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THE TIME HISTORY OF 2.22 MeV LINE EMISSION IN SOLAR FLARES

Prince, T.A.[1], Forrest, D.J.[2], Chupp, E.L.[2], Kanbach, G.[3], and Share, G.H.[4]

[1]California Institute of Technology, Pasadena, CA, U.S.A.; Visiting Scientist at University of New Hampshire, 1982.

[2]University of New Hampshire, Durham, NH, U.S.A.

[3]Max-Planck-Institut für Extraterrestrische Physik, Garching bei München, Germany

[4]Naval Research Laboratory, Washington, D.C., U.S.A.

1. INTRODUCTION

During solar flares, neutrons are produced by the interaction of energetic nuclei with the solar atmosphere. These neutrons may escape from the sun, decay, interact in energetic nuclear collisions, or be captured on ambient ^{1}H or ^{3}He. Capture on ^{1}H produces a γ-ray at 2.22 Mev energy; capture on ^{3}He is radiationless.

In this paper we examine the time dependence of 2.22 MeV emission using observations of the Solar Maximum Mission (SMM) gamma-ray spectrometer. We will determine the decay time constant for the 2.22 MeV emission process and from this derive implications concerning the density at which neutrons are captured and the value of the ^{3}He/H ratio. We will also set upper limits on the number of low energy neutrons produced in solar flares. The 2.22 MeV line provides a unique tool for probing the physics of the solar atmosphere since the neutrons which produce the line penetrate to depths exceeding the opacities at which optical observations can be made.

2. OBSERVATIONS

Among the many flares observed by the SMM instrument, this paper will concentrate on four strong flares occurring at heliocentric angle $\sim 70^{\circ}$. This angular selection was made to eliminate variations in the time dependence of the observed 2.22 MeV emission due to variations in the absorption length for photons in the photosphere.

Figure 1 shows 2.22 MeV and 4.1-6.4 MeV time profiles for the four flares under consideration. In the following discussion, the 4.1-6.4 MeV flux time history will be taken as indicative of the time dependence of energetic neutron production on the sun. The justification for this choice is based on the observation that the 4-6 MeV γ-rays in solar flares are predominantly nucleonic in origin (Forrest et al. 1981) and on the observation that the ratio of 2.22 MeV fluence to 4-6 MeV fluence is correlated over a large range of solar flare intensities (Chupp 1982).

It is apparent from Fig. 1 that by far the largest 2.22 MeV producing flare is that of 3 June 1982. This flare is discussed elsewhere in these proceedings in regard to energetic neutron events observed at 1 A.U. in both spacecraft and ground level observations (papers SP3-1 and SP3-2). For the 3 June 1982 flare, Fig. 1 shows an impulsive burst of 4.1-6.4 MeV photons lasting approximately 1 minute followed by low level emission which extended until the sun was occulted by the earth, 1260 s after flare maximum. Emission of 2.22 MeV photons was observed within 25 s after flare maximum and continued until occultation of the sun. Unfortunately, the very early part of the 2.22 MeV time history could not be accurately observed due to instrumental dead time and gain shifts which occurred near flare maximum, and therefore the 3 June 1982 2.22 MeV data of Fig. 1 begin 30 s after the peak of the flare.

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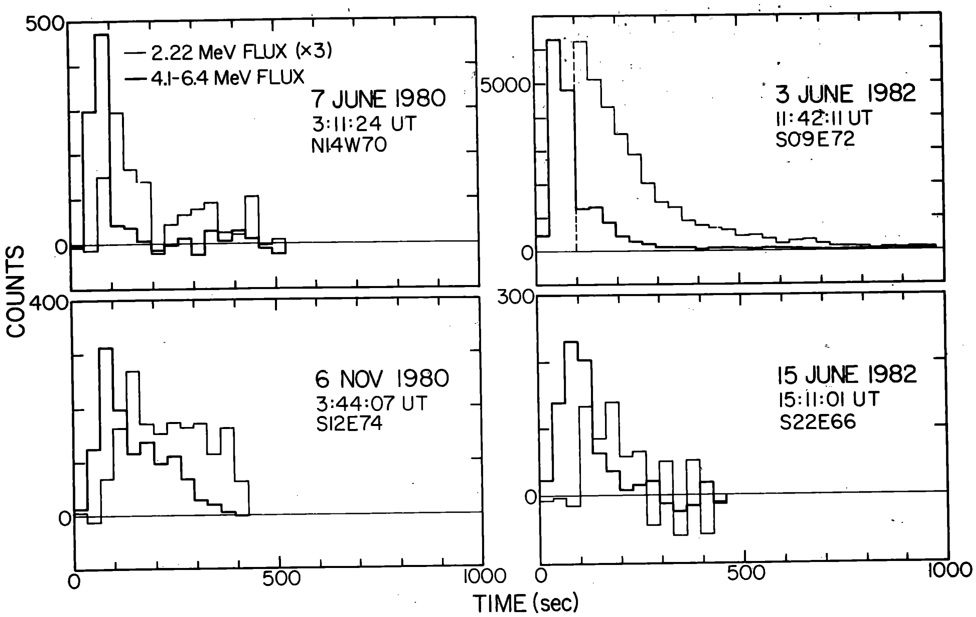

Figure 1: Time profiles for 2.22 MeV and 4.1-6.4 MeV emission. (Note: Data for 6 Nov 1980 terminated by sunset after 425 s.)

3. TIME HISTORY ANALYSIS

The flux of 2.22 MeV photons is related to the neutron production rate by:

$$F_{2.2}(t) = \int_{-\infty}^{t} S(T)R(t,T)dT \tag{1}$$

where: $F_{2.2}(t)$ = Observed 2.22 MeV flux
$S(t)$ = Neutron production history (taken to be $F_{4.1-6.4}(t)$)
$R(t,T)$ = Response function giving the 2.22 MeV photon contribution at time t due to neutrons produced at time T.

The simplest model would have $R(t,T)$ be a sum of exponentials, $\int_\tau R(\tau)exp(-(t-T)/\tau)\ d\tau$.

The time constants τ are of the form

$$\tau = \left(\frac{1}{\tau_H}+\frac{1}{\tau_{He}}+\frac{1}{\tau_d}\right)^{-1} \ ; \ \tau_H = \frac{1.4\times10^{19}}{n_H}\ s \ ; \ \tau_{He} = \frac{8.5\times10^{14}}{\mathbf{r}\times n_H}\ s \tag{2}$$

where τ_H is the time constant for capture on ^{1}H, τ_{He} is the time constant for capture on ^{3}He, τ_d is the neutron decay time, n_H is the hydrogen number density (in cm^{-3}), and r is the ^{3}He/H ratio. Because the neutrons are thermal for most of their lifetime (Wang 1975), the cross sections for capture on ^{1}H and ^{3}He are inversely proportional to the hydrogen density, n_H, at which capture occurs.

While the time response function is in general a sum of exponentials with different time constants, we find that the data for each of the flares is adequately fit with a single exponential

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time constant response. For instance, Figure 2 shows the time history of the 2.22 MeV emission for the 3 June 1982 event together with a fit to the data using a single exponential decay time response to the observed 4.1-6.4 MeV flux. The best model fit is obtained with a decay time of 100 s and a 2.22 MeV fluence of 314 cm^{-2}.

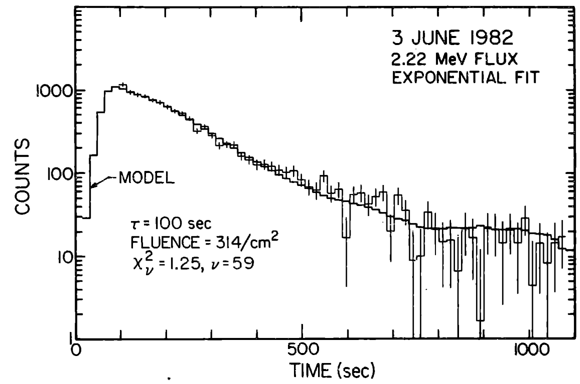

Figure 2: Single exponential time constant fit to data of 3 June 1982.

Figure 3 summarizes the time history analysis results for all four flares. Shown are the 90% confidence levels for a two parameter fit involving the exponential time constant and an overall 2.22 MeV normalization relative to the 4.1-6.4 MeV fluence. The figure indicates that all four flares are consistent with a single exponential time response of ~100 s. We conclude that 100 s represents the average or "dominant" time constant for 2.22 MeV emission.

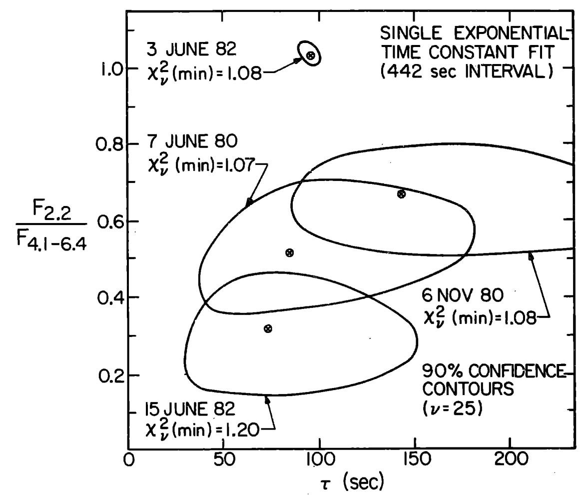

Figure 3: 90% confidence contours for the exponential time constant (τ) and the ratio of 2.22 MeV to 4.1-6.4 MeV fluence. Small circles indicate best fit points.

4. ^{3}He/H RATIO AND NEUTRON CAPTURE DENSITY

The ^{3}He/H ratio and the distribution of densities at which neutron capture occurs are directly related (Eq. 2). Thus, to determine the ^{3}He/H ratio, we must first obtain an estimate for the average neutron capture density, n_H, or equivalently the average time constant, τ_H, for neutron capture on ^{1}H. This is done by considering the solar hydrogen density profile together with the results of Monte Carlo calculations of neutron propagation.

Kanbach et al. (1981) have found in Monte Carlo calculations that the time constant, τ_H, for 2.22 MeV decay involving capture on ^{1}H is on the average ~100 seconds and is surprisingly independent of the spectral index of the energetic neutrons. Their results were obtained by averaging over all emission directions and obtaining the best fit decay constant from the first 150 second interval after the time of neutron production. The reasons for a dominant time constant of ~100 s are:

1) The existence of a "plateau" in the solar hydrogen density distribution at the top of the photosphere where the density is roughly constant at 1.2–1.4x10^{17} H/cm^3 (Allen 1976), corresponding to time constants of τ_H = 98-114 seconds.

2) The suppression of short time constants due to attenuation of 2.22 MeV photons from deeper regions (>1.5 attenuation lengths for τ_H <90 s at 70°).

3) The suppression of longer time constants due to the limited column density that contri-

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butes (<2.5 g/cm^2 for $\tau_H>150$ s). Also, the restriction of the analysis to the first 150 s after the flare (as in Kanbach et al. 1981) preferentially selects the shorter time constants.

We conclude that a measurement of the time constant during the first 150 seconds after the impulsive phase of the 3 June 1982 flare is essentially a measurement of the time constant, τ, for 2.22 MeV emission from the "plateau" density of $\sim 1.3 \times 10^{17}$ H/cm^3. This time constant includes the contribution from capture on ^{1}H ($\tau_H \sim 105$ s), from decay ($\tau_d = 917$ s), and from capture on ^{3}He. The best fit time constant over the 150 second period following the flare peak is $\tau = 89 \pm 10$ seconds. Using Eq. 2, this yields a ^{3}He/H ratio in the range $0.0-1.3 \times 10^{-5}$

We stress that the ^{3}He/H ratio derived here is a model dependent result and relies on Monte Carlo simulations of neutron propagation. More precise modeling of the 2.22 MeV decay time for flat spectra and 70° heliocentric angle is needed, as well as an investigation of the sensitivity of the ^{3}He/H ratio to changes in the solar atmosphere density profile models. However a lower limit to the average neutron capture density of 1×10^{17} H/cm^3, corresponding to an average τ_H of 140 s, is probably conservative. We thus *estimate* an upper limit to the ^{3}He/H ratio of 3.8×10^{-5}

In summary, the derived ^{3}He/H ratio is $0.4^{+3.4}_{-0.4} \times 10^{-5}$. The solar ^{3}He/H ratio is of interest in determining the evolution of the ^{3}He/H ratio from the protosolar value of $1.1-1.2 \times 10^{-5}$ (Anders and Ebihara 1982 and Cameron 1982) due to processes which destroy ^{3}He or burn D to ^{3}He. The value derived here is lower than, but consistent with, the estimate inferred from Geiss (1982) for the ^{3}He/H ratio in the outer convective zone which uses indirect arguments involving ^{3}He/^{4}He ratios in meteoritic samples and protosolar D/H estimates.

5. LOW ENERGY NEUTRON PRODUCTION

We will derive an upper limit on neutron production in the 1-20 MeV range for the 3 June 1982 flare. We first make the conservative assumptions that *all* 2.22 MeV photons are due to low energy (<20 MeV) neutrons and that the ^{3}He/H ratio is $\leqslant 5 \times 10^{-5}$. Monte Carlo results (Wang and Ramaty 1974, Wang 1975, and Kanbach et al. 1981) indicate that the number of 2.22 MeV photons per neutron at 70° is roughly constant over the 1-20 MeV range at a value of ~ 0.09.

For the 3 June 1982 flare, the 2.22 MeV fluence of 314/cm^2 implies an upper limit of 7.8×10^{29} neutrons/sr below 20 MeV. This integral flux is orders of magnitude below the low energy extrapolation of the high energy neutron spectra (>50 MeV) measured in direct observations at 1 A.U, and implies a bend in the neutron spectrum from a spectral index of $\alpha < -3$ at high energies to a spectral index flatter than $\alpha = -1$ below 20 MeV. A flattening at low energies to $\alpha > -0.5$ is expected (Lingenfelter and Ramaty 1967) due to the form of the cross sections for secondary neutron production at low energies.

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