X-693-71-177
PREPRINT

NASA TM X-65542

RELATIVISTIC ELECTRONS ASSOCIATED WITH SOLAR FLARES

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ABSTRACT

Solar flares which produce relativistic electrons generally occur within sunspot groups which are active in the emission of meter type I noise storms. It is suggested that relativistic electrons in solar flares are accelerated from the Kev-energy electrons responsible for the type I noise storms. The relationship between flare developments and the ejection of Kev-electrons is briefly considered.

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1. Introduction

Relativistic electrons from solar flares was first observed by Meyer and Vogt (1962) by using balloons born instruments located above the atmosphere. The importance of such relativistic electrons was considered by Boischot (1957) in interpreting some characteristics of type IV radio bursts. He recognized synchrotron emission from relativisitc electrons as a source of such radio bursts.

Since flares which produced solar cosmic ray particles were associated with type IV radio bursts, it seemed natural that relativistic electrons were produced simultaneously with solar cosmic ray protons and heavier nuclei in the same flares. The relationship between solar cosmic ray events and type IV radio bursts was, therefore, studied by many authors (e.g., Hakura and Goh, 1959; Reid and Leinbach, 1959; Kundu and Haddock, 1960; Maxwell and Thompson, 1960; Obayashi and Hakura, 1960; Sakurai, 1960; Sakurai and Maeda, 1961). It was shown, furthermore, that the observed characteristics of type IV radio bursts were fully explained by taking into account gyrosynchrotron emission from 100 - 10,000 Kev electrons (e.g., Takakura, 1959, 1960; Takakura and Kai, 1961; Wild, 1962).

Cline and McDonald (1968) first observed the relativistic solar electrons with satellites and established that these relativisitc electrons were generated from flares which produced solar cosmic ray nuclei. It has been shown that these solar flares take place in sunspot groups which are very active in type I noise emissions (Sakurai, 1971a). The acceleration of the Kev energetic electrons ambient in type I noise active regions may be the source of the relativistic electrons.

In this paper, we consider the characteristics of solar flares which produced relativistic electrons and their relation to solar cosmic ray production. The acceleration processes of these electrons and the relationship to type IV radio bursts is briefly considered.

2. Relativistic Electrons from Solar Flares and Associated Phenomena

Since the first observation of solar relativistic electrons on March 16, 1964 by satellite, twenty one events were reported as of the end of 1967 (Cline and McDonald, 1968) and are summarized in Table 1. In this table, parent solar flares, their positions, importance, and the radio bursts spectral type (I and IV) are indicated. Furthermore, 40 Kev-electron events which accompanied the same solar flares are shown. The signs S and C are a classification based on the analysis of Lin and Anderson (1967) and Lin (1970). It is certain that all but one of these solar flares produced both relativistic and 40 Kev electrons simultaneously. All these flares also produced solar cosmic rays of Mev and/or Bev energy.

It is well known that flares which produce solar cosmic rays are always associated with the emission of type IV radio bursts. As shown in Table 1, flares which produced relativisitc electrons with solar cosmic ray nuclei were all associated with the emission of type IV radio bursts. This result suggests that the relativistic electrons are at least partly responsible for the origin of the bursts. Here, the gyrosynchrotron emission process involves radiation by intermediate and relativisitic electrons spiralling in the sunspot magnetic fields in and near the flare sites (e.g., Takakura, 1960; Boischot and Denisse, 1957).

Frequency spectra of nine type IV radio bursts at peak flux were obtained for solar relativisitic electron events tabulated in Table 1, and are shown in Fig. 1. The characteristics of such spectra are very similar to those which were observed for type IV radio bursts associated with solar proton flares (e.g., Castelli et al., 1967, 1968; Sakurai, 1969, 1971b). This result follows from the fact that solar proton flares are all associated with the emission of type IV radio bursts.

It is known that the microwave component of type IV radio bursts is closely connected with the generation of solar cosmic rays (e.g., Kundu and Haddock, 1960; Sakurai and Maeda, 1961). It seems, therefore, that the high peak flux at microwave frequencies may be related to the acceleration efficiency of solar cosmic rays.

The emission of type IV radio bursts at microwave frequencies starts during the explosive phase of solar flares (e.g., Sakurai, 1964). This means that intermediate energy and relativistic electrons will be accelerated during this phase and will become the source for type IV radio bursts at microwave frequencies. It seems that such emissions are responsible for the formation of the peak flux spectra at microwave frequencies as shown in Fig. 1.

The formation of the peak flux spectra at metric frequencies is probably related to the radio sources moving outward from the flare sites (e.g., Wild, 1962). The formation of U-shaped peak flux spectra as shown in Fig. 1 seems to be due mainly to some cooperative action of both microwave and metric emissions of type IV radio bursts (e.g., Sakurai, 1971b).

3. Acceleration of Relativistic Electrons

As shown in Table 1, all but one of the solar flares which produced relativistic electrons took place in sunspot groups which were very active in the emission of type I noise storms. It is thought that energetic electrons of kinetic energy 1-100 Kev are responsible for the generation of type I noise storms (e.g., Takakura, 1963; Fokker, 1965; Trakhtengerts, 1966). Since solar flares which produce relativistic electrons take place in such sunspot groups as is evident from Table 1, the injection process of electron acceleration may be related to the presence of the ambient Kev electrons. If these electrons are accelerated to relativisitic energy in solar flares, we do not need to consider the acceleration of thermal electrons since we already have a supply of 1-100 Kev electrons. The acceleration of these relativistic electrons must, indeed, start with electrons of kinetic energy higher than ~1 Kev, although the value of this injection energy for electrons is dependent on the ambient hydrogen ion density in the accelerating regions (Sakurai, 1971b). In fact, Sakurai (1971b) estimates the order of such ambient ion density as 10^8 - 10^{10} cm^{-3}.

The region where the acceleration occurs must, therefore, be higher than that at which the Hα brightening is observed since such ion density in the latter region is much higher than that for the fromer region (e.g., de Jager, 1969; Svestka, 1966, 1969). Therefore, the region where the acceleration occurs is necessarily located high above the Hα flare region and may be just below or within type I noise sources as schematically shown in Fig. 2. The cross sign in this figure indicates the one of such regions where solar flares are triggered and relativisitc electrons are accelerated. The forgoing discussion inevitably requires that the Kev-energy electrons must be ambient in the region where the acceleration occurs. We suggest that such Kev electrons responsible for the generation of type I noise storms become the source electrons which are injected to be accelerated to relativisitic energy.

After injection into the accelerating regions, these Kev electrons will be mainly accelerated by the Fermi mechanism to higher energy during the explosive phase of solar flares (Sakurai. 1971b). Since it has been established that this mechanism mainly works to produce solar cosmic rays during this phase (e.g., Hayakawa et al. 1964; Sakurai, 1965a,b,1971c), we conclude that this mechanism is the most important process for the acceleration of high-energy particles in solar flares.

4. Emission of Energetic Electrons $\lesssim$ 40 Kev from Solar Flares

Solar flares which produced relativisitic electrons were all associated with the emission of energetic electrons $\gtrsim$ 40 Kev as summarized in Table 1. We here consider the origin of these electrons.

Such solar flares occurred in the sunspot groups which are active in the emission of type I noise storms. In fact, Kev-energy electrons are continuously accelerated and ambient in such type I noise active regions (e.g., Takakura, 1963). During the explosive phase of these flares, some of these Kev-energy electrons may be ejected from these active regions into interplanetary space without any efficient acceleration. These electrons seem to be observed as distinct electron events at the earth's orbit as reported by Lin and Anderson (1967). Distinct electron events are produced only in association with the ejection of Kev-energy electrons trapped in type I noise active regions at the time of the occurrence of solar flares.

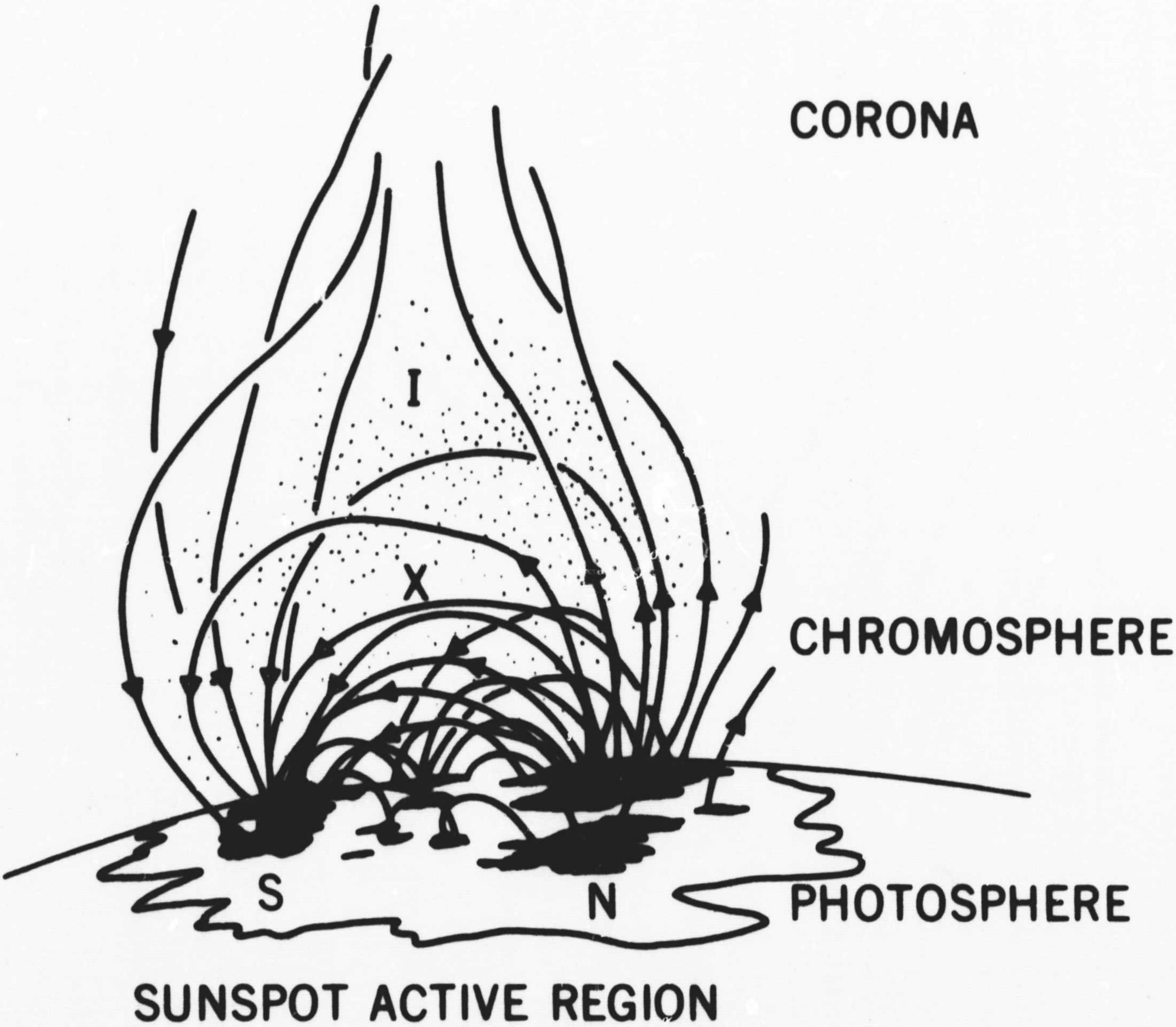
We, therefore, propose that the relativisitic electrons are produced through the two-step acceleration processes as discussed in this paper. The acceleration mechanism for the first step, to produce Kev-energy electrons in type I noise active regions, is not known as yet. But it is clear that some unstable modes associated with sunspot magnetic fields are responsible for this acceleration. The acceleration mechanism of relativisitic electrons has been recently identified as the Fermi mechanism (Sakurai, 1971b).

5. Concluding Remarks

In this paper, we have pointed out that all but one of the solar flares which produced relativistic electrons occurred in sunspot groups which were also active in the emission of type I noise storms. The acceleration of these relativisitic electrons appears to begin with Kev-energy electrons ambient in type I noise sources.

As has been considered (Sakurai, 1971d), distinct Kev-energy electron events are also produced from solar flares which occur in type I noise active regions. In fact, solar flares which produced relativisitic electrons were associated with such distinct electron events as described in Table 1.

These distinct Kev electron events are only produced from the escape of Kev-energy electrons generated in type I noise active region in association with solar flares without any efficient acceleration. We have proposed this two step



X: FLARE TRIGGERING POSITION (RELATIVISTIC ELECTRONS ARE ACCELERATED AROUND THIS POSITION)

I: TYPE I NOISE SOURCE REGION

Figure 2. The model of active regions which are accompanied by the occurrence of solar flares which produce relativistic electrons and Kev-energy distinct electron events at the earth. Type I noise active region is located high above the main sunspot groups.

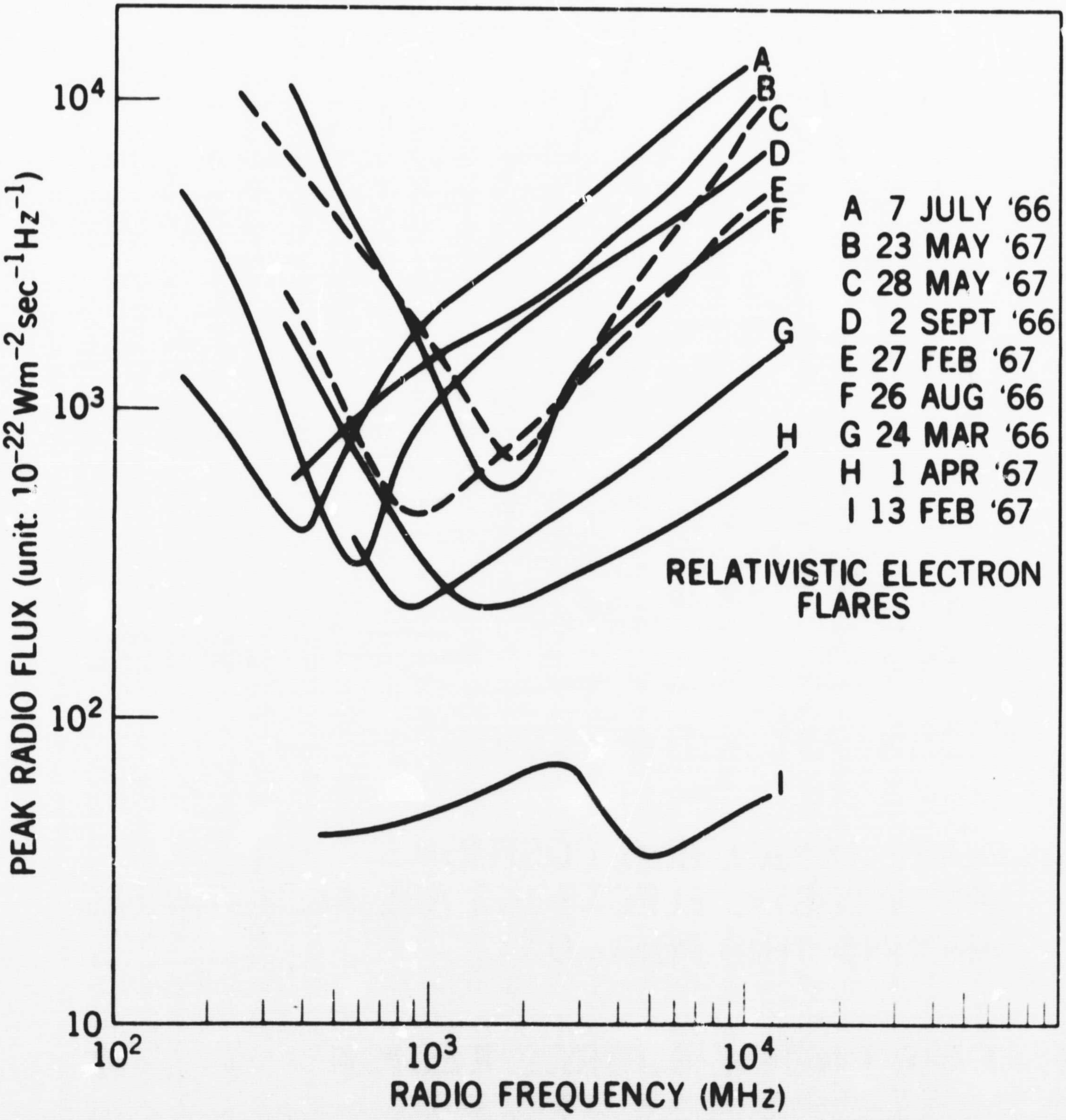


Figure 1. The frequency spectra of the peak flux of type IV radio bursts for nine solar flares.

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Table 1. Relativistic Electrons from Solar Flares (1964-1967)
($E_K > 2.7$ Mev)

Date	Flare Time (UT)	Imp.	Position	MacMath	Type I Activity	Associated 40 Kev Events (Type)	Radio Burst
1964							
March 16	1554	2	N05 W75	7182	Yes	S	IV(Small)
1965							
Feb. 5	1750	2B	N08 W25	7661	Yes	S	IV
Oct. 4	0935E	2	S20 W31	8012	Yes	?	IV
1966							
March 24	0225	3B	N18 W37	8207	Yes	C	IV
July 7	0023	2B	N34 W45	8362	(Weak)	S	IV
Aug. 28	1522	3F	N23 E04	8461	Yes	C	IV
Sept. 2	0542	3	N22 W58	8461	Yes	S	IV
Sept. 14	1014	1B	S21 W90	8484	(Weak)	S	(IV)
1967							
Jan. 28	<0238		Over Limb		Yes	C	?
Feb. 2	<2030		Over Limb		Yes	(C)	?
Feb. 13	1749	3	N21 W10	8687	Yes	(C)	IV
Feb. 27	1637	2B	N27 E02	8704	Yes	(C)	IV
March 11	<1933	No Flare Patrol	(N15 W80)	8714	Yes	C	?
April 1	1416	1B	N20 W79	8740	(Weak)	S	IV
May 28	0527	3B	N28 W33	8818	No Data	S	IV
June 6	1858 (June 5)	2B	S20 W58	(8831)	Yes	S	IV
July 5	<0810		Over Limb	(8878)	?	S	No data
Nov. 2	0855	1B	S18 W02	9047	Yes	C	IV
Dec. 3	<0928		Over Limb	9091	?	(S)	?
Dec. 16	0423	IF	S15 W80	9108	?		(IV)

References: Cline and McDonald (1968)
Lin and Anderson (1967)
Lin (1970)

acceleration processes for the generation of relativistic electrons. However, we need to study the continuous acceleration mechanism of Kev-energy electrons responsible for type I noise storms.