Imprimir Fechar

Referência Completa

Tipo da Referência	Journal Article
Repositório	sid.inpe.br/iris@1905/2005/07.27.00.19.39
Metadados	sid.inpe.br/iris@1905/2005/07.27.00.19.48
Site	mtc-m05.sid.inpe.br
Rótulo	5078
ISSN	0004-6361 1432-0746
Chave Secundária	INPE-3363-PRE/
Chave de Citação	KaufmannCorrCostVaz:1986:SyCoIn
Autor	1 Kaufmann, Pierre 2 Correia, Emilia 3 Costa, Joaquim Eduardo Rezende 4 Vaz, Ana Maria Zodi
Grupo	1 CRAAE-INPE-BR
Título	A synchrotron/inverse compton interpretation of solar burst producing fast pulses at lambda < 3 mm and hard x-rays
Revista	Astronomy & Astrophysics
Ano	1986
Volume	157
Número	:
Palavras-Chave	RADIOASTRONOMIA.
Páginas	11-18
Tipo Secundário	PRE PI
Divulgação	WEBSCI; PORTALCAPES.
Area	CEA
Projeto	RADIO
Ultima Atualização dos Metadados	2014:09.29.15.19.32 sid.inpe.br/banon/2001/04.03.15.36 administrator {D 1986}
Estágio do Documento	concluido
e-Mail (login)	marciana
Grupo de Usuários	administrator
Visibilidade	shown
Transferível	1
Tipo do Conteudo	External Contribution
Política de Arquivamento	allowpublisher allowfinaldraft
Conteúdo da Pasta source	não têm arquivos
Conteúdo da Pasta agreement	não têm arquivos
Histórico	2014-09-29 15:19:32 :: administrator -> marciana :: 1986
Campos Vazios	abstract affiliation alternatejournal archivist callnumber copyholder copyright creatorhistory descriptionlevel documentstage doi e-mailaddress electronicmailaddress format isbn language lineage mark mirrorrepository month nextedition nexthigherunit notes numberoffiles parameterlist parentrepositories previousedition progress readergroup readergroup readpermission resumeid rightsholder secondarydate secondarymark session shorttitle size sponsor subject targetfile tertiarymark tertiarytype typeofwork url versiontype
Data de Acesso	23 jul. 2015

atualizar

1. Publication Nº
INPE-3363-PRE/641

2. Version

3. Date
Dec., 1984

5. Distribution
☐ Internal ☒ External
☐ Restricted

4. Origin
DAS-DRA

Program
RADIO

6. Key words - selected by the author(s)
SOLAR BURSTS - MM-WAVE COMPONENT - RADIATION MECHANISMS - SYNCHROTRON/INVERSE COMPTON.

7. U.D.C.: *523.03*

8. Title *INPE-3363-PRE/641*

A SYNCHROTRON/INVERSE COMPTON INTERPRETATION OF A SOLAR BURST PRODUCING FAST PULSES AT $\lambda < 3$ MM AND HARD X-RAYS

10. Nº of pages: *27*

11. Last page: *26*

12. Revised by

Pierre Kaufmann

9. Authorship

P.Kaufmann
E.Correia
J.E.R.Costa
A.M.Zodi Vaz

Responsible author

13. Authorized by

Parada
Nelson de Jesus Parada
Director General

14. Abstract/Notes - *The recently discovered new class of solar burst emission component exhibiting very fast pulses (durations ≈ 60 ms) at mm-waves ($\lambda \lesssim 3$ mm) and at hard X-rays, poses serious constraints for interpretation assuming the acceleration of low energy electrons. We suggest an alternative interpretation assuming that the mm-wave emission component is part of a synchrotron radiation spectrum with peak emission in the infrared range of frequencies and accounting for fluxes reported for "white-light" flare emission in the visible range. Electron energies are reduced primarily by inverse Compton quenching on the synchrotron source photons, producing the observed X-rays and explaining the pulses' short time scales. According to this interpretation, the burst pulse sources must be very small (~ 10^6 cm) with high brightness temperatures (~ 10^{10} K). In a following step of the fast pulse, for $t \lesssim 60$ ms, the electrons energies decay to mildly relativistic or thermal energies, which may produce the better known longer lasting ($t > 60$ ms) emissions at microwaves and X-rays. Although this interpretation is shown to be self-consistent, it raises the need of a number of further theoretical studies and of some crucial observational tests, specially in the sub-mm and infrared range of wavelengths.*

15. Remarks - *Submitted to Astronomy & Astrophysics. Partially supported by FINEP.*

a) Title:

A Synchrotron/Inverse Compton Interpretation of a Solar Burst Producing Fast Pulses At $\lambda < 3$ mm And Hard X-Rays.

b) Authors:

P.Kaufmann, E.Correia, J.E.R.Costa, and A.M.Zodi Vaz

c) Institution:

INPE: Instituto de Pesquisas Espaciais, CNPq,
C.P. 515,
12.200 - São José dos Campos, SP,
Brazil.

d) Running Title:

Synchrotron/Inverse Compton Solar Burst Emission

e) Address for proofs:

INPE: Instituto de Pesquisas Espaciais, CNPq,
R. Traipú, 423
01235 - São Paulo, SP.
Brazil.

f) Principal author:

P.Kaufmann

g) Code numbers:

07.36.1, 09.02.1, 16.11.1, 18.03.2, 19.73.1, 19.78.1, 19.85.1, 19.91.1, 19.94.1

h) Section:

The Sun

i) Main Journal

SUMMARY: The recently discovered new class of solar burst emission component exhibiting very fast pulses (durations $\approx$ 60 ms) at mm-waves ($\lambda \lesssim 3$ mm) and at hard X-rays, poses serious constraints for interpretation assuming the acceleration of low energy electrons. We suggest an alternative interpretation assuming that the mm-wave emission component is part of a synchrotron radiation spectrum with peak emission in the infrared range of frequencies and accounting for fluxes reported for "white-light" flare emission in the visible range. Electron energies are reduced primarily by inverse Compton quenching on the synchrotron source photons, producing the observed X-rays and explaining the pulses' short time scales. According to this interpretation, the burst pulse sources must be very small ($\sim 10^6$ cm) with high brightness temperatures ($\sim 10^{10}$K). In a following step of the fast pulse, for $t \gtrsim 60$ ms, the electrons energies decay to mildly relativistic or thermal energies, which may produce the better known longer lasting ($t > 60$ ms) emissions at microwaves and X-rays. Although this interpretation is shown to be self-consistent, it raises the need of a number of further theoretical studies and of some crucial observational tests, specially in the sub-mm and infrared range of wavelengths.

Key Words:

Solar bursts - mm-wave component - radiation mechanisms - Synchrotron/ Inverse Compton.

1. Introduction

The first high sensitivity/high time resolution solar observations at 30 GHz and 90 GHz performed by the Itapetinga 13.7-m antenna revealed an extraordinary radio burst with peak emission frequency $\gtrsim$ 90 GHz (λ=3.3 mm), and negligible emission at 30 GHz, and at smaller microwave frequencies observed in 21 May 1984, 1326UT (Kaufmann et al., 1984a). The burst consisted of multiple fast pulses in each major time structure. The e-folding rise time scale of such pulses was 30 ms at 90 GHz (durations $\approx$ 60 ms). Coincident hard X-ray emission (photon energy $>$ 30 keV) was detected by the Hard X-Ray Burst Spectrometer on board of Solar Maximum Mission satellite with a time resolution of 128 ms. In Figure 1 we show the event and the expanded the first major time structure of the burst at 90 GHz and at hard X-rays, Figure 2 shows the radio spectrum of this structure. As the time elapsed, the 30 GHz emission started showing up more intensively, with the fast pulses in phase with 90 GHz pulses and hard X-ray emission (Kaufmann et al., 1984a). Such fast multiple pulses in bursts were already known for other bursts at larger mm-wavelengths (Kaufmann et al., 1980, 1984b), and correlated to hard X-rays pulses (Takakura et al., 1983; Cornell et al., 1984). Fast time structures in X-rays burst were found independently (Charikov et al., 1981; Kiplinger et al., 1983; Bogovalov et al., 1984).

As it has been briefly discussed (Kaufmann et al., 1984a), the 21 May 1984, 1326 UT burst, with such high radio turnover frequency ($\nu > 10^{11}$ Hz) and short time scales (~ 0.03s), could hardly be interpreted with the usual assumption of emission produced by relativistic, mildly relativistic, or thermal electrons. The synchrotron emission turnover frequency $\nu_{sm} > 10^{11}$ Hz is too high in the approximation for mildly relativistic electrons for which the formulae derived by Dulk and Marsh (1982) do not differ much from equations used for fully relativistic electrons. We might thus relate ν_{sm} to the energy E of the electrons accelerated by (Ginzburg and Syrovatskii, 1965)

$$\nu_{sm} = 4.6 \times 10^{-6} \, B \left[E \, (eV) \right]^2 \quad Hz \tag{1}$$

which, for B = 1000-100 gauss, gives $E > 5 - 15$ MeV (or Lorentz factor $\gamma > 10$-30), in the ultrarelativistic range. On the other hand the time scales might be associated to length scales, $\ell_s < v_A \delta t$, where v_A is the Alfvēn velocity. For $v_A \approx 10^8$ cms^{-1}, we have $\ell_s < 3 \times 10^6$ cm (or apparent angular size at the Sun $\theta_s < 0.04$ arc sec). The apparent brightness temperature T_B can be estimated from $S = (2kT_B/\lambda^2)(\ell_s/d)^2$, where S is the flux density, d the distance to the Sun ($= 1.5 \times 10^{13}$ cm), k the Boltzmann constant, and λ the wavelength. With the observed S = 70 s.f.u. at 90 GHz we obtain $T_B > 10^{10}$K (Kaufmann et al., 1984a). In thermal models, if we assume that the annihilated field energy goes entirely into thermal energy of the plasma, the maximum temperature attainable $T_{max} \approx B^2/8\pi kN$, which for the usually assumed B=500 gauss electron density $N = 10^{11}$ cm^{-3}, becomes $T_{max} \approx 7 \times 10^8$K $< T_B$. However, in this case, a density of $N = 10^{11}$ cm^{-3} wouldn't prevent the 30 GHz emission to escape. The radio turnover frequency for thermal models (Dulk et al., 1979) $\nu_{tm} \approx$ $\approx 2.3 \, T_{max}^{0.7} \, B \ll 10^{11}$ Hz for any assumptions given for T_{max} and B. Alternatively if we assume the time scales associated to the speed of light, we obtain $\ell_s \lesssim 10^9$ cm, or $\theta_s \lesssim 13$ arcsec, and therefore $T_B \gtrsim 10^5$K, which is considerably smaller than temperatures generally given for flare plasmas. Furthermore, there are evidences that the flare spatial structures at microwaves and ultraviolet are considerably smaller than few arcseconds (Marsh et al., 1980;Cheng,et al., 1981).

However the extremly good time coincidence of 90 GHz and $>$ 30 keV fast pulses in the 21 May 1984, 1326 UT burst (i.e., less than 128 ms) suggest that both the mm-waves and the hard X-rays are emitted by a single population of electrons. The initially strongly attenuated 30 GHz emission suggest the burst source to be opaque at $\nu \lesssim 10^{11}$ Hz, and slowly expanding with time. We suggest one model initially based on an early interpretation of white-light flare emission by synchrotron radiation, peaking somewhere in the visible (Stein and Ney, 1963), reconciling it with the observed mm-wave $\lambda <$ 3 mm spectral component, and with the possible effectiveness of inverse Compton scattering in producing hard X-rays (Shklovsky, 1964; Zheleznyakov, 1970), but with the difference that the radiation field photons are in our case the flare produced synchrotron photons. The resulting inverse Compton quenching of the synchrotron photons accounts well for the flux ratio and for the short time scales observed. Such interpretation is in fact often used to explain the transient emission in compact extragalactic sources (Kellermann and Pauliny-Toth, 1968; Jones et al., 1974; Dent et al.,1983).

2. mm-wave burst component and "white-light" continuum

One possible interpretation for a mm-wave burst emission spectrum with fluxes rising with frequency is that they are a part from a synchrotron spectrum, peaking somewhere at $\nu > 10^{11}$ Hz. Shklovsky (1964) predicted important synchrotron emission in the submillimetric to infrared range of frequencies (electrons accelerated in the 10-100 MeV range in magnetic fields of 100-1000 gauss). The possibility was explored by Stein and Ney (1963) to explain white light continuum and was further discussed by Nagita and Orral (1970) and by Ohki and Hudson (1975). However the measurements of white light continuum in flares has been very difficult, and emission diagnostics in the $10^{11} \lesssim \nu \lesssim 10^{15}$ Hz range of frequencies are nearly non-existent. Even in the 10^{11} Hz range the burst data are scarce. The highest frequency for which a flare emission was reported, 250 GHz (Clark and Park, 1968), suggested an energy dissipation level higher than for estimates given to large optical flares. There were very few cases of bursts measured at about 100 GHz that suggest a spectral "flattening" towards higher frequencies (Croom, 1970; Cogdell, 1972; Shimabukuro, 1970; 1972; Akabane et al., 1973). A similar trend was found for a flare displaying flashes at λ = 3835 Å, and disappearing when the such flashes ceased (Zirin and Tanaka, 1973). One burst exhibiting about 40 solar flux units (1 s.f.u. = 10^{-22} w m^{-2} Hz^{-1}) at 90 GHz had no measurable flux (at the few s.f.u. level) in the usual microwave range (2 - 15 GHz) (Shimabukuro, 1970), might well be a case similar to the event of 21 May 1984, 1326 UT. Figure 3 shows the mm-wave spectra for the events mentioned above.

A careful inspection of spectra in Figure 2 indicates that the "flattening" towards higher frequencies is not real, exhibiting a spectral reduction somewhere around 30-50 GHz, with a rise in flux for $\nu \gtrsim$ 30 GHz. This double spectral structure is also seen in the "U-shaped" microwave spectra (Castelli et al., 1973), usually associated to proton events (and also "white-light" flares). The mm-wave emission component, rising with frequency might be, in this case, a U-shaped spectra event, with the U displaced to an higher frequency.

In view of this scattered evidence it is likely that the higher mm-wave spectral component is a genuine feature of many flares, suggesting a peak emission somewhere in the infrared to visible range of wavelengths, and accounting for the so called "white-light" continuum emission. It might be relevant to remark that proton flares and "white-light" flares might also occur with relatively weak microwave bursts (Cliver *et al.*, 1983; Neidig and Cliver, 1983).

The present interpretation require that ultrarelativistic electrons are accelerated during flares. This requirement arise also from the many independent observational results from the gamma-ray experiments, which do imply in electrons accelerated to the 10^2 MeV range, in the first few seconds of the bursts (Chupp *et al.*, 1983; Forrest and Chupp, 1983).

3. The synchrotron flux and time scales.

We will concentrate in the 21 May 1984, 1326 UT burst, which was the first event well measured at 30 GHz, 90 GHz and hard X-rays. Assuming that the 30-90 GHz observed spectrum is attributed to a compact synchrotron source, its flux will rise with frequency accordingly to $F(\nu_s) \propto \nu^{5/2}$ (Ginzburg and Syrovatskii, 1965) in the optically thick part of the spectrum. According to Ginzburg and Syrovatskii (1965), the peak emission will occur at

$$\nu_{sm} = 1.2 \times 10^6 B \gamma^2 \quad \mathrm{Hz} \tag{2}$$

where γ is the Lorentz factor. On the other hand, the time scale for electron losses by synchrotron emission is

$$t_s = 5.5 \times 10^{11} B^{-3/2} \nu_{sm}^{-1/2} \quad \mathrm{s} \tag{3}$$

From the observed flux at $\nu_s \simeq 10^{11}$ Hz, $F(\nu_s)=7\times10^{-18}$ erg/cm^{2}s Hz, we can extrapolate for fluxes at higher frequencies $10^{11} < \nu_s \lesssim \nu_{sm}$, in the optically thick part of the spectrum:

$$F(\nu_s) \approx 1.2\times10^{-45}\,\nu_s^{5/2} \quad \text{erg/cm}^2\,\text{s Hz} \qquad (4)$$

If we assume that the synchrotron losses can account for the observed small time scales, and equating (2) with (3), we have

$$t_s = 5\times10^{8}\,B^{-2}\gamma^{-1} \quad \text{s} \qquad (5)$$

Therefore the observed pulses time scales $2\delta t \approx 0.06\text{s} \approx t_s$, and for a typical $B \approx 500$ gauss, will require $\gamma \gtrsim 3 \times 10^4$ (or 1.5×10^4 MeV electrons, which is entirely unrealistic), emitting with a peak frequency (2) of $\nu_{sm} = 5.4 \times 10^{17}$ Hz (in the soft X-ray range, which is also unlikely). It appears that the observed time scales are too short to be explained by purely synchrotron losses, and another mechanism must be added in order to reduce the lifetime of ultrarelativistic electrons, with more plausible magnitudes for the energies to which they are accelerated.

4. The inverse Compton quenching of synchrotron photons in a compact source.

One of the most effective mechanism to reduce the electron energy in short time scales is the inverse Compton scattering of the relativistic electrons on the "soft" photons emitted by a background radiation field (Shklovsky, 1964; Ginzburg and Syrovatskii, 1964; Felten and Morrison, 1966; Jones *et al.*, 1974; Tucker, 1975). One of the first suggestions on inverse Compton effect to explain X-rays emission from solar bursts was given by Shklovsky (1964). He assumed a radiation field consisting in Ly-α quanta closed in the flare region itself, and predicted important synchrotron emission produced in the same area, in the submillimeter to infrared region (electrons accelerated in the 10-100 MeV range). Acton (1964), however, argued that for the time scales then believed to be involved (300 sec), the bremsstrahlung mechanism by ultrarelativistic electrons was still more efficient, setting ion densities of about 10^{11} cm^{-3} as a limit for the burst duration by collisional losses. For the pulse durations found here, however (~ 10^4 times smaller) Acton's (1964) argument becomes impossible, since it would imply in ion densities unrealistically high (~ 10^{15} cm^{-3}) for the solar atmosphere.

The possibility of assuming inverse Compton scattering to explain hard X-rays in solar bursts was also raised by Zheleznyakov (1970), who associated the radiation field with the solar optical emission. Korchak (1971) has reviewed this problem, which was also discussed by Brown (1976).

In order to have inverse Compton emission dominating over synchrotron for producing the X-rays the photon energy density $U_{ph} >$ the magnetic energy density $U_B = B^2/8\pi$ (for example, Tucker, 1975). We find, however, that this do not seem to be the case for the solar blackbody optical background, for which the temperature $T \approx 6000K$, and thus $U_{ph} = 4\pi\sigma T^4/c$ where σ is the Stephan-Boltzmann constant and c the speed of light. We obtain $U_{ph} \approx 30$ erg/cm^3 $<< U_B$. Zheleznyakov (1970), however, still consider possible to have hard X-rays by inverse Compton scattering of 100 MeV electrons on optical quanta with radiation density of ~ 5 erg/cm^3.

In this interpretation we assume the condition $U_{ph} > U_B$ on the grounds that if synchrotron was competing or dominant at X-rays, the observed time scales for the pulses are too short. We will analyse now the denser radiation field produced by the synchrotron emission itself (Kellermann and Pauliny-Toth, 1972; Tucker, 1975). Using a Rayleigh-Jeans approximation for the emitted radiation, which is approximately true for the optically thick part and for the peak of the spectrum,

$$U_{ph} = \frac{4\pi I}{c} \quad \mathrm{erg/cm^3} \tag{6}$$

where I (erg/cm^{2}s) is the emittance at the burst source. Therefore for $U_{ph} > B^2/8\pi$ ($\approx 10^4$ erg/cm^3, for B = 500 gauss) we shall need $I > 2.3 \times 10^{13}$ erg/cm^{2}s. White-light flare observed powers are of the order of $P \approx 10^{26} - 10^{27}$ erg/s in the visible range (Stein and Ney, 1963; Hudson, 1972; Ohki and Hudson, 1972; Neidig and Cliver, 1983). We therefore need source sizes $\ell_s^2 < P/I$, or $\ell_s < 4 \times 10^6$ cm. This limitation can be well compared to the size of the compact synchrotron source assumed here (Tucker, 1975)

$$\ell_s < 10^{15} F(\nu_s)^{1/2} B^{1/4} \nu_{sm}^{-5/4} d \quad \mathrm{cm} \tag{7}$$

which for B = 500 gauss, d the distance to the Sun (= 1.5×10^{13} cm) $\nu_{sm} \gtrsim 10^{11}$ Hz, and $F(\nu_s) \gtrsim 7 \times 10^{-18}$ erg/cm^{2}s Hz, as suggested by observations, provides $\ell_s \lesssim 3 \times 10^6$ cm.

We can conclude that the compact synchrotron source can provide the necessary photons to produce efficient inverse Compton scattering. (If we have many of these sources scattered accross a typical flare area(say $A \approx 10^{16}$ cm^2), and are not resolved spatially by instrumentation, the apparent emittance from that area will be the usually reported $P/A \approx 10^{10}$ erg/cm^{2}s for white-light flares, much smaller than the actual emittance from individual sources).

For the burst of 21 May 1984, 1326 UT, we can estimate the frequency of peak emission. It should satisfy both the relationship (4) and the observed time scales $2\delta t \approx t_c$. The inverse Compton time scale for electron losses (Tucker, 1975)

$$t_c = 3.8 \times 10^{13} \frac{m c^2}{U_{ph}\,\gamma} \quad s \tag{8}$$

with U_{ph} given by (6). The emittance I is related to the flux density observed at the Earth by

$$I = \int_0^{\nu_{sm}} I(\nu)\, d\nu = \frac{F(\nu_s)\, 4\pi d^2\, \nu_{sm}}{\ell_s^2} \quad erg/cm^2 s \tag{9}$$

with $d = 1.5 \times 10^{13}$cm, $t_c \approx 0.06$s, $B = 500$ gauss, assuming $\ell_s \sim 10^6$ cm, and equating (8) with (2) and (4) we obtain

$$F(\nu_{sm})\, \nu_{sm}^{3/2} = 10^7 \tag{10}$$

From (4), $F(\nu_{sm}) = 1.2 \times 10^{-45}\, \nu_{sm}^{5/2}$, and therefore substituting in (10) we obtain $\nu_{sm} \approx 10^{13}$ Hz, in the infrared range. For the peak emission at that frequency, we have from (2), $\gamma \approx 130$ (or electrons accelerated in the 66 MeV range). The inverse Compton X-ray photons produced by the synchrotron emitted photons should be at (Ginzburg and Syrovatskii, 1964; Tucker, 1975)

$$\nu_c \approx \gamma^2 \nu_s \quad Hz \tag{11}$$

or $\nu_c \approx 1.6 \times 10^{17}$ Hz, for $\nu_s \approx 10^{13}$ Hz, which is entirely reasonable.

In Figure 4, we show the observed data on the 21 May 1984, 1326 UT burst, as full lines at the radio and X-ray bands. Dashed line indicate the suggested synchrotron spectrum with $\nu_{sm} = 10^{13}$Hz, as required by inverse Compton quenching of synchrotron photons on a time scale $t_c \approx 0.06$s. The white-light continuum typical fluxes measured by various authors (Nagita and Orrall, 1972; Ohki and Hudson, 1975; Neidig and Cliver, 1983) are indicated in the visible and fits very well into the predicted synchrotron spectrum. We note again that X-rays cannot be produced by synchrotron radiation, not only because of $U_{ph} > U_B$ for the compact sources described here, but also because the pulse time scale for $\nu_{sm} = 10^{13}$ Hz which would be, according to (3), $t_s \approx 15$ sec $\gg \delta t$.

5. Synchrotron and inverse Compton fluxes and pulses' energy

We shall assume now that the ultrarelativistic electrons have a power law distribution in energy where the density

$$N(\gamma) = K \gamma^{-n} \tag{12}$$

where the energy spectral index n is related to the emitted photons energy spectral index q (for inverse Compton which is the same as the synchrotron spectral index for $\nu_s \gtrsim \nu_{sm}$):

$$q = \frac{n-1}{2} \tag{13}$$

The volume emissivity of the synchrotron radiation at $\nu_s \gtrsim \nu_{sm}$ is (for example Tucker, 1975):

$$j(\nu_s) = 1.7\times10^{-21}\, K\, a(n)\, B^{q+1} \left(\frac{4\times10^6}{\nu_s}\right)^q \text{erg/cm}^3\,\text{s Hz} \tag{14}$$

where a(n) is calculated by a formula given by Ginzburg and Syrovatskii (1965).

For an emitting source size ℓ_s we have

$$F(\nu_s) = j(\nu_s)\, \ell_s \left(\frac{\ell_s}{d}\right)^2 \text{erg/cm}^2\,\text{s Hz} \tag{15}$$

where $(\ell_s/d)^2$ is the source's solid angle. We rewrite (14)

$$F(\nu_s) = 1.7\times10^{-21}\, \frac{KV}{d^2}\, a(n)\, B^{q+1} \left(\frac{4\times10^6}{\nu_s}\right)^q \text{erg/cm}^2\text{s Hz} \tag{16}$$

where $V \approx \ell_s{}^3$. From the hard X-ray spectrum (Kaufmann et al., 1984a) $q \approx 3.2$, $n = 7.4$ $a(n) = 0.2$, for $\nu_{sm} = 10^{13}$ Hz, we obtain from (4) $F(\nu_{sm}) = 4 \times 10^{-13}$ erg/cm^2 s Hz. For $B = 500$ gauss in (16) we obtain $KV \approx 3.6 \times 10^{44}$ electrons/γ^{1-n} . With $\ell_s \approx 10^6$ cm, we obtain $K \approx 3.6 \times 10^{26}$ electrons/ $\gamma^{1-n}\cdot$cm^3.

In order to estimate the total number of electrons accelerated, we have

$$N_t\,(>\gamma_1) = V\int_{\gamma_1}^{\gamma_2} N(\gamma)\, d\gamma \tag{17}$$

where $N(\gamma) = K\gamma^{-n}$. An assumption must be made for the smaller limit γ_1, while $\gamma_2 \to \infty$. From the predicted synchrotron spectrum (Figure 4), the maximum emission occurs for $\nu_{sm} = 10^{13}$ Hz. We can estimate for a power law distribution of electrons (Ginzburg and Syrovatskii, 1965):

$$\gamma_1 \approx 5 \times 10^{-4} \left[\frac{\nu_{sm}}{y_1(n)\ B} \right] \tag{18}$$

where $y_1(n=7.5) = 5$. Therefore, for B = 500 gauss, we have $\gamma_1 \approx 30$. Integrating (17), with K as above (= 3.6×10^{26}), and $V \sim \ell_s^3$ ($=10^{18}$ cm^3) we obtain $N_t \approx 2 \times 10^{34}$ electrons. The total energy per pulse, $W_t \approx \gamma_1 N_t mc^2 \approx 5 \times 10^{29}$ erg, which is one or two orders of magnitude larger than estimates found in the literature for the smaller flares.

The volume emissivity of inverse Compton radiation, with the electron energy distribution (13) can be written as (for example, Tucker, 1975):

$$j(\nu_c) = \pi r_0^2 c h K\, 2^{n+3} \frac{n^2+4n+11}{(n+3)^2(n+1)(n+5)}\, \nu_c^{-(n-1)/2} \int_0^{\nu} \nu_i^{(n-1)/2}\, n_{ph}(\nu_i)\, d\nu_i \tag{19}$$

where $r_0 = e^2/mc^2$, e is the electron charge, ν_i is the frequency of the photons of the radiation field, with a density $n_{ph}(\nu_i)$. For $\nu_i \lesssim \nu_{sm}$, we may approximate to a Rayleigh-Jenas spectrum in the optically thick part of the spectrum, and thus

$$n_{ph}(\nu) = \frac{I(\nu)}{c h \nu} \text{ photons/cm}^3\text{ Hz} \tag{20}$$

where $I(\nu) = 2\,kT_{eq}\,\nu^2/c^2$, (erg/cm^{2}s Hz) and T_{eq} is an equivalent blackbody temperature. For practical calculations, the dependence of $I(\nu)$ on ν^2 doesn't differ much from the $\nu^{5/2}$ dependence assumed before for the synchrotron radiation. Substituting (20) into the integral in (19), and integrating from $\nu_i = 0$ to $\nu_i = \nu_{sm}$, we obtain

$$\int_0^{\nu_{sm}} \nu_i^{(n-1)/2}\, n_{ph}(\nu_i)\, d\nu_i \approx \frac{2}{(n+3)}\, \nu_{sm}^{q+2} \quad \text{photons/cm}^3 \tag{21}$$

Substituting (21) in (19), with $F(\nu_c) = j(\nu_c)\,\ell_s\,(\ell_s/d)^2$ (similarly to (15)) we obtain for hard X-ray fluxes

$$F(\nu_c) = 1.5\times10^{-61}\, Q(n)\, \frac{KV}{d^2} \left(\frac{\nu_{sm}}{\nu_c}\right)^{q} \nu_{sm}^{2}\, T_{eq} \quad \text{erg/cm}^2\text{s Hz} \tag{22}$$

where $Q(n) = \left[2^{n+3}(n^2 + 4n + 11)/(n+3)^3(n+1)(n+5)\right]$ The ratio between inverse Compton flux to synchrotron flux for $\nu_s \lesssim \nu_{sm}$ and for a radiation field following approximately Rayleigh-Jeans relationship for frequencies $\nu_i \lesssim \nu_{sm}$, is obtained from (16) and (22).

$$\frac{F(\nu_c)}{F(\nu_s)} \approx 8.7\times10^{-41}\,(4\times10^{6})^{-q}\, \frac{Q(n)}{a(n)}\, B^{-(q+1)}\, \nu_s^{2(q+1)}\, \nu_c^{-q}\, T_{eq} \tag{23}$$

For the present application, at $\nu_{sm} = 10^{13}$ Hz, we have estimated from (14) that a flux $F(\nu_{sm}) \approx 4\times10^{-13}$ erg/cm^{2}s Hz should be observed. The observed X-ray flux at 30 KeV (7×10^{18} Hz) was $F(\nu_c) \approx 2\times10^{-25}$ erg/cm^{2}s Hz (or 1 photon/cm^2 s KeV). Therefore the observed ratio is

$$\frac{F(\nu_c)}{F(\nu_s)} \approx 5\times10^{-13} \tag{24}$$

Substituting (24) in (23), with $q = 3.2$, $n = 7.4$, $\nu_{sm} = 10^{13}$Hz, $\nu_c = 7\times10^{18}$ Hz, we obtain $a(n) = 0.2$ and $Q(n) = 1.1$, and thus

$$B^{-4.2} T_{eq} \gtrsim 1.8 \times 10^{-1} \qquad (25)$$

For B = 500 gauss, we obtain $T_{eq} \gtrsim 4 \times 10^{10}$K, which is consistent with the high brightness temperature inferred for the compact opaque synchrotron source. (Similar results can be obtained adopting for $F(\nu_s)$ the fluxes reported for white-light flares).

Similarly to what has been obtained from (16), we can alternatively determine the same KV from (22), with all parameters established above.

6. Concluding remarks

It has been shown that the newly discovered solar burst spectral component for $\lambda \lesssim 3$ mm can be interpreted as part of the optically thick section of a synchrotron radiation emitted by ultra-relativistic electrons ($E > 15$ MeV). The maximum of the spectrum is somewhere in the infrared range, and can account for the white-light continuum observed for some flares in the visible. This interpretation is applicable to burst producing multiple fast pulses, with time scales set by inverse Compton quenching of the synchrotron photons, and accounting for the hard X-rays observed. The individual pulse source must be very small ($\ell_s \sim 10^6$ cm) and present very high brightness temperatures ($T_B \sim 10^{10}$K). These scale magnitudes are set by assuming both the compact synchrotron sources' limitations or by assuming Alfvēn times involved in the acceleration region.

According to this interpretation we may conceive the flare impulsive phase generated by multiple fast energetic pulses and consisting into two steps. The first one lasts less than about 60 ms, during which the initially ultrarelativistic electrons loose most of their energy primarily by inverse Compton scattering producing the observed fast mm-waves and hard X-ray pulses. The second phase, for $t > 60$ ms the electrons have decayed to energies $\ll 15$ MeV (to mildly relativistic or even thermal energies), and producing the well known microwave and X-rays emission, interpreted by the usual thermal and non-thermal models. For more complex bursts, as the time elapses, the received radiation might contain contribution from all processes added together, if energetic injections continue to act.

The present interpretation explains self-consistently the synchrotron/inverse Compton flux ratio, and the accounts for the observed fast time scales. It raises, however, a number of new theoretical problems to be further investigated and requires new observational evidences on flares not yet available in the frequency range $10^{11} - 10^{14}$ Hz. One problem is relative to estimates of the importance of gamma-ray continuum produced by bremsstrahlung (both electron-ion and electron-electron) of ultrarelativistic electrons. Such excess gamma-ray continuum was in fact not observed for the 21 May 1984 event (Chupp, 1984). If existent, it might have been smoothed out by the relatively large time constant of the gamma-ray detector. On the other hand, the competition of Compton quenching and bremsstrahlung in a compact and short-lived source requires a detailed study.

Burst diagnostics obtained with relatively poor time resolution ($>$10 ms) wouldn't be able to distinguish the fast time structures, and the suggested two steps in the pulses. Of great importance will be measurements in the sub-millimetric and infrared ranges, and in the harder X-rays ($>$ 100 keV) with considerably better sensitivity and time resolution than the presently available ones.

Acknowledgements

The authors acknowledge the helpful discussions and suggestions received from Prof.J.C.Brown and Dr.A.MacKinnon (U.Glasgow) on this paper. This research was partially supported by Brazilian research agency FINEP. INPE operates CRAAM and Itapetinga Radio Observatory.

REFERENCES

Acton.L.W.: 1964, Nature, 204, 64.

Akabane,K., Nakajima,H., Ohki,K., Moriyama,F., and Miyaji,T.: 1973, Solar Phys., 33, 431.

Bogovalov,S.V., Iyudin,A.F., Kotov,Y.D., Dolidze,V.I., Estulin,I.V., Vedrenne,G., Niel,M., Barat,C., Chambon,G., and Talon,M.: 1984, Soviet Astron.Lett., 9, 163.

Brown,J.C.: 1976, Phil.Trans.R.Soc.Lond., A281, 473.

Charikov,Y.E., Korchanov.G.E., and Lazutkov,V.P.: 1981, 17th Int.Cosmic Ray Conf., Paris, 13-25 July.

Cheng,C.C., Tandberg-Hanssen,E., Bruner,E.C., Orwig,L.E., Frost,K.J., Kenny,B.J., Woodgate,B.E., and Shine,R.A.: 1981, Astrophys.J., 248,L39.

Chupp,E.L., Forrest,D.J., and GRS Team: 1983, in SMM-Workshop, NASA/GSFC, USA.

Chupp,E.L.: 1984, private communication.

Clark,C.D., and Park,W.M.: 1968, Nature, 219, 922.

Cliver,E.W., Kahler,S.W., and McIntash,P.S.: 1983, Astrophys.J., 264, 699.

Cogdell,J.R.: 1972, Solar Phys., 22, 147.

Cornell,M.E., Hurford,G.J., Kiplinger,A.L., and Dennis,B.R.: 1984, Astrophys.J., 279, 875.

Croom,D.L.: 1970, Solar Phys., 15, 414.

Castelli,J.P., Aarons,J., Guidice,D.A., and Straka,R.M.: 1973, Proc.IEEE, 61, 1307.

Dent,W.A., O'Dea,C.P., Balonek,T.J., Hobbs,R.W., and Howard,R.J.: 1983, Nature, 306, 41.

Dulk,G.A., and Marsh,K.A.: 1982, Astrophys.J., 259, 350.

Felten,J.E., and Morrison,P.: 1966, Astrophys.J., 146, 686.

Forrest,D.J.,and Chupp,E.L.: 1983, Nature, 305, 291.

Ginzburg,V.L., and Syrovatskii,S.I.: 1965, Ann.Rev.Astron.Astrophys., 3, 297.

Hudson,H.S.: 1972, Solar Phys., 24, 414.

Jones,T.W., O'Dell,S.L., and Stein,W.A.: 1974, Astrophys.J., 192, 261.

Kaufmann,P., Strauss,F.M., Opher,R., and Laporte,C.: 1980, Astron. and Astrophys., 87, 58.

Kaufmann,P., Correia,E., Costa,J.E.R., Zodi Vaz,A.M., and Dennis,B.R.: 1984a, Nature, in press.

Kaufmann,P., Correia,E., Costa,J.E.R., Dennis,B.R., Hurford,F.J., and Brown,J.C.: 1984b, Solar Phys., 91, 359.

Kellermann,K.I., and Pauliny-Toth,I.I.K.: 1968, Ann.Rev.Astron.Astrophys., 6, 417.

Kiplinger,A.L., Dennis,B.R., Emslie,A.G., Frost,K.J., and Orwig,L.E.: 1983, Astrophys. J., 265, L99.

Korchak,A.A.: 1971, Solar Phys., 18, 284.

Marsh,K.A., Hurford,G.J., Zirin,H., and Hjellming,R.M.: 1980, Astrophys.J., 242, 352.

Nagita,K., and Orrall,F.Q.: 1970, Solar Phys., 15, 1976.

Neidig,D.F., and Cliver,E.W.: 1983, A Catalog of Solar White-Light Flares (1859-1982), including their statistical Properties and Associated Emissions, Rept. AFGL-TR-83-0257.

Ohki,K., and Hudson,H.S.: 1975, Solar Phys., 43, 405.

Shimabukuro,F.I.: 1970, Solar Phys., 15, 424.

Shimabukuro,F.I.: 1972, Solar Phys., 23, 169.
Shklovsky,J.: 1964, Nature, 202, 275.
Stein,W.A., and Ney,E.P.: 1963, J.Geophys.Res., 68, 65.

Takakura,T., Kaufmann,P., Costa,J.E.R., Degaonkar,S.S., Ohki,K., and Nitta,N.: 1983, Nature, 302, 317.

Tucker,W.H.: 1975, Radiation Processes in Astrophysics, The MIT Press, USA, Chapters 3 and 4.

Zheleznyakov,V.V.: 1970, Radio Emission of the Sun and Planets, Pergamon Press, U.K., Chapter IX.

Zirin,H., and Tanaka,K.: 1973, Solar Phys., 32, 173.

CAPTIONS TO THE FIGURES

Fig. 1 - The solar burst of 21 May 1984, 1326 UT, observed at 7 GHz, 30 GHz, 90 GHz and hard X-rays (after Kaufmann et al., 1984a). In (a) the burst is shown in compressed time scale, and where the first major time structure A have negligible emission at 30 GHz and at 7 GHz. It exhibits the very good correspondence of 90 GHz and hard X-ray time structures. A 4s time expansion of structure A is shown at the bottom, (b), where the hard X-ray time resolution was limited to 128 ms. The e-folding onset time was of about 30 ms at 90 GHz, and was coincident to less than 128 ms at hard X-rays.

Fig. 2 - Spectrum of Structure A of the 21 May 1984 burst, suggesting a mm-wave component. Other data points were obtained from AFGL and HIA-Ottawa.

Fig. 3 - Examples of solar burst spectra published in the litterature, exhibiting a "flattening" towards mm-wavelengths or the superposition of a mm-wave spectral component. These results were obtained by the authors indicated at the upper left corner. The measurements were taken with relatively poor time resolution and sensitivity.

Fig. 4 - The presently suggested interpretation associate the observed mm-wave spectrum (solid line for $\lambda \overset{\sim}{<} 3$mm) to a synchrotron spectrum peaking at 10^{13} Hz, in the infrared range. The reported fluxes for white-light continum in flares are close to the predicted synchrotron fluxes in the visible. Observed hard X-rays (solid line) are explained by inverse Compton quenching of the synchrotron produced photons, accounting for the short time scale durations ($\approx$ 60 ms).

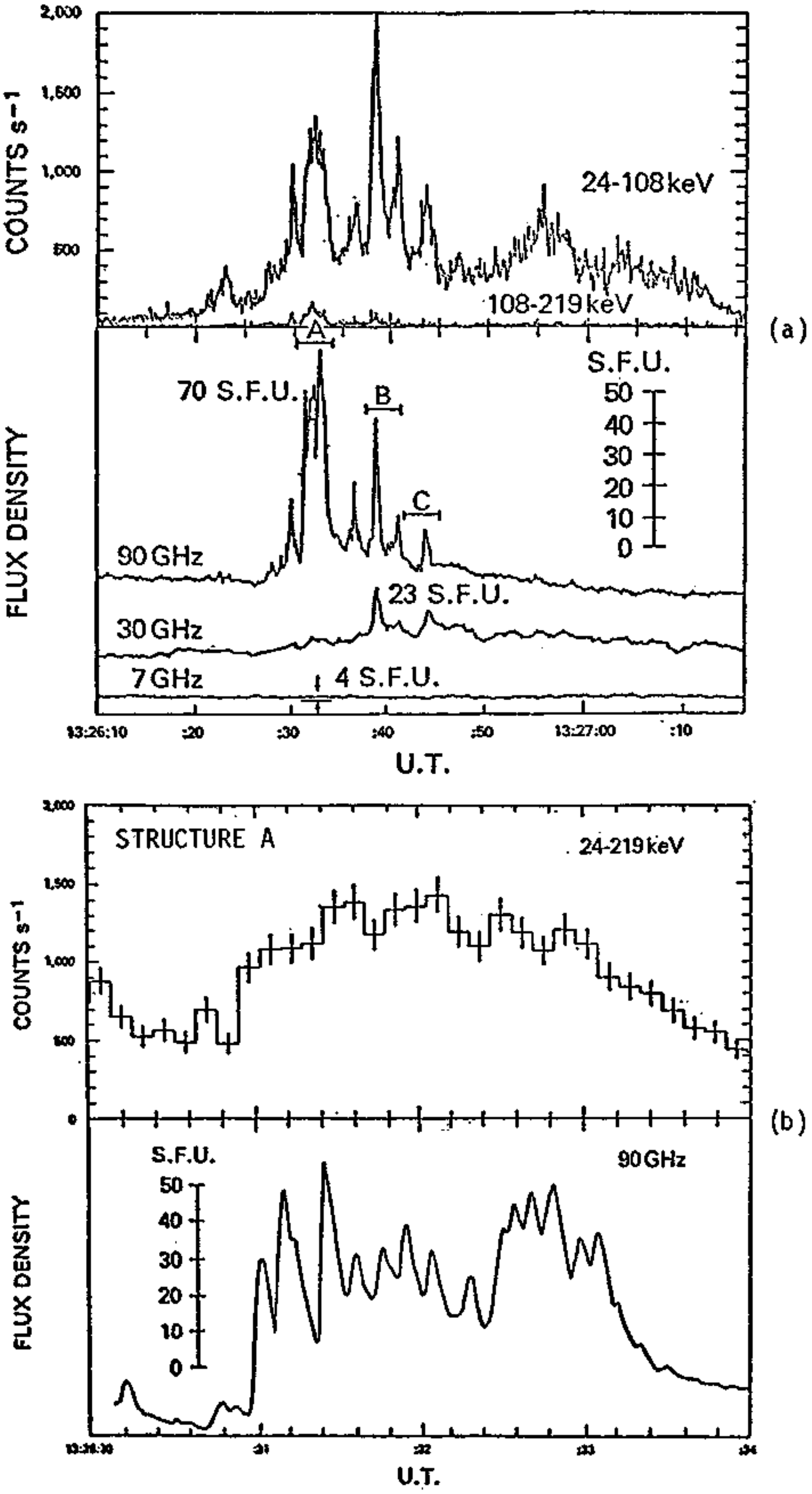
2,000
1,500
1,000
500
COUNTS s⁻¹
24-108 keV
108-219 keV
(a)
A
70 S.F.U.
B
C
S.F.U.
50
40
30
20
10
0
FLUX DENSITY
90 GHz
23 S.F.U.
30 GHz
7 GHz
4 S.F.U.
13:26:10
:20
:30
:40
:50
13:27:00
:10
U.T.
2,000
STRUCTURE A
24-219 keV
1,500
1,000
500
0
COUNTS s⁻¹
(b)
S.F.U.
90 GHz
50
40
30
20
10
0
FLUX DENSITY
13:26:30
:31
:32
:33
:34
U.T.

FIG. 1

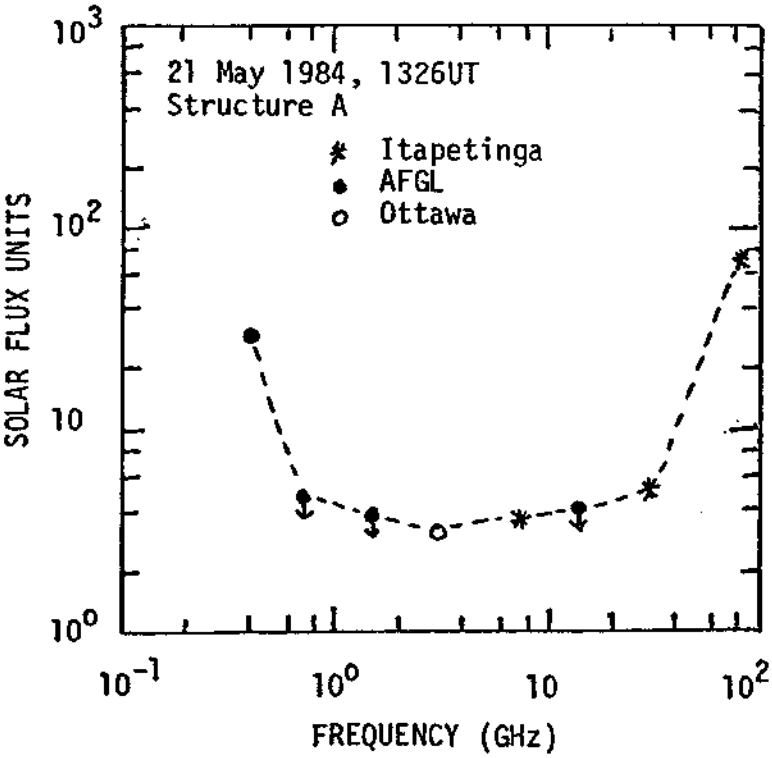
21 May 1984, 1326UT
Structure A
* Itapetinga
● AFGL
o Ottawa
SOLAR FLUX UNITS
10^3
10^2
10
10^0
10^{-1}
10^0
10
10^2
FREQUENCY (GHz)

FIG. 2

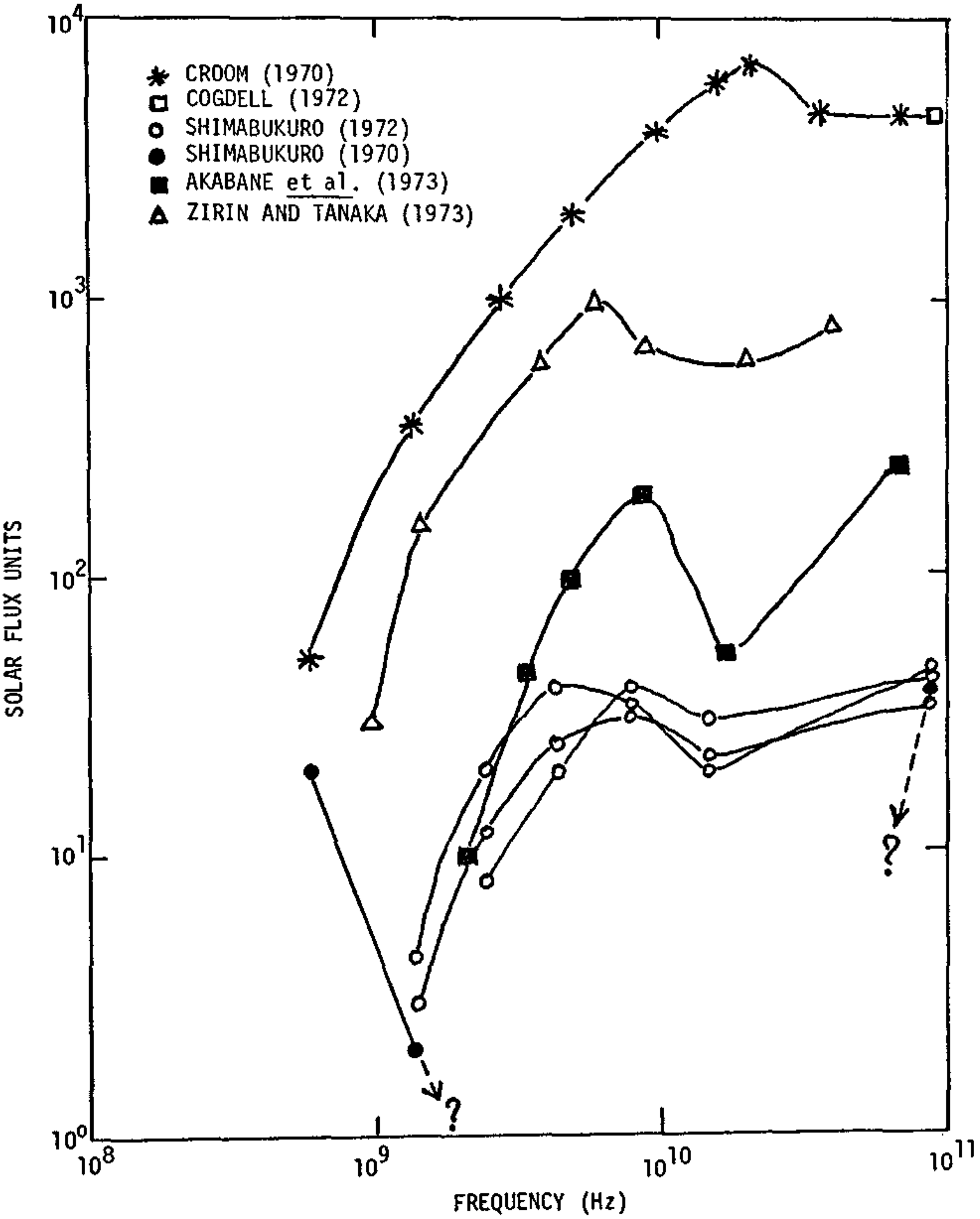
✱ CROOM (1970)
□ COGDELL (1972)
○ SHIMABUKURO (1972)
● SHIMABUKURO (1970)
■ AKABANE et al. (1973)
△ ZIRIN AND TANAKA (1973)
SOLAR FLUX UNITS
FREQUENCY (Hz)
10^0
10^1
10^2
10^3
10^4
10^8
10^9
10^{10}
10^{11}
?
?

FIG. 3

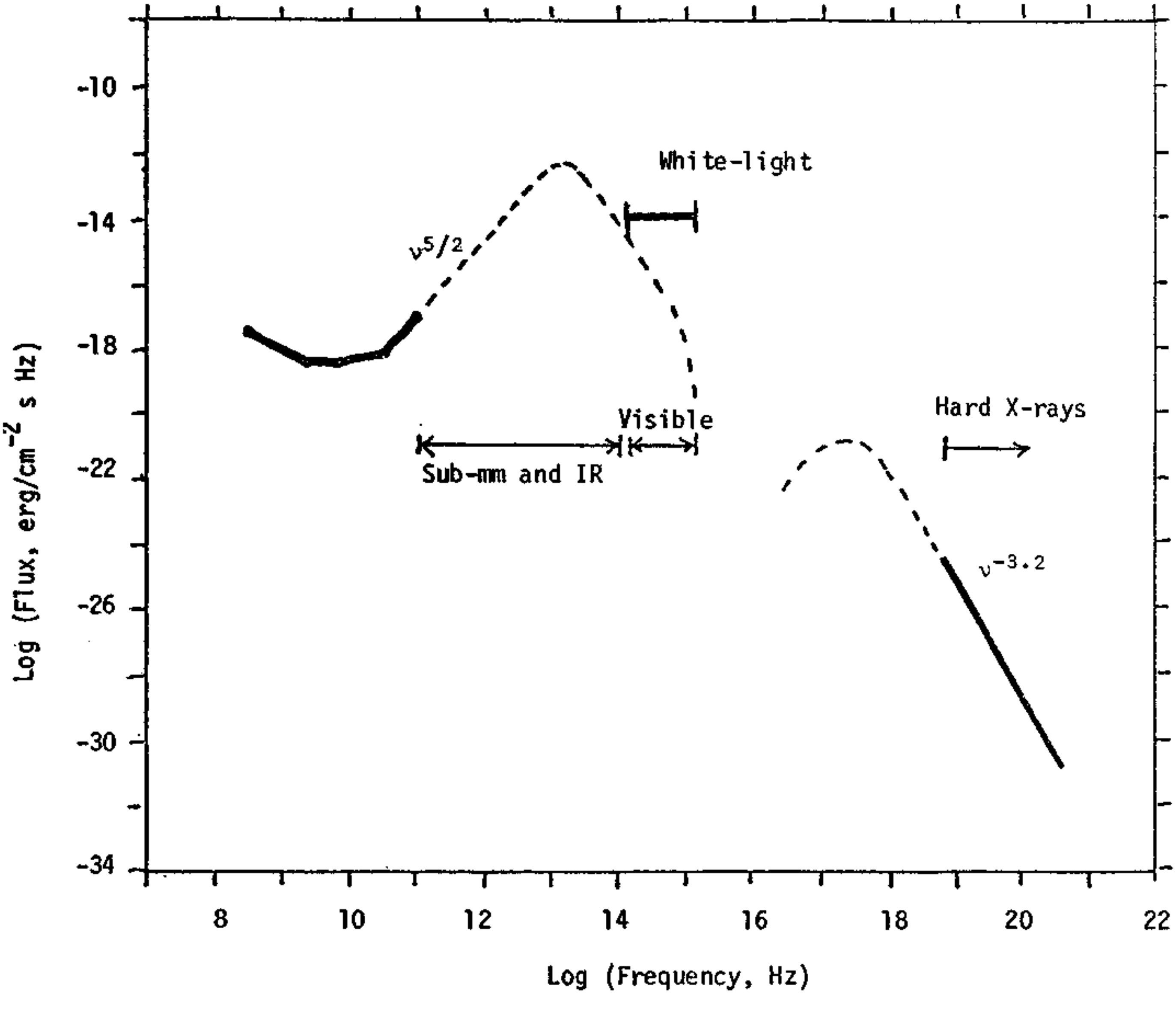
-10
-14
-18
-22
-26
-30
-34
Log (Flux, erg/cm^{-2} s Hz)
8
10
12
14
16
18
20
22
Log (Frequency, Hz)
White-light
$\nu^{5/2}$
Visible
Sub-mm and IR
Hard X-rays
$\nu^{-3.2}$

FIG. 4