum, but coincide in time with the explosive phases of flares. These phases are known to be distinctly pre-maximum phenomena. The explosive phenomena show velocities on the disc of the order of 100 kms or more (normal velocities occurring with flares are of the order of 10 km/s).

Possible interpretation : Trapped energetic electrons emitting synchroton radiation.

Class IIb : A smaller number of hard X-ray bursts occurs simultaneously with type III radio bursts. Since type III radio bursts are due to jets of electrons accelerated upward and passing through the corona, we must in this case have the simultaneous acceleration of electron jets into the upward direction (causing the III radio bursts) and the downward acceleration (causing Bremsstrahlung bursts or, if the electrons are trapped in a solar magnetic field, of synchroton radiation).

The differences between the types II*a* and II*b* must apparently be due to the geometry of the accelerating fields. To class II*b* belongs perhaps 10 % of the class II bursts.

Class IIc : A few hard X-ray bursts occur without any clear radio phenomena together with quite unimportant optical flares. They occur at the very beginning of these flares. The optical and radio flares rise only slowly and show their maximum intensity nearly half an hour after the flare's start, which is unusually long. This shows that the acceleration of particles to great energies may occur independent of the occurrence of important optical flares and of a hot plasma. It may be significant that these hard X-ray bursts occur in the very beginning phase of the optical and radio flares. It may also be significant, as has been noted by Mrs. DODSON-PRINCE and coworkers for the case of the flare of 18 September 1963, that the gradient of the magnetic fieldstrength in the adjacent sunspot group was extremely steep.

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Discussion

G. A. **Newkirk**. — There exists no really unambiguous means to separate those portions of the radio radiation from a flare into that due to thermal radiation and that due to particle acceleration mechanisms. It should be noted that the temperature of 10^7 °K derived for the material in a flare be excessively high due to :

1) Misidentification of non thermal radio events as thermal.

2) The assumption that the area of the radio source is simply the optical area.

3) Neglect of the cyclotron absorption mechanism of **Ginzburg** and **Zelesniakov** which has been shown by **Kakinuma** and **Swarup** to increase the absorption in the plasma of the flare. This mechanism increases the efficiency of radiation of the plasma in the 10 cm region. This would suggest that a temperature of 4.10^7 °K is more appropriate.

K. A. **Pounds**. — It would be difficult to accept a non-thermal source lasting for so long as the measured X-ray enhancement in many flares. In addition, the spectral variation during the long enduring X-ray enhancements indicate a gradual heating during the rise of the flare and a cooling during the decay phase.

C. **de Jager**. — It is for that reason that I assume that the non-thermal bursts are those that last only a very short period.

L. **Biermann**. — You emphasized the non-optical aspects of the flare phenomenon. Do you see already any practical way to classify flares according to their importance from this point of view ?

C. **de Jager**. — One should have more simultaneous hard X-ray and spectral radio observations of flares to make such a classification possible.