INTERPLANETARY PARTICLE OBSERVATIONS ASSOCIATED WITH SOLAR FLARE GAMMA-RAY LINE EMISSION

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ABSTRACT

Until recently, models for solar flare particle acceleration have assumed that there are two phases of acceleration, with acceleration of 10-100 keV electrons occurring in the first phase and acceleration of nucleons and higher energy electrons in the second phase. Nuclear gamma-ray lines, observed in only a few flares, were presumed to be produced by nucleons accelerated in the secondary phase. Recent observations from the Solar Maximum Mission spacecraft, however, show for the June 7, 1980 event that these gamma-rays are associated with the primary phase. The June 7, 1980 event and also an event on July 1, 1980 occurred within the so-called "preferred connection" heliolongitude range from 20°W-80°W. Flares occurring in this range have been considered to be well-connected magnetically to observers at 1 A.U. In the two instances cited here, however, relatively few nucleons were observed. We have evaluated the total number of energetic particles which must have interacted at the sun to produce the observed gamma-rays for the June 7 event and thus the expected intensity at 1 AU assuming good connection. The observed intensity is $\sim 10^2$ times less. It is concluded that only a small fraction, if any, of the primary phase accelerated nucleons escaped into interplanetary space.

1. Introduction

Until recently, models for solar flare particle acceleration have assumed that particle acceleration occurs in two separate phases. In the first phase, 10-100 keV electrons are accelerated, leading to impulsive hard X-ray and microwave bursts. Only a small fraction of these electrons escape from the sun to interplanetary space. It has been assumed, as was indicated by the work of Canfield and Cook (1978), that the primary phase accelerated mostly electrons. The primary phase also causes a shock-wave to move outward through the corona, giving rise to Type II and Type IV radio emission. Second phase acceleration presumably results from interaction between the shock and the ambient coronal medium. Nuclear gamma-ray lines, observed in only a few flares, were presumed to be produced by nucleons accelerated in the secondary phase. Solar gamma-ray lines were first observed for an event on August 4, 1972 (Chupp, et al. (1973)). This event was accompanied by very high intensities of low energy nucleons in interplanetary space. Estimates of the number of interplanetary nucleons exceeded the number required to produce the observed gamma-rays by factors of at least 3-6 (Ramaty and Lingenfelter, 1975).

Recent observations from the Solar Maximum Mission spacecraft, however, show for the June 7, 1980 event that 4-8 MeV gamma-rays were

emitted within seconds of the impulsive hard X-ray burst and with rather similar time structure (Forrest, et al., 1981). The peak flux of the 4.4 MeV gamma-ray line was ~ $(2.7 \pm 1.3) \times 10^{-2}$ photons/cm^2/sec and the event lasted for ~ 40 seconds. The August 4, 1972 event had a similar peak flux but lasted longer, ~ 1000 seconds. Ramaty, Kozlovsky and Suri (1977) have shown that gamma-rays in the 4-8 MeV interval are produced almost entirely as the result of nucleonic interactions. Hence the SMM results establish that large numbers of nucleons were accelerated in the primary phase of the June 7, 1980 event.

In what follows we will present observations of interplanetary particle intensities for three solar flares for which 2.22 MeV gamma-ray line emission was observed by SMM. For the June 7, 1980 event the number of nucleons necessary to produce the observed 4.4 MeV photons is estimated and, in turn, the flux of particles which might be expected at 1 AU is estimated assuming good magnetic connection to the source region. The actual observed fluxes are ~ 10^2 times less. Assuming that there was reasonably good magnetic connection between the earth and the sun in interplanetary space, it must be concluded that few, if any, of the nucleons accelerated in the primary phase were able to escape into interplanetary space.

2. Observations

Table I summarizes the salient characteristics of four recent flares known to have produced 2.22 MeV gamma-ray line emission. This line is produced by neutron capture on hydrogen. The neutrons in turn were produced by nucleons accelerated in the flare. This is the most intense of the nuclear gamma-ray lines which are observed in solar flares. Of these four flares, the second and fourth were within the so-called "preferred connection" heliolongitude range from 20°W to 80°W. Flares occurring in this range have been considered to be well-connected magnetically to observers near earth (Van Hollebeke, et al., 1975). The June 7 event is the only event in Table I for which the observed 4.44 MeV gamma-ray line flux has been reported (Forrest et al., 1981) and is therefore the event on which we will concentrate.

The upper half of Figure 1 shows intensity time histories for 6.4-12 MeV and 19-27 MeV protons obtained from ISEE-3 (~ 240 Re upstream from the earth). The time period covers the last three events in Table I. The lower half of Figure 1 shows corresponding intensity time histories for 6-12 MeV/n and 20-30 MeV/n protons plus helium as derived approximately from rate counters on Helios-I. Figure 2 shows the locations of Helios-I (numbered stars) for each of the events. Figure 2 also shows nominal Archimedean spiral field lines corresponding to a solar wind speed of 400 km/second and the longitudes of the three parent flares. For the June 7 event, ISEE-3 and HELIOS-I were about equally close to the nominal field line. ISEE-3, however, must have been better connected because the intensities at ISEE-3 were approximately double those at HELIOS-I despite the fact that HELIOS-I was considerably closer to the sun. The interplanetary field was steady at approximately the nominal Parker spiral angle at ISEE-3 throughout June 7. Substantially fewer particles were seen at ISEE-3 for the July 1 event.

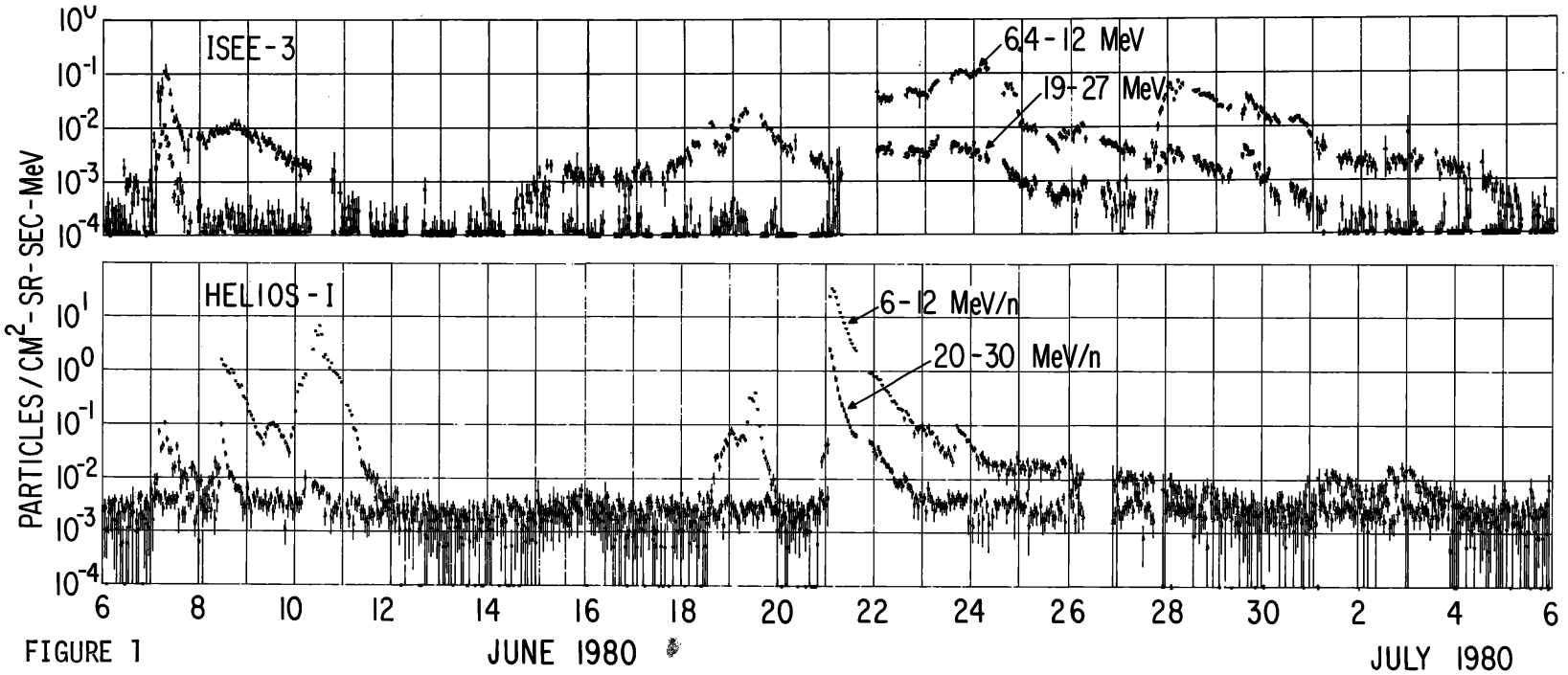

FIGURE 1

TABLE I: FLARES WITH 2.22 MeV γ-RAY LINE EMISSION

START DAY	Hα START U.T.	LOC.	IMP.	HARD X-RAYS*	MICROWAVES†	METRIC II INT.	METRIC IV INT.
Nov. 9, 1979	03:04	S13, E06	1B	--	4579	3	WEAK
June 7, 1980	03:09	N14, W70	SB	39,400	530	3	3
June 21, 1980	01:17	N20, W90	1B	141,000	~ 1370	2	WEAK
July 1, 1980	16:21	S12, W38	1B	27,200	1400	3	2

* Peak Counts/Sec, 26- ~ 380 keV, FROST, SMM

† 8800 MHz, 1 SFU = 10^{-22} W/m² - Hz

3. Discussion

To obtain a crude estimate of the number of particles N(E)dE, released at the sun from the intensity $dJ/dE^{(E,t)}$ observed at r = 1 A.U., we will begin with a simple isotropic diffusion model with impulsive injection at t=0:

$$N(E) = \frac{2\pi r^3}{3t_m}\int\left(\frac{4\pi \frac{dj}{dE}}{v}\right) dt = \frac{2\pi r^2}{3} \frac{(r/v)}{t_m} \int 4\pi \frac{dj}{dE}\, dt \qquad (1)$$

$(r/v)/t_m$ is the ratio of the time for straight line propagation for particles with velocity v to reach earth as compared to the time of maximum intensity for such particles at earth. This ratio was ~ 5 at 10 MeV/n. The peak intensity spectrum observed at ISEE-3 for the June 7 event was $\propto E^{-2.8}$. Incorporating this energy dependence and integrating $\int_{10}^{\infty} N(E)E\, dE$ we obtain the result that the observed intensities at earth correspond to overall release of ~ 4×10^{26} ergs in energy for particles > 10 MeV at the Sun. If we presume that particles were not actually emitted isotropically, this number could in fact be reduced, perhaps by a factor of 10 or more. Production of the 4.44 MeV gamma-ray line is increasingly inefficient below ~ 10 MeV; above 10 MeV the required energy/photon is ~ 8 ergs/photon. Thus the observed 4.44 MeV gamma-ray line intensity requires ~ $3 \times 10^{-2} \times 4\pi(1.5 \times 10^{13})^2 \times 40$ sec $\times 8 \sim 3 \times 10^{28}$ ergs, or two orders of magnitude more than the previously calculated upper limit to that available from the particles observed in space. Although questions regarding interplanetary connection remain, it appears that at most a small fraction of the primary phase accelerated nucleons escaped into interplanetary space.

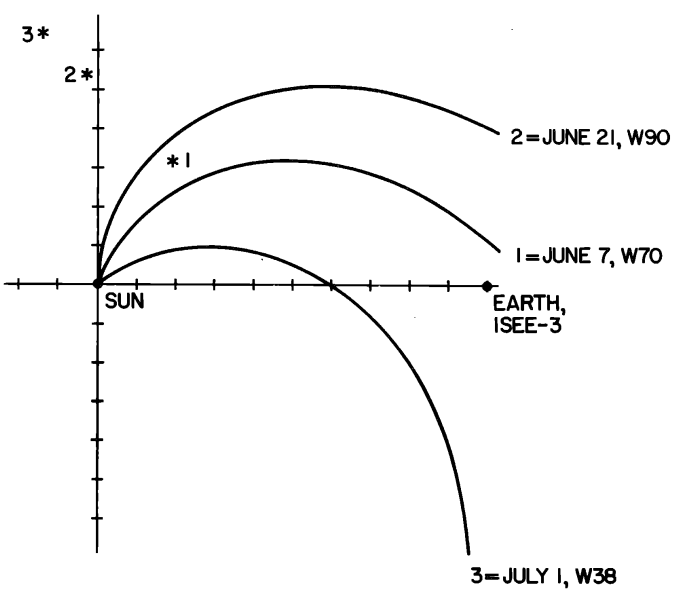

Figure 2

References

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