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与高能质子共生的两类太阳微波爆发

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摘　　要

在分析了近年来对太阳射电爆发与高能质子观测的基础上指出，既非 II 型也非米波 IV 型而是强微波爆发几乎总是同高能质子共生的；这一结果否定了以前长期所持的观点。同高能质子共生的微波爆发可分成两类：强脉冲型和强微波 IV 型，前者共生的被俘质子或相互作用质子要多于逃逸质子，后者则常共生有更多的逃逸质子。作者对每种情况中质子的有效加速过程进行了考虑，并对强微波爆发为何几乎总是有高能质子共生的缘由作了解释。

关 键 词　太阳：粒子辐射 — 太阳：耀斑 — 太阳：射电辐射 — 太阳：γ 射线

Two Classes of Solar Microwave Bursts Associated With Energetic Protons

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Abstract

Based on the data analysis of recent observations of solar radio bursts and energetic protons, it is shown in this paper that neither type Ⅱ nor meterwave type Ⅳ but intense microwave bursts are nearly always associated with energetic protons. This result is contrary to the previous long-held views. The microwave bursts associated with energetic protons may be devided into two classes: intense impulsive and type Ⅳ bursts. The former is associated with more trapped or interacting protons than the escaping ones, and the latter is often associated with more escaping protons. Furthermore, the authors considered the efficient acceleration pro-

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cess of protons in each case and explained why the intense microwave bursts are almost always associated with energetic protons.

Key words Sun: particle emission–Sun: flares–Sun: radio radiation–Sun: gamma rays

1 Introduction

It has been known for a long time that a proton flare in the radio range is characterized by the occurrence of metric type Ⅱ and type Ⅳ bursts. Only in the seventies, however, the correlation between type Ⅱ bursts and acceleration of protons was found[1]. Since then, the acceleration of protons by shock waves in type Ⅱ bursts has been believed to be the necessary condition for the occurrence of solar proton events. Recently Cane and Reames[2] pointed out that there are 11 of 45 events with detectable 7–12 MeV protons without associated type Ⅱ bursts, contrary to the long-held view mentioned above. They suggested that the meterwave type Ⅳ burst appears to indicate the existence of the required conditions for efficient acceleration process of solar energetic protons(SEPs).

In this paper, we try to make a further investigation on this problem. We start to enumerate some relevant results of data analysis in §2, then consider the related physical processes of particle acceleration in §3. Discussions and conclusions are in §4.

2 Data Consideration

2.1 Data analysis

Using the data published in SGD from April 1979 to October 1991, Zhou, Xu and Li[3] obtained statistical results about the association between the solar proton events (>10MeV) and radio bursts, which are listed in Table 1.

Table 1 Percentage of Proton Events Associated with Solar Radio Bursts

Type of Associated Radio Burst	No.of Associated Bursts	Percentage of Association
Ⅱ (meter-wave)	37	67.3%
Ⅳ (meter-wave)	47	85.5%
Intense microwave Ⅳ burst	55	100%

Cliver *et al.*[4] studied the solar flare gamma-rays and interplanetary proton events. In their paper, the Table 1 and Table 2 provided a total of 92 proton events with detectable 9–21 MeV protons for the period from 1980 February to 1985 January.

Comparing the related data in these two tables, one can find that the percentage of solar proton events associated with microwave (9 GHz) bursts and type Ⅱ bursts are 99% (91/92) and 72% (66/92), respectively.

Furthermore, in terms of the data analysis of solar radio bursts observed at Toyokawa Observatory (at 9.4,3.75,2.0 and 1.0 GHz) and Yunnan Observatory (at 4.26,2.84,2.13 and 1.42 GHz) and the proton events taken from NOAA SESC during the period 1976 to 1992, we concluded that nearly all long duration and intense multiplepeak microwave type Ⅳ bursts(32 bursts) are associated with energetic protons (>10MeV) in interplanetary space.

All the above statistical results demonstrated that neither type Ⅱ nor meterwave type Ⅳ but intense microwave bursts possess the required conditions for the production of solar energetic protons.

2.2 Two classes of microwave burst events associated with energetic protons

After detailed study of the microwave bursts and associated energetic protons, however, they may be divided into two classes with different properties, namely:

2.2.1 Microwave impulsive burst/γ-ray line (GRL)flare

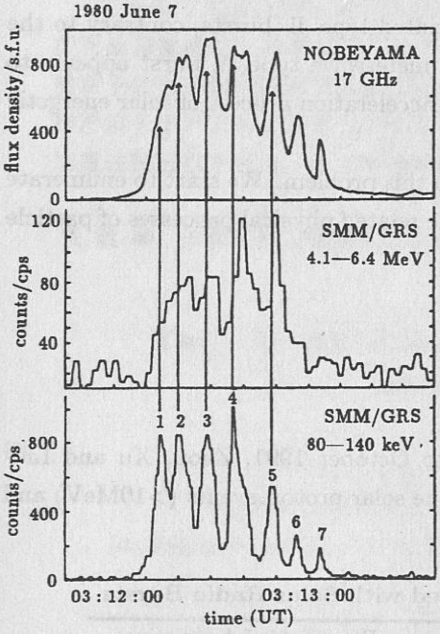

Fig.1 Time profiles of hard X–rays (80 to 140 keV), prompt gamma–ray lines (4.1 to 6.4 MeV) and microwaves (17 GHz) for the 1980 June 7 event (After Nakajinma *et al.*,[5])

The typical example is shown in Figure 1 for the 1980 June 7 flare [5]. The γ-rays appeared as quasi-periodic amplitude oscillations which closely correlated with the amplitude oscillations in both impulsive microwave and hard X-ray bursts. This implies that the gamma-ray producing protons and non-thermal electrons can be simultaneously accelerated to high, even relativistic energies within 1s in the same flaring loop. The accelerated protons are trapped in the flaring loops and injected from the coronal part to the chromospheric portions of the loops where the gas density ($10^{14} \cdot \mathrm{cm}^{-3}$) is much denser than that in the corona, where the interactions of the energetic protons with ambient gas occur and subsequently produce γ-ray emissions[6]. Bai[7] obtained the number of interacting energetic (> 30 MeV) protons and those protons escaping to interplanetary space for the 1980 June 7 event, whick are 9.3×10^{31} and 8.0×10^{29} respectively. Thus, the interacting protons are much more than the escaping ones in the impulsive flares. The peak-flux density of the impulsive microwave bursts for the 1980 June 7 event reached about 880 s. f. u. (solar flux unit). It is a rare intense flare. The other parameters are listed in Table 2.

2.2.2 Intense microwave type Ⅳ (type Ⅳ $_{\mu}$) burst

These bursts are characterized by distinct impulsive and delayed phases, hence they occur frequently as a long duration flare. Generally, the intense microwave type Ⅳ bursts are almost always associated with much more energetic protons escaping to interplanetary space than in the

Table 2 Related Data of Typical Intense Microwave

Bursts and Associated Energetic Protons

Event		Microwave Bursts					Particle Event			Associated Flares and Active Region			
	Date	f	Type	Start/End	Peak Time(UT)/	γ-ray flare	Start Time	Maximum	Proton Flux	Maximum	Importance	Location	Region
No.		/GHz		Time(UT)	Flux Density(s.f.u.)		(Date/UT)		(pfu@>10MeV)	(Date/UT)	(X-ray/opt)		(SESC)
1	1980 Jun 7	17	Impulsive	0312/0317.5	0312.5/953	Yes	-	Jun 7/(08±1)^b	(9–23)MeV2.7±0.3*	Jun 7/0314	M7/1B	N12W74	-
2	1989 Apr 19	9.4	IV_μ	0040/0132	0058/4900	-	Apr 11/0435	Apr 12/0125	00450	Apr 9/0105	X3/4B	N35E20	5441
3	1990 Mar 19	2.84	IV_μ	0430/0512	0452/3254	-	Mar 19/0705	Mar 19/2315	00950	Mar 19/0508	X1/2B	N31W43	5969
4	1991 Jun 15	5.2	IV_μ	0810/0945	0835/40000	Yes(GLE)	Jun 14/2340	Jun 15/1950	01400	Jun 15/0821	X12/3B	N33W69	6659

* Taken from Table 1 in the paper by Cliver et al.[4]

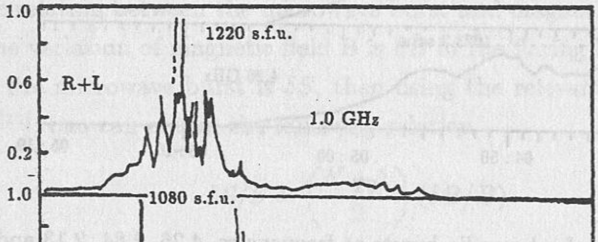

Fig.2 Time profiles of solar radio bursts at frequencies 9.4, 3.75, 2.0 and 1.0 GHz at Toyokawa Observatory for the 1989 April 9 event (After Enome and Shihasaki, 1990)[8].

case of impulsive microwave bursts, as long as their peak flux densities reach ≥ 500 s.f.u.. These conditions often take place whether they are associated with γ-ray flares or not. We selected some typical examples as follows:

(1) The 1989 April 9 event was observed at four frequencies 9.4, 3.75, 2 .0 and 1.0 GHz at Toyokawa Observatory (After Enome and Shibasaki, 1990) (cf. Figure 2)[8].

(2) The 1990 March 19 event was observed at 4.26, 2.84, 2.13 and 1.42 GHz at Yunnan Observatory (cf. Figure 3)[9].

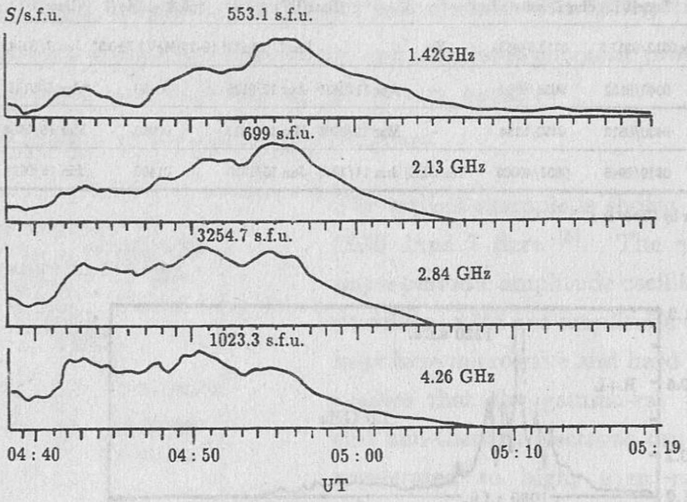

Fig.3 Time profiles of solar radio bursts at frequencies, 4.26, 2.84, 2.13 and 1.42 GHz at Yunnan Observatory for the 1990 March 19 event[9]

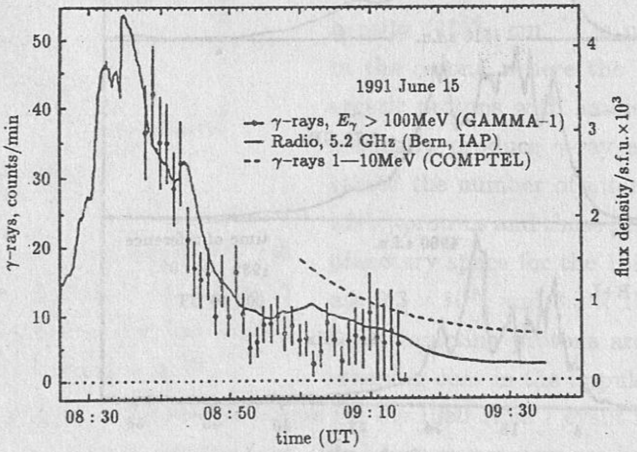

Fig.4 Enlarged gamma–ray and microwave (5.2 GHz) time profiles of the delayed component for the 1991 June 15 event (After Akimov *et al.*).[10]

(3) The 1991 June 15 event was observed in the range of optical, radio and gamma-ray emissions. It is obviously associated with a strong proton event and also a ground level enhancemant

(GLE). One can see from Figure 4 that the enlarged gamma-ray ($E_\gamma > 100$ MeV) and microwave (5.2 GHz) time profiles are similar to each other in the delayed phase for this event[10] (cf. Figure 4).

The related parameters of the above-mentioned three events are taken from NOAA SESC and listed in Table 2.

3 Physical Processes of Particle Acceleration

It is now quite certain that a significant fraction of the total energy of a solar flare appears in the form of accelerated particles. This energy is most probably stored in magnetic fields and is released by rapid reconnection of magnetic field lines. The microwave emission is the most compelling radio evidence for the presence of energetic, even relativistic electrons in flares. The intense microwave burst is generally believed to be generated by the relativistic electrons interacting with the magnetic fields in the flaring loop through the synchrotron emission process. Thus to understand the relation between the microwave burst and magnetic field is very important.

Supposing the variation of magnetic field B is δB in the flaring loop, and the fluctuation of flux density S of the microwave burst is δS, then using the relevant expression of synchrotron emission by Dulk[11], one can obtain the following relation

$$\delta S/S \approx \left(\frac{\delta' + 1}{2}\right)(\delta B/B) \tag{1}$$

if the optical thickness $\tau_f \ll 1$[12], during the impulsive phase of a solar flare, where δ' represents the electron energy spectral index for a power law distribution.

From equation (1), a variation $\delta B(t)$ happened in the magnetic field $B(t)$ of flaring loop should cause a corresponding variation $\delta S(t)$ in the flux density $S(t)$ of the microwave burst. According to Faraday's law, a time-varying magnetic field in the flaring loop will readily set up a fluctuating electric field so as to accelerate the particles (electrons and protons) to high, even relativistic energies.

Recent studies show (Melrose[13], Ramaty *et al*[16].) that stochastic acceleration by MHD turbulence seems capable of accounting for the prompt acceleration of ions and relativistic electrons in solar flares . The MHD turbulence includes fast-mode magnetosonic and Alfvén waves; the diffusive shock acceleration by an ensemble of weak shocks may be also treated as a form of stochastic acceleration. Probably, the microwave impulsive burst/GRL flare for the 1980 June 7 event and the microwave type IV burst associated with interplanetary energetic protons (>10 MeV) for the 1989 April 9 flare could be explained by the stochastic accelaration processes due to fast-mode magnetosonic waves, while the proton event associated with the 1990 March 19 flare could be due to gyroresonant acceleration process by Alfvén waves[12].

The Faraday's law can be also described as follows: a time varying magnetic field gives rise to electric currents in a conducting medium that encircles the field. The plane in which this curent flows is perpendicular to the direction of the time-varying field component. In integral form Faraday's law is expressed as

$$\frac{1}{c}\frac{\partial}{\partial t}\int B\cdot \mathrm{d}s=-\oint E\cdot \mathrm{d}l, \tag{2}$$

where the integral on the left is a surface integral over the area enclosed by the loop through which the current is flowing. The integral on the right is a line integral taken over that loop and the current observed by Faraday has been replaced by the induced electric field. We note now that, if any region of solar atmosphere space should suddenly be subjected to a rising magnetic field, electric charges would experience an effective electrical field E proprttional to the time rate of change of B. This process might be active in the solar atmosphere accelerating charged particles to the very high, even relativistic energies.

By means of a comparison of the gamma-ray emission with microwave bursts and other associated phenomena, one can find that the radio time profile at 5.2 GHz for the 1991 June 15 flare provides evidence for additional energy release taking place just at the time of the delayed gamma-ray component. This means that during the post-impulsive phase of the flares the magnetic field above the active region is strongly disturbed by a coronal mass ejection (CME), and relaxes to its initial state through magnetic reconnection in the coronal vertical current sheet. This process results in particle accelection, and protons can be accelerated up to 20 GeV.

The delayed phase (post-impulsive phase) acceleration may also occur when the preflare magnetic structures are disturbed by a large loop prominence, or rapidly expanding and evolving coronal loops.

4 Discussions and Conclusions

As our investigation stated above, in recent years a lot of major advances have been made in the understanding of the relationship between solar flares and associated protons and in distinguishing the sources and acceleration mechanism for SEP associated with solar radio bursts of various types. This association has led to a significant revision of our knowledge of the origin of energetic particles and their escaping out into the interplanetary space.

We should, however, carry on some disscussions and draw some conclusions.

(1) We have demonstrated by statistical analysis of recent observations that neither Type Ⅱ nor meter-wave Type Ⅳ but intense microwave bursts(including intense impulsive microwave bursts and intenes microwave type Ⅳ bursts)possess the required conditions for the production of solar energetic, even relativistic protons.

The reason appears to be related to the radio source site and its environment. Generally, the microwave burst source is located in the lower corona than the type Ⅱ or meter-wave type Ⅳ burst. At the microwave burst site the magnetic field strength B ranges from 100 to 1000 G, the ambient electron density from 10^9 to $10^{11}\mathrm{cm}^{-3}$ and the height from a few 10^3 to some 10^4 km. Hence there exist enough particles to be accelerated and enough magnetic energy stored to be released by rapid magnetic reconnection. Moreover, there are also numerous chances favorable to occurrence of interactions of loops, such as coalescence or collision of two current loops[14,15]. Such interaction processes can result in an increase in the magnetic reconnection and accelerate the particles to high, even relativistic energies through stochastic acceleration by MHD turbulence. For instance, the large amplitude magnetosonic waves (such as shock waves) can promptly accelerate the resonant protons to relativistic energies (> 1 GeV)[16]. Particularly, the source of microwave type Ⅳ burst with delayed phase acceleration is located nearer to the dense chromosphere; hence it provides the required distance, unable to be damped rapidly, for the energetic protons injected into the dense chromosphere and producing GRL emissions through collisions with the heavier nuclei. These reasons may be used to explain why the intense microwave bursts are nearly always associated with energetic protons.

(2) Intense impulsive microwave bursts are characterized by having more intense magnetic field strength, shorter duration and denser particle number density than the microwave type Ⅳ bursts. The plasma beta is $8\pi NkT/B^2 \ll 1$ in the radio sources, and produces much more trapped or interacting energetic proton (GRL flare producing protons) than the escaping interplanetary protons.

As for intense microwave type Ⅳ bursts, they always have to experience the impulsive and delayed phase acceleration. During the evolution period the plasma beta becomes ≥ 1, and the magnetic field can be opened to provide for the energetic protons an access to interplanetary space. This leads to the fact that intense microwave type Ⅳ bursts are nearly always associated with more escaping interplanetary protons.

(3) All stated above have demonstrated that intense microwave bursts can be considered as a good electromagnetic signature of particle acceleration and a good indicator of proton producing solar flares.

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