What We Know And Do Not Know About High Energy Neutral Emissions From Solar Flares (A Challenge For Future Missions)

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Abstract

Satellite missions since 1980 have observed at least 40 flares for which there is direct observational evidence for photon and neutron emissions with energies above 10 MeV, the latter sometimes also detected at ground level. In this presentation we will focus on a class of events for which these "High Energy Neutral Emissions" show successive phases: an impulsive phase ($\sim$ one minute) with strong nuclear lines and often meson production (signature of $>$ 300 MeV/nucleon ions) followed by an extended phase (a few minutes up to several hours) with emission $>$ 10 MeV dominated by meson and neutron production. In addition, relativistic electron bremsstrahlung is observed during both phases. The time evolution of the spectral characteristics of the High Energy Neutral Emissions suggests that both phases correspond to different acceleration/transport processes. However the lack of imaging data at photon energies in the 10-100 MeV range, and of spectral data above 100 MeV, prevents us from determining the location of the acceleration/interaction region(s), and the upper-energy cutoff of the accelerated particles, and therefore the mechanisms involved. We will propose a realistic experimental method to eliminate this deficiency.

1. Introduction

In order to determine the basic mechanism(s) for flare-associated particle acceleration we must know: the composition of the accelerated particles, the complete energy spectra of particles, the acceleration and interaction sites, and the relationship of particle acceleration to other manifestations of solar activity. It is thus of vital importance that these observations be made with instruments which have adequate spectral and imaging capability so results can be compared with observations at other wavelengths, such as H_α, soft x-rays, EUV, and radio emission from sub-millimeter to meter waves.

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Table 1. Solar flares with significant π^0 or neutron production.

Flare Start (UT)	Class	Position (Θ_{HC})	Impulsive Duration	Lines	Extended Duration[1] Δ, D	>10 MeV π^0, n	CME	GLE
6/21/1980 (01:18:20)	X2.6 1B	W90N20 (89°)	<80 s >25 MeV	Nuclear 0.51 MeV 2.223 MeV		>10 MeV π^0(?),n		Yes
6/3/1982 (11:42:44)	X8.0 2B	E72S09 (72°)	< 100 s	Nuclear 0.51 MeV 2.223 MeV	$\Delta \sim 1$ min $D > 20$ min	>10 MeV π^0, n	Yes	Yes
4/24/1984 (23:59:42)	X13 3B	E45S11 (45°)	~ 100 s	Nuclear 0.51 MeV 2.223 MeV	$\Delta \sim 1$ min $D \geq 20$ min	>10 MeV π^0(?) n (?)		Yes
12/16/1988 (08:28:50)	X4.7 2B	E33N27 (43°)	~ 100 s double burst	Nuclear 0.51 MeV 2.223 MeV	$\Delta \sim 2$ min $D \geq 12$ min	>10 MeV π^0, n		
3/6/1989 (14:04:51)	X15 3B	E71N33 (76°)	complex	Nuclear 0.51 MeV 2.223 MeV		>10 MeV π^0, n		
9/29/1989 (~11:20)	X9.8 1B	Behind W limb		Nuclear 2.223 MeV	$D > 25$ min	n	Yes	
10/19/1989 (<12:56)	X13 4B	E09S25 (~26°)	~ 100 s	Nuclear 2.223 MeV	$\Delta \sim 1$ min $D > 25$ min	n	Likely	
5/24/1990 (20:46)	X9.3 1B	W78N33 (~ 80°)	~ 60 s	2.223 MeV	$\Delta \sim 1$ min $D > 8$ min	>10 MeV n	Moreton wave	Yes
3/22/1991 (22:41)	X9.4 3B	E28S26 (~37°)	10-15 s 10-22 MeV	2.223 MeV		n	Moreton wave	Yes
3/26/1991 (20:24)	X4.7 4B	W23S68 (~70°)			$\Delta \sim 8$ min $D > 10$ min	π^0	Yes	
6/11/1991 (01:56)	X12.0 3B	W17N31 (~ 35°)	~ 100 s 30-100 MeV	2.223 MeV	$\Delta \sim 3$ min $D > 8$ hrs	>10 MeV π^0, n		Yes
6/15/1991 (08:10)	X12 3B	W69N33 (~ 72°)		Nuclear 2.223 MeV	$D > 60$ min	π^0	Yes (?)	

[1] Δ is the delay between the impulsive phase and the beginning of the extended duration, D.

Table I shows twelve events which have a similar time behavior that is broadly characterized by: an impulsive phase lasting on the time scale of at most a few minutes and, a time extended phase lasting for tens of minutes to hours. Dunphy and Chupp [5] have argued that this may be a common feature of flares with significant production of pions and neutrons.

Our goal in this paper is to summarize what we can conclude about the accelerator from existing observations of this particular class of events and to emphasize what new observations are needed to advance our understanding of relativistic ion and electron acceleration.

2. The 1991 June 11 flare

The best example typical of the events listed in Table I is the 1991 June 11 flare which occurred in NOAA active region 6659, commencing at $\sim$ 01:56 UT in Hα. CGRO observations were made by: the EGRET spark chamber which observed meson-decay γ-rays and electron bremsstrahlung to > a GeV [8]; the EGRET/TASC which observed high energy neutrons [6]; the COMPTEL spectrometer which observed 2.223 MeV line emission for $\sim$ 5 hours [13,14,17]; and the OSSE spectrometer which observed several γ-ray lines and continuum to > 16 MeV as well as neutrons [10]. In addition the PHEBUS spectrometer on GRANAT observed γ-ray lines and continuum to 8–10 MeV during the first 10 minutes of the event (impulsive phase), but emission above 10 MeV was below the sensitivity of PHEBUS [15].

The EGRET and EGRET/TASC observations show that the first impulsive emissions included intense "prompt" nuclear lines and the extended emissions included strong, long-lasting (8 hrs) meson-decay γ-rays, especially from π^0 decay, indicating a strong interacting flux of protons with energies > 300 MeV. Gamma-rays extending in energy to ~ 2 GeV were also observed during the extended emission phase, probably from ultra-relativistic electron bremsstrahlung. Furthermore, It was shown by Dunphy et al. [6] that the EGRET/TASC data during the extended emission was also consistent with the presence of a flux of high-energy neutrons near the Earth.

The data from this event were first interpreted in terms of either long-term trapping of particles in non-turbulent coronal loops [9], or continuous acceleration [e.g., 13, 14]. Mandzhavidze et al. [9] proposed a scenario which is broadly consistent with the γ-ray observations of both the impulsive and extended phases. In their model, they consider that at least three episodes of acceleration and subsequent trapping in coronal loops occurred. Each episode corresponds to γ-ray emissions with different characteristics reflecting that the spectrum of interacting ions is significantly harder during the extended phase than during the impulsive phase and that this spectrum softens again in the second part of the extended phase. This indicates that different episodes of acceleration correspond to different acceleration/transport processes. Other high-energy events for which radio imaging data are available also show that larger coronal regions are involved as the flare, starting in a small active region, evolves in time with intense higher energy emissions occuring later (See Chupp et al. [2] and Trottet et al. [16]). This suggests that, during the impulsive phase, particle acceleration and interactions could take place within small scale loops (e.g., active region loops), whereas, subsequent acceleration of the highest energy particles occurs in much larger loops or loop systems. This is in line with a study of the composition of the accelerated and interacting particles of the 1991 June 4 flare from the active region NOAA-6659 [11] that indicates that the acceleration/interaction region moves to higher coronal regions as the flare evolves in time.

Finally, concerning the acceleration mechanism(s) for the ions and electrons, the full range of experimental data possible is needed to determine the viable mechanism(s). It is clear that a future flare mission requires high cadence multi-wavelength spectral and imaging observations. If sufficient data is obtained on the type of event we have described, then simulations and modeling could be done to compare with observations. Also, there must be an instrument which will give source locations and the detailed spectra of γ-ray and neutron emissions throughout the event.

3. Imaging of High Energy Neutral Emissions for Future Flare Missions

The imaging of solar flares at x-ray energies by the YOKHOH, SXT and HXT, and anticipated by HESSI, has greatly advanced our knowledge of the geometry, acceleration and interaction regions for solar flare electrons (e.g., Gallagher [7]). Thus, it is clear that, to advance our understanding of the highest energy flare processes, imaging of the relevant emissions to arc-second accuracy is a requirement for a future high energy flare mission.

This goal can be achieved by use of a track chamber with mm spatial resolution for interactions of γ-rays and neutrons with energies above 10 MeV, extending to several hundred MeV. The track chamber should be coupled to a coded aperture mask, which will give a source location accuracy of *arc-seconds*. Such a scheme has been described by Chupp et al. [3], using a liquid xenon time projection chamber [1] for the track chamber, coupled with a suitable coded aperture at least two meters distant from the imager, giving a coded field of view of radius $2R_\odot$, centered on the sun.

4. References

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