FURTHER OBSERVATIONS OF PROTONS RESULTING FROM THE DECAY OF NEUTRONS EJECTED BY SOLAR FLARES*

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ABSTRACT. The solar flare of 1984 April 24 produced a large γ-ray fluence with energy >2MeV. The time profile of the interplanetary proton flux from this flare indicates the presence of decaying solar neutrons. This makes a total of three neutron flares so far observed by this method. The three flares are used to place constraints on the fluence and spectra of neutrons emitted by the sun.

1. INTRODUCTION. Neutrons emitted from the sun by large solar flares have been observed by two methods; direct detection as the neutrons pass the earth[1-3], and detection of protons which result from the decay of the neutrons[4,5]. The first unambiguous identification of decay protons was made during the 1982 June 3 event[4]. More recently, on 1984 April 24 at 2354 UT, another solar event occurred showing a similar behaviour that fully confirms the earlier interpretation. This flare was located on the sun at S12 E43 and had the largest gamma ray fluence (>2MeV) thus far detected by ISEE-3. A third neutron flare occurred on 1980 June 21[5].

In this paper, we use the decay proton method to interpret data collected from the University of Chicago experiment onboard the ISEE-3 spacecraft. The energy of the decay protons is essentially the same as that of the parent neutrons. Thus, we can obtain precise neutron energy spectra near 1 AU in the range 25-138 MeV. These results yield information on the propagation of charged particles in the inner heliosphere as well as the fluence and spectrum of emitted neutrons.

2. MEASUREMENTS. The signature of neutron production is a flux enhancement prior to the expected arrival of the flare protons. Neutrons travel in straight lines from the flare site, hence their travel time is simply distance divided by velocity. Protons are influenced by the solar and interplanetary magnetic field. On a scale large compared with the proton gyro radius, their motion appears diffusive resulting in significant travel time delays. In flares which are poorly connected magnetically to the spacecraft these delays can be on the order of several hours. This is evident for the flares of 1984 April 24 (located at E55 relative to ISEE-3) and 1982 June 3 (located at E72). The measured proton rates from 25.7-47.5 MeV for these two flares are in figures 1 and 2. In both flares we observe a large initial gamma ray burst followed by a rise in the proton flux approximately 20-30 minutes later - the expected delay

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for the arrival of neutrons. The initial rise in the proton flux is rapid, corresponding to the time when the expanding shell of neutrons passes the instrument. This is followed by a slow decline in flux as the decay protons diffuse away. Protons produced directly by the flare cause the flux to rise again about 4 hours after the initial gamma ray burst in the 1984 flare, 16 hours in the 1982 flare, and only 1 hour in the neutron flare of 1980 June 21 (not shown here). The solid line in these two figures is a result of modeling proton propagation in the inner heliosphere using a mean free path of 0.3 AU and an isotropic emission of neutrons.

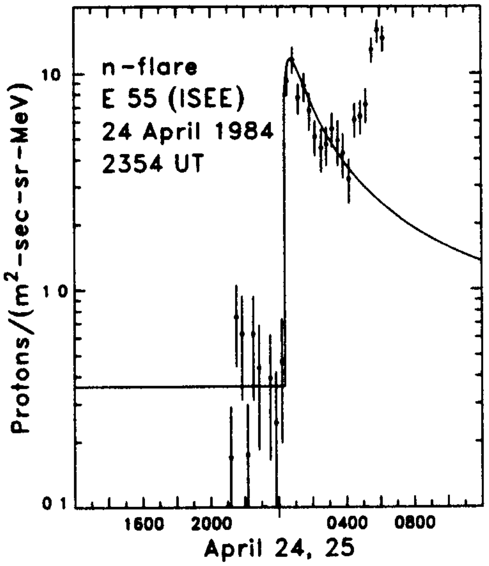

Figure 1

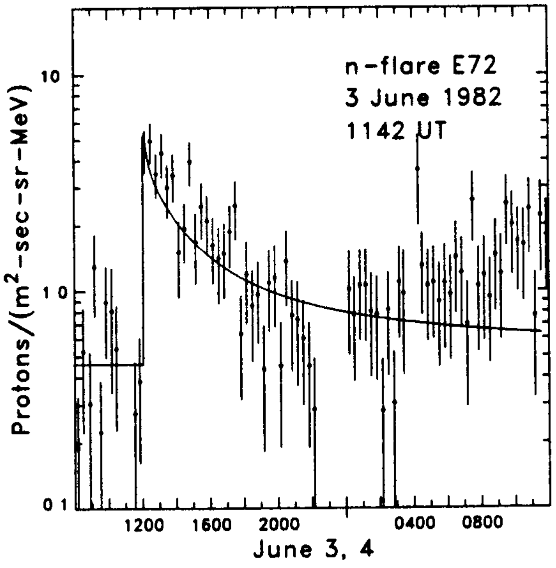

Figure 2

The intensity at the onset of the decay proton flux depends only on the number of neutrons emitted in the direction of the spacecraft. This flux is determined by decay protons which were produced in the vicinity of the spacecraft. In figure 3 we show the spectrum of decay protons collected from 30 to 90 minutes after the initial gamma ray burst. During this time the flux of decay protons is expected to vary by less than about 30% from its initial value. Most of the protons have undergone several scatterings and are nearly isotropic in their pitch angle distribution.

3. <u>DISCUSSION</u>. We consider two models which both are able to describe the profile of the decay proton fluxes. In one model, the neutrons are emitted from the sun isotropically in all directions . The sun blocks all downward moving neutrons. The remaining neutrons form an expanding hemispherical shell. In the other model, the neutrons are all emitted in the plane parallel to the local horizon at the flare site, half of which escape the sun. The models are referred to as the isotropic and the pancake model. For both models, we assume that the neutrons are produced impulsively at the time of the gamma ray burst. As they move outward they decay to form energetic protons in the inner heliosphere. We assume

that these protons rapidly become isotropic in pitch angle. Propagation is treated using a spherically symmetric diffusion model with negligible cross field diffusion.

The rate of decline in the decay proton flux depends primarily on the scattering mean free path for protons along the direction of the solar magnetic field. We find that the same mean free path fits our data in both models and that it is impossible to distinguish between them on the basis of our measurements alone. Described physically, the number of neutrons moving outward falls exponentially with distance from the sun. In both models, the density of decay protons is greatest at the inner most exposed portion of the magnetic field line connected to the spacecraft.

For both models we calculate the number of neutrons required to fit our measured fluxes. These results are shown in figures 4 and 5 for the isotropic and pancake emission models respectively. We indicate the spectral index of the power law that best fits the data in both figures. The calculated neutron fluence differs by a factor of 2.3 depending on which of the two models is used.

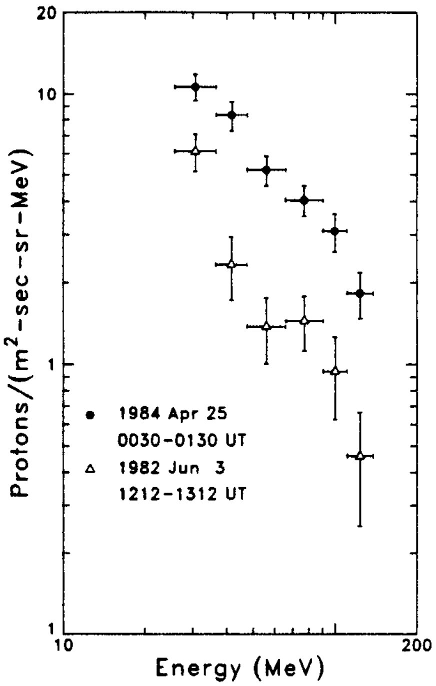

Figure 3

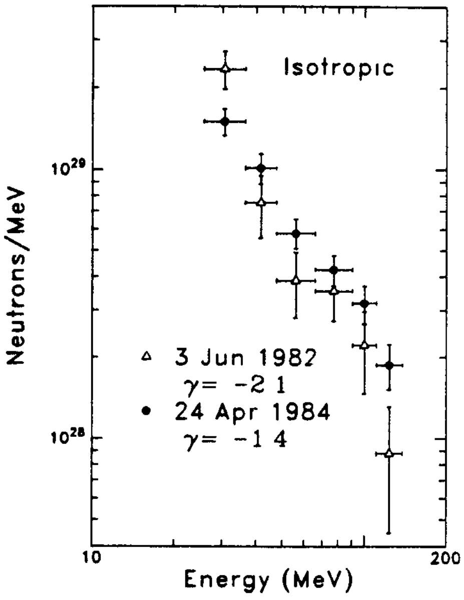

Figure 4

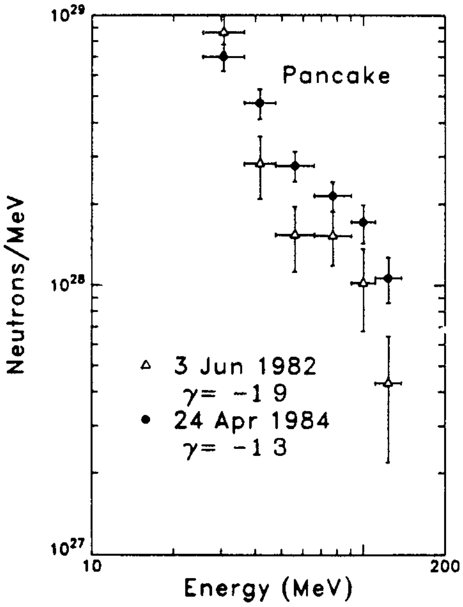

Figure 5

Figure 6 relates the neutron fluence (25.7-47.5 MeV) to the gamma ray fluence (E >2MeV). We have not observed neutron emission from small gamma ray flares. Results from all large gamma ray flares are included in this figure except for one when the proton background was very high due to a previous flare. The 1983 flare occurred at 2217 UT on May 7.

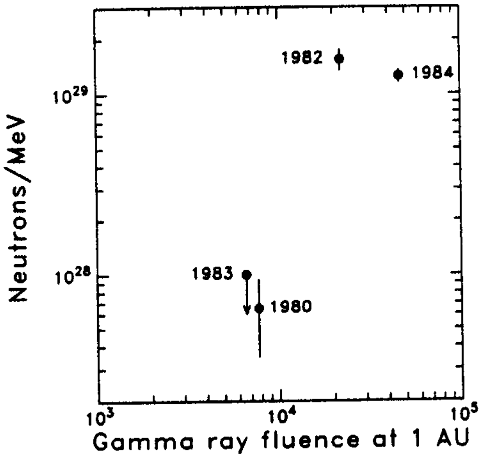

Figure 6

4. CONCLUSION. All three neutron flares have similar neutron emission spectra. Neutrons, along with γ-rays, result from a primary population of particles accelerated in the flare which most likely interact in the solar corona[7]. Since the neutrons result mostly from higher energy particles than the γ-rays, the correlation in figure 6 is related to the shape of the primary particle spectrum. Our results suggest that the shape of this spectrum is relatively invariant in the three flares though possibly somewhat harder in the larger flares.

The scattering mean free path of protons in the inner heliosphere does not depend strongly on the isotropy of the neutron emission. Therefore, the 1982 and 1984 neutron flares offer a unique and clean chance to study charged particle propagation in the inner heliosphere without being affected by phenomena that occur near the sun. A mean free path of roughly 0.3 AU fits the decay proton profile in both flares quite well suggesting this value may be applicable to other propagation problems too.

5. REFERENCES.

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