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UPPER LIMIT ON THE STEADY EMISSION OF THE 2.223 MeV NEUTRON CAPTURE γ-RAY LINE FROM THE SUN

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Abstract. Data accumulated by the Solar Maximum Mission Gamma Ray Spectrometer (GRS) have been searched for evidence of the 2.223 MeV neutron capture line from the Sun, outside the times of γ-ray-emitting solar flares. Background-corrected spectra accumulated over 3-day intervals between 1980 and 1989 show no evidence of the line. Upper limits are reported separately for periods of high and low solar activity.

A conservative 3σ upper limit of $5.7 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$ is placed on the steady flux in the 2.223 MeV line during inactive periods, which is nearly two orders of magnitude lower than previously published results. After correction for limb darkening of the line emission from off-center positions, this upper limit becomes $7.1 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$. Our 3σ upper limit on the steady flux in the line during periods of high solar activity is $6.9 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$, or $8.6 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$ after correction for limb darkening. Our results imply that the quiescent solar corona cannot be heated by ions accelerated above 1 MeV in microflares (or a continuous acceleration process), so long as the ion energy spectrum is similar to that measured in large flares. We also use our results to derive the rate of tritium production at the solar surface; our upper limit of 9 nuclei $(\mathrm{cm}^2\,\mathrm{s})^{-1}$ is about a factor of 9 below the upper limit from searches for ^{3}H in the solar wind. We place upper limits of the order 10^{33} on the number of energetic ($>$ 30 MeV) protons which can be stored in active regions prior to being released in solar flares, which imply that the strongest observed flares cannot be produced by such a mechanism.

1. Introduction

The 2.223 MeV γ-ray line arising from the direct capture reaction $^1\mathrm{H}(n, \gamma)^2\mathrm{H}$ is the dominant spectral feature in many solar flares (Chupp, 1982). In this paper we present a search for steady emission of this line outside of the times of known γ-ray flare activity. If there is a steady-state population of accelerated protons in the corona of the Sun, correlating with the level of solar activity (Elliot, 1964), then steady emission of the 2.223 MeV line might be expected. Alternatively, since 'microflares' have been observed at ultraviolet and X-ray wavelengths at all times over large areas of the solar surface (Porter *et al.*, 1987; Golub *et al.*, 1974; Lin *et al.*, 1984), our measurement addresses the question whether these microflares are also sites of particle acceleration which might also produce observable levels of γ-radiation.

Our analysis of the Solar Maximum Mission (SMM) data is described in Section 2. We have obtained upper limits on the flux in the 2.223 MeV line separately for times of high('active') and low ('inactive') solar activity. In this way the specific model suggested by Elliot (1964), by which a population of accelerated protons is continuously

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present during the existence of an active region, may be tested. These upper limits are presented in Section 3.

The nuclear processes involved in the production of the 2.223 MeV line in the solar atmosphere during flares are quite well understood (Hua and Lingenfelter, 1987a, b). These processes can be studied both by 2.223 MeV γ-ray line observations and by detection at Earth and by interplanetary spacecraft of those neutrons which escape from the Sun (Chupp *et al.*, 1987). The neutrons are produced by the spallation of ambient solar material by flare-accelerated protons and α-particles (Ramaty and Murphy, 1987). Those neutrons which do not escape or decay are thermalized in the photosphere by elastic scattering and can then undergo either radiative capture by protons, yielding the 2.223 MeV line, or non-radiative capture by ^{3}He in the reaction ^{3}He$(n, p)^3$H. Thus measurements of the 2.223 MeV line have implications for the ^{3}H abundance in the Sun. We discuss these implications in Section 4, together with implications concerning the possible contribution of small flares to the heating of the solar corona. In Elliot's (1964) model, a steady level of 2.223 MeV line emission ought to arise from interactions between the accelerated protons which are trapped above active regions and the ambient coronal material, a possibility which is also discussed in Section 4.

2. Observations and Analysis

The Solar Maximum Mission was in operation between 1980 January and 1989 December, with a 5-month intermission from 1983 November to 1984 April prior to an in-orbit repair. The GRS is described in detail by Forrest *et al.* (1980). It comprised seven 7.6×7.6 cm NaI detectors surrounded on the sides and rear by a CsI anti-coincidence shield. It was sensitive to photons in the energy range 0.3 to 8.5 MeV, which were binned into 460 energy channels and accumulated over 16.384 s intervals. The gains were actively maintained at a very stable level, allowing summation of the spectra over the entire mission. The GRS aperture was determined by Monte-Carlo simulations to be $\simeq 170°$ FWHM at 2.223 MeV.

The data were analyzed by a method which has previously been applied to 2.223 MeV line emission from cosmic sources (Harris and Share, 1991). The 16-s spectra were summed into 1-min accumulations from which data contaminated by solar flares, γ-ray bursts and other transient backgrounds were rejected. We also rejected data taken during orbits traversing the South Atlantic Anomaly, and within $\simeq 10^4$ s thereafter, so as to eliminate backgrounds from short-lived radioactivities induced in the spacecraft and detector by the impact of trapped particles. The remaining 1-min spectra were summed over 3-day intervals into bins defined by the values of the vertical geomagnetic cutoff rigidity and the Sun–Earth-satellite angle θ. The widths of the bins in θ were 36°; therefore, since the Earth's disk subtended an angle of $\simeq 137°$ as seen from SMM's orbit, the four bins with $108° \leq \theta \leq 252°$ corresponded almost exactly to times when the Sun was occulted by the Earth (referred to as 'Earth-viewing').

The Sun was visible to the spacecraft for values of θ between 0°–111.5° and 248.5°–360°, but not all of these data were used in the analysis. We performed a

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normalized subtraction of data taken at $288° \leq \theta \leq 360°$, $0° \leq \theta \leq 72°$ ('Sun-viewing') from the Earth-viewing data at $108° \leq \theta \leq 252°$, since the strong background due to long-lived instrumental radioactivities can be eliminated almost entirely by this subtraction (Harris *et al.*, 1990). The live times used in the normalization were those over which the spectra were accumulated in the 3-day intervals. The subtraction yields an Earth-albedo spectrum with any solar spectrum superimposed in negative*. In Figure 1

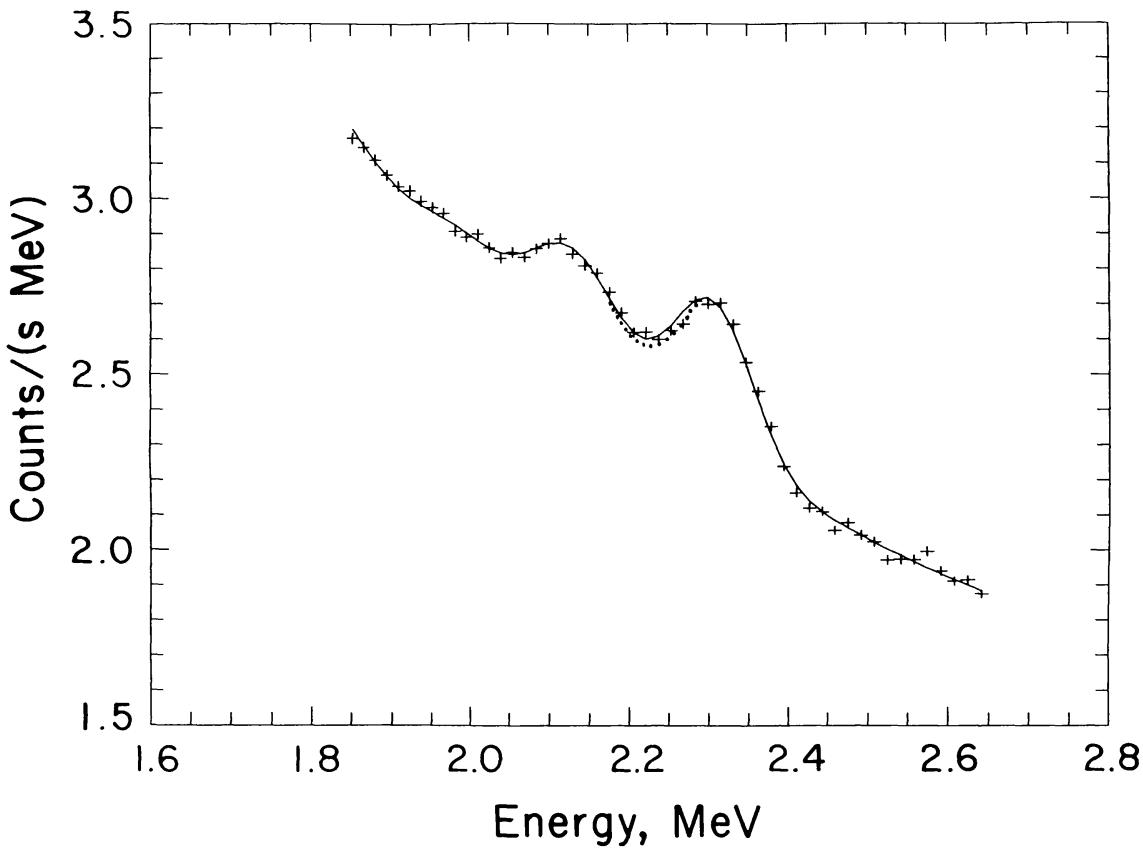

Fig. 1. 'Earth minus sky view' count spectrum accumulated over the entire mission 1980–1989. A four-component model (see text) fitted to it after propagation through the instrument response function is also shown. Full line represents the best-fitting model, including lines at 2.135 and 2.310 MeV and power law. Dotted line includes the effect on the fit of adding a solar 2.223 MeV line flux of $4.1 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$ (our conservative upper limit); note that a solar line appears negative in such a spectrum.

we show the resulting 'Earth minus Sun view' spectrum around 2 MeV, summed over the entire mission (1980–1989).

We fitted each 3-day 'Earth minus Sun view' spectrum between 1.85–2.65 MeV by a model spectrum consisting of a power law plus three lines at 2.135, 2.310, and 2.223 MeV. As Figure 1 shows, the power law and lines at 2.135 and 2.310 MeV are the dominant features of the Earth-albedo spectrum in this energy interval (Letaw *et al.*, 1989). Any 2.223 MeV line emission expected from the Sun ought to appear as a

* A small error ($\simeq 5\%$) was introduced into this negative solar spectrum by the small exposure to the Sun which was included in the Earth-viewing angle bins, as noted above, partially cancelling the Sun-viewing spectrum.

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negative feature. This model spectrum was folded with the GRS instrument response, with the strengths of the lines, power-law amplitude and power-law index being varied to obtain the best agreement with the 3-day count spectrum. The intrinsic widths of the atmospheric lines were fixed at 74 keV (2.135 MeV line) and 58 keV (2.310 MeV line), which are the revised values obtained by Letaw (1989, private communication); the intrinsic width of the 2.223 MeV line was fixed at 1 keV, a value much smaller than the instrumental resolution, the predicted width being < 0.1 keV. We derived the error in the strength of the 2.223 MeV line by the standard method of varying the χ^2 parameter (Press *et al.*, 1986).

We thus obtained a time series of 2.223 MeV line strengths during 3-day intervals throughout the mission. A consistent negative value of 2.223 MeV line strengths would indicate steady emission of this line from the Sun*. However, trends due to systematic errors must be removed from the time series, the most important of which is the temporal behavior of Earth albedo γ-radiation.

Emission of the 2.223 MeV line itself from the Earth's atmosphere is expected to be very weak. This can be shown by comparing the products σN for ^{1}H and for any other isotope which produces an observable atmospheric line, where σ is the (n, γ) reaction cross-section and N the atmospheric abundance by number at the relevant altitude. We used ^{14}N in this comparison, since the (n, γ) cross-section ratio is then expected to be roughly constant over a wide range of energies (Fowler, Caughlan, and Zimmerman, 1967). For the ^{15}N de-excitation line at 7.299 MeV the cross-section ratio is $\sigma(^1\mathrm{H})/\sigma(^{14}\mathrm{N}) \simeq 50$, and the abundance ratio is $N(^1\mathrm{H})/N(^{14}\mathrm{N}) \simeq 10^{-6}$. Therefore, the flux in the 2.223 MeV line should be $\simeq 5 \times 10^{-5}$ times the flux in the 7.299 MeV line. From the Earth's atmosphere spectrum of Letaw *et al.* (1989) we find that the 7.299 MeV line flux is $< 2.8 \times 10^{-4}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$ (3σ upper limit). It follows that the 2.223 MeV line flux from the Earth's atmosphere should be $< 1.4 \times 10^{-8}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$, far below the limit of detectability by SMM. The presence of the Earth-albedo lines in the spectrum at 2.135 and 2.310 MeV introduced a small systematic error into the fitted 2.223 MeV line strengths. We removed this error by fitting the 2.223 MeV line strength time series by a model of the temporal behavior of the Earth-albedo line spectrum. The variation of the 4.4 MeV line observed in GRS spectra, which is due to proton impacts on atmospheric ^{14}N and ^{12}C, has been found to be a suitable model of this behavior (Harris *et al.*, 1990). The 4.4 MeV line strengths (obtained from Share *et al.*, 1992), in the proportions derived from this fit, were subtracted from the 2.223 MeV line strengths before determining whether the latter were consistently negative.

The solar radio flux at 2800 MHz is frequently used as a measure of solar activity (especially in the form of accelerated particles). We used the daily measurements of the 2800 MHz flux made at Ottawa, Canada, by the Herzberg Institute of Astrophysics during 1980–1989 to select periods of high solar activity. We defined 3-day periods with averaged radio fluxes greater than $1.1 \times 10^{-20}\ \mathrm{J\,s^{-1}\,m^{-2}\,Hz^{-1}}$ as being 'active', the

* Note that Harris and Share (1991) found no evidence for any emission of the 2.223 MeV line from several cosmic sources, which would also appear in negative, but with a more complicated temporal pattern.

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remainder being 'inactive'. The 2.223 MeV line strengths for the active subset of the 9-year time series were in turn examined to see whether they were consistently negative. (Henceforward, we refer to the 'solar' 2.223 MeV line strength as the negative amplitude of the measured line strength, as in Figure 1.)

3. Results

3.1. The entire period 1980–1989

The time series of solar 2.223 MeV line strengths over the whole mission, summed up to 48 days for clarity of presentation, is shown in Figure 2. The average strength of the solar line from the 3-day line strength time series was $-0.5 \pm 1.2 \times 10^{-5}\ \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$. There is thus no evidence for a steady solar line feature at 2.223 MeV down to a conservative upper limit* of $4.1 \times 10^{-5}\ \gamma\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$ (Table I). A very similar upper limit

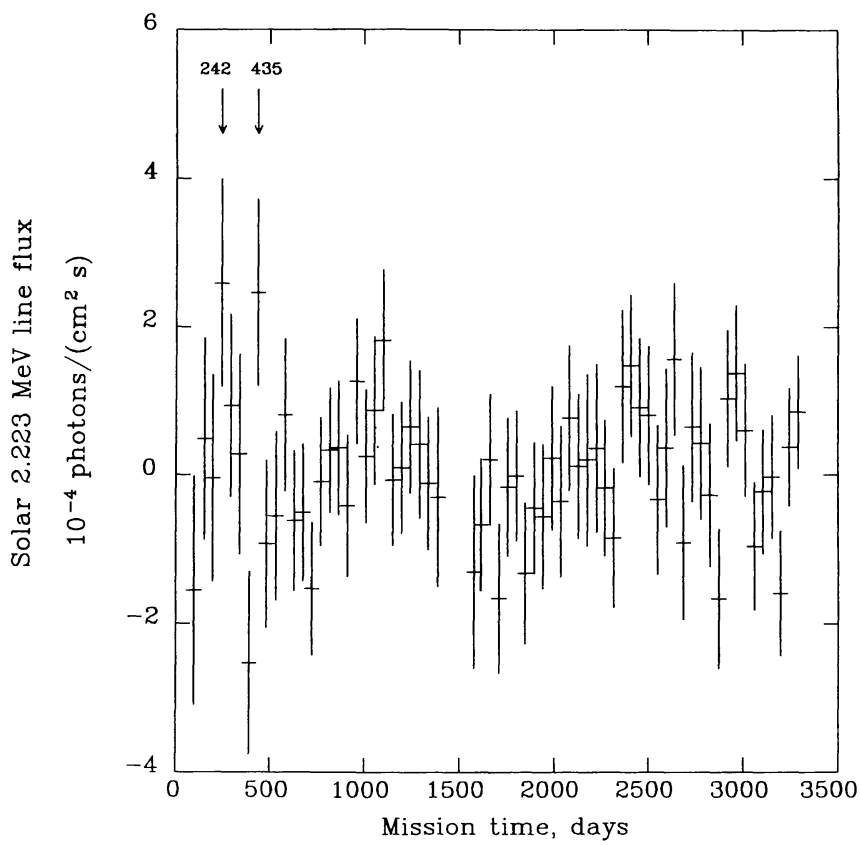

Fig. 2. Intensities of the solar 2.223 MeV line from fits to the 3-day 'Earth minus sky view' spectra (cf. Figure 1) throughout the mission. The fitted background varying as the 4.4 MeV line has been subtracted (Section 2), and the intensities have been summed to 48 days for illustrative purposes. The error bars on the data points are 1σ. The abscissa is expressed in days after January 1980. Note that a positive flux in this figure represents an excess in the flux from the Sun.

* We define a 'conservative' 3σ upper limit by taking the measured value as an estimate of the systematic error, even when it is consistent with zero. The upper limit is then the absolute value of the systematic error plus three times the 1σ statistical error.

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TABLE I

2.223 MeV line flux upper limits

Experiment	Measurement interval, s	Flux upper limit $\gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$ [a]
Range r spacecraft [b]		5×10^{-3}
Balloon flight [c]	1.8×10^3	5×10^{-3}
Present work:		
Total 9 years	2.6×10^7	4.1×10^{-5} [d]
Inactive periods	1.3×10^7	5.7×10^{-5} [d]
Active periods	1.3×10^7	6.9×10^{-5} [d]

[a] 2σ upper limits unless noted otherwise.
[b] Metzger *et al.* (1964).
[c] Chupp, Lavakare, and Sarkady (1968).
[d] Conservative 3σ upper limit equals three times statistical 1σ error plus absolute value of systematic error. No correction for limb-darkening (Section 3.3) is applied.

would be obtained by fitting a 2.223 MeV line to the total 'Earth minus Sun view' spectrum summed over the entire mission (see dotted line in Figure 1).

Figure 2 contains evidence for small residual systematic errors on $\simeq 48$-day time scales in the 2.223 MeV line strength measurements; the value of χ^2 per degree of freedom for the fit rises from 0.964 for data in 3-day bins up to 1.153 for data in 48-day bins (less than 20% probability for 66 deg of freedom). We enquire in Section 3.2 whether the intensity of active regions, with a characteristic time scale $\simeq 14$ d, was correlated with any such systematics.

3.2. Active and Inactive Periods

We identified 484 3-day periods of high solar activity, and 517 'inactive' 3-day periods of lower activity, according to the Ottawa 2800 MHz radio flux measurements. We then examined each subset to see whether the solar 2.223 MeV line strengths were correlated with the level of activity, as would be expected on the hypothesis of Elliot (1964). No such correlation was found. In Figure 3, for the high-activity periods, we plot the average solar 2.223 MeV line strength against the 2800 MHz flux; there is no statistically significant trend. The apparent decrease in line strength for 3-day intervals experiencing $> 2.25 \times 10^{-20}\,\mathrm{J\,s^{-1}\,m^{-2}\,Hz^{-1}}$ is of very low significance (overall significance of the departure from zero line strength for all these points is less than 2σ, and the trend is in the opposite direction to expectations). The simplest hypothesis is that the average solar 2.223 MeV line strength during active periods is consistent with zero. The average value of the line strength during such periods was $-1.8 \pm 1.7 \times 10^{-5}\,\gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$, giving a conservative upper imit of $6.9 \times 10^{-5}\,\gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$ (Table I).

We conclude that the positive (i.e., possibly solar) excursions seen in Figure 2 are not likely to be due to the real presence of the 2.223 MeV line during active periods. Although two such excursions are visible around days 242 and 435, near the peak of

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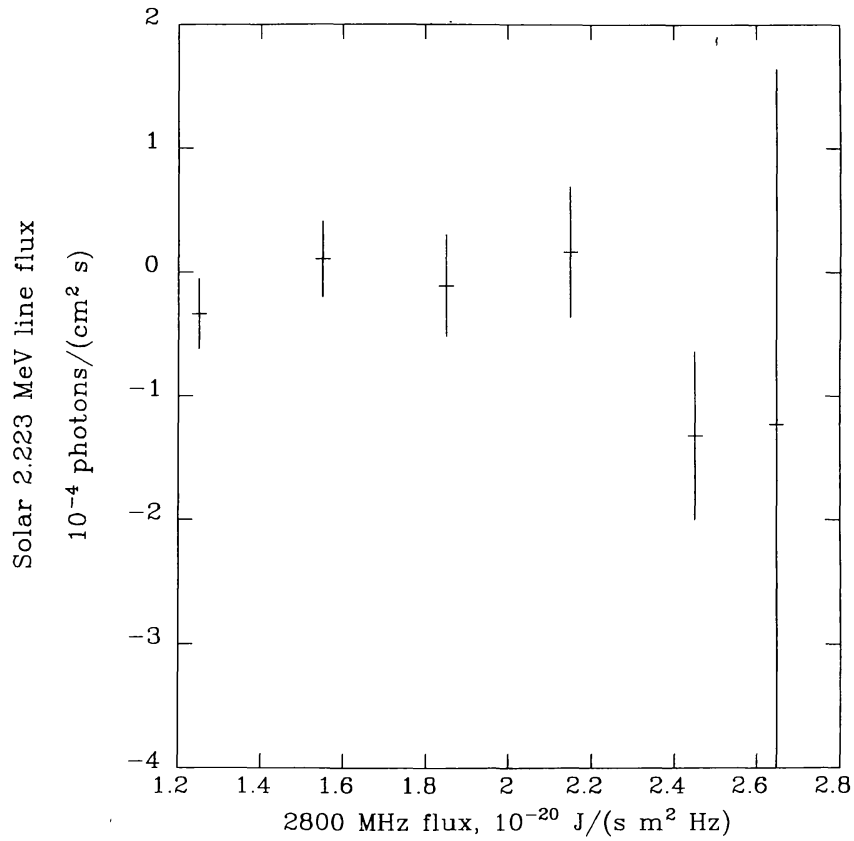

Fig. 3. Average intensity of the solar 2.223 MeV line during active-region 3-day periods, as a function of the solar 2800 MHz radio flux during each period. The line intensities are binned into radio flux intervals of 2.5×10^{-21} J s^{-1} m^{-2} Hz^{-1}. The error bars are the 1σ uncertainties on the binned line intensities. Note that a positive flux in this figure represents an excess in the line flux from the Sun.

sunspot cycle 21 when strong activity was present, they do not correlate well on 3-day time-scales with the actual intensities of the active regions. In fact, several of the backgrounds discussed in Section 2 (e.g., strength of Earth-atmosphere lines) also vary according to the solar cycle, and we attribute these weak systematics on $\simeq$ 48-day time scales to imperfect elimination of one or more of these backgrounds.

In the same way, the average solar line strength during inactive 3-day periods was found to be $0.8 \pm 1.6 \times 10^{-5}$ γ (cm^2 s)$^{-1}$, which is also consistent with zero solar 2.223 MeV line flux. The corresponding conservative upper limit on the flux is 5.7×10^{-5} γ (cm^2 s)$^{-1}$. It improves by nearly two orders of magnitude upon the results of previous measurements of this line during times of solar quiescence (Table I).

3.3. Correction for Limb Darkening

The γ-radiation from photospheric points at large heliocentric angle θ from the center of the solar disk is attenuated by absorption along the line of sight to the instrument. We took the attenuation factor for a flare at heliocentric angle θ to be $f(\theta)/f(0°)$, where f is the efficiency of conversion of neutrons to 2.223 MeV photons calculated by Hua and Lingenfelter (1987a). Given the θ-distribution of solar active regions, and assuming

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that the neutrons are produced by accelerated ions interacting with a thick target in a horizontal beam, we found that $\langle f(\theta)/f(0°)\rangle \simeq 0.8$ (varying weakly with the accelerated particle energy spectrum). When this correction is applied to our measured upper limits on the flux (Table I), they become:

total 9 years	$5.1 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$;
inactive periods	$7.1 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$;
active periods	$8.6 \times 10^{-5}\ \gamma\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$.

4. Discussion

4.1. The distribution of 2.223 MeV line fluences in flares

The 2.223 MeV line is very commonly observed in strong solar flares (Chupp, 1982), and the frequency distribution of 2.223 MeV line fluences may be obtained from such observations. Our upper limit on the 2.223 MeV line flux during periods of high activity may then be compared with what would be expected from the extrapolation of this distribution downward to low-fluence values. The total clock time in the high-activity periods during which SMM could have detected flares* was 4.83×10^7 s; our limb-corrected upper limit on the flux therefore corresponds to a steady fluence of $4150\ \gamma\,\mathrm{cm}^{-2}$ during active periods.

An analysis of the distribution of fluences in the 2.223 MeV line from SMM flare measurements is in progress. We will use the preliminary results presented by Share *et al.* (1983) to estimate the differential frequency distribution of fluences $\mathrm{d}N/\mathrm{d}F$ during 1980–1989. Out of a total of 81 flares during the period 1980 February–1983 September, Share *et al.* found that thirty produced a line detectable at a level $\geq 2\sigma$. A total of 195 flares were observed during the whole mission. To date, about 63 of them have been found to exhibit the 2.223 MeV line at a level $\geq 2\sigma$. We have assumed that the fluences of these flares were distributed in the same way as those of the 81 flares for which the analysis is complete. The distribution of fluences for these 81 flares is well represented by

$$\mathrm{d}N/\mathrm{d}F = A(F/F_0)^{-b}\,, \tag{1}$$

where F is the fluence corrected for the limb darkening appropriate to the heliocentric angle θ between Earth and flare, F_0 is $1\ \gamma\,\mathrm{cm}^{-2}$, and A and b are constants:

$$A = 38.6 \pm 18.5\ \gamma\,\mathrm{cm}^{-2}\,, \qquad b = 1.75 \pm 0.18\,.$$

If we assume the same distribution for the period 1980–1989 of the entire mission, then the constant A must be normalized by a factor 195/81. We also assumed that the

* Note that this differs from the *live time* during which the spectra were accumulated, as given in Table I.

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distribution is valid down to zero fluence with no low-fluence cut-off and no change in index.

Equation (1) implies a total fluence

$$F_{\text{low}} = \int_0^{\phi} F \, \mathrm{d}N/\mathrm{d}F \, \mathrm{d}F$$

in flares weaker than the SMM threshold fluence ϕ. For a 2σ threshold fluence of $\phi = 1\ \gamma\ \mathrm{cm}^{-2}$ (Share *et al.*, 1983) this yields a value $F_{\text{low}} = 370^{+1170}_{-320}\ \gamma\ \mathrm{cm}^{-2}$. The 1σ upper limit on this expected value is about a factor of 2 below our measured upper limit $4150\ \gamma\ \mathrm{cm}^{-2}$. To this extent, we can exclude a sharp steepening of the $\mathrm{d}N/\mathrm{d}F$ distribution function for small fluences below $F = 1\ \gamma\ \mathrm{cm}^{-2}$.

4.2. Heating of the Solar Corona by Small Flares

Many hypotheses have been proposed for the source of the energy necessary to heat the solar corona (Narain and Ulmschneider, 1990). Lin *et al.* (1984) identified a large number of hard X-ray 'microflares' during a time of solar activity and demonstrated that they were capable of depositing $\simeq 10^{27}\ \mathrm{erg\ s}^{-1}$, sufficient to heat the active corona. Porter *et al.* (1987), having observed ultraviolet microflares on the quiet Sun, suggested that the $\simeq 10^{28}\ \mathrm{erg\ s}^{-1}$ necessary to heat the quiet corona might also come from very small flares. Our results for the 2.223 MeV line strength during inactive periods imply an upper limit on the energy release in accelerated particles during times of solar quiescence, which is relevant to the latter hypothesis.

We will argue that, in observed flares, the 2.223 MeV line fluence is approximately proportional to the total energy contained in accelerated nuclei. We can thus obtain an upper limit on the power in accelerated nuclei during inactive periods from the upper limit on the steady 2.223 MeV line flux which we have measured during such periods. This power is unlikely to be wholly converted into coronal heating (thick-target models of solar flare γ-ray production imply that most of it is deposited at lower depths), but we will show that even if 100% of it were deposited in the corona it would be insufficient. Electrons accelerated simultaneously with the nuclei are more likely to heat the corona; we will argue (tentatively) from estimates of the ratio of the powers in accelerated electrons and nuclei in *strong* flares that, if the same ratio holds for the hypothetical microflares during inactive periods, the total energy in accelerated electrons is also insufficient to heat the corona.

The energy spectrum above $\simeq 1\ \mathrm{MeV\ nucl}^{-1}$ of particles accelerated in solar flares may be represented by a Bessel function, whose shape is parametrized by the product αT of the acceleration efficiency α and the escape time T (Ramaty, 1986). Murphy and Ramaty (1985) demonstrated that αT could be deduced from measurements of the ratio of the fluence in the 2.223 MeV line to the fluence in the energy band 4–7 MeV for any flare. Hua and Lingenfelter (1987a) presented such measurements and derived values of αT for 15 flares. When αT and the absolute fluence values are known, it is a straightforward matter to calculate the total energy W in the accelerated-particle energy

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spectrum, by integrating over the whole Bessel function shape* (Ramaty, 1986).

The 2.223 and 4–7 MeV γ-rays do not give information about the energy spectrum below 1 MeV; if a Bessel function is assumed, the energy in particles of < 1 MeV can be neglected. We therefore performed the integration for the flares listed by Hua and Lingenfelter (1987a) over particles energies > 1 MeV. The total flare energies W thus derived were compared with the Hua and Lingenfelter 2.223 MeV line fluences after they had been corrected for limb darkening as described in Section 3.3. The ratio of W to the corrected 2.223 MeV line fluence F' was found to be approximately constant:

$$W/F' = 1.3 \pm 0.1 \times 10^{28} \text{ erg } (\gamma \text{ cm}^{-2})^{-1} . \tag{2}$$

If this relationship also holds true for flares below the threshold of detection, then our upper limit $7.1 \times 10^{-5}\ \gamma\,(\text{cm}^2\ \text{s})^{-1}$ immediately implies a steady power input in accelerated nuclei above 1 MeV of $\leq 10^{24}$ erg s^{-1}.

Even under the very conservative assumption that 100% of this power is available to heat the corona, it is insufficient for this purpose by about four orders of magnitude. This conclusion – that the energy in accelerated nuclei alone is not enough to heat the inactive corona – is, however, dependent on the validity of the assumptions we have made in obtaining it. In particular, we have assumed that the spectrum of the accelerated ions both in inactive periods and in γ-ray line flares has a Bessel function form. Ramaty (1979, 1986) has presented both theoretical and experimental evidence for this spectrum at energies above 1 MeV. However, we cannot exclude the possibility that a sufficiently large population of nuclei at energies < 1 MeV might contribute the required power to heat the corona. These low-energy nuclei might be detected indirectly by recombination radiation following charge-exchange reactions (Canfield *et al.*, 1986) or directly by low-energy γ-ray line emission** (MacKinnon, 1989).

Accelerated nuclei are likely to be accompanied by other forms of energy release, whose contribution to coronal heating is more difficult to assess. The fraction of the total energy released in flares which is carried by accelerated nuclei is not well-established. Ramaty (1986), by comparing the values of W for several flares with the energy in accelerated electrons as deduced from hard X-ray spectra by Lin and Hudson (1976), estimated that several percent of the total flare energy was in accelerated nuclei***. Thus it may conservatively be assumed that $> 1\%$ of the total flare energy in observed flares

* It is assumed that the fraction of the accelerated nuclei which escape from the Sun (and therefore do not contribute to the measured 2.223 and 4–7 MeV fluences, and to the normalization of the energy spectrum) is small. This has been shown by Ramaty and Murphy (1987) to be the case for nearly all flares in a sample of $\simeq 20$ considered by them. It is also assumed that the accelerated nuclei interact with a thick (photospheric) target in a horizontal beam. By these assumptions, only the escaping nuclei are available to heat the corona, and the energy W deposited in the photosphere is a conservative upper limit upon the energy which they carry.

** These lines, for example the 8.07 MeV line from de-excitation of ^{14}N produced by the reaction ^{13}C$(p, \gamma)^{14}$N, are expected to be much weaker than the 2.223 MeV line, and are therefore undetectable by the SMM GRS.

*** It is assumed in this argument that there is no large unobserved population of accelerated electrons at low energies below about 25 keV.

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is carried by the nuclei. If this assumption is also true for weak flares below the SMM threshold, then our upper limit on 2.223 MeV line emission implies that the total steady energy input available for heating the corona is $< 10^{26}$ erg s^{-1}.

This energy input is insufficient, by a factor $\simeq 100$, to heat the quiet solar corona. Our conclusion is therefore that microflares cannot meet the quiet corona's heating requirement unless their properties differ from those of observed flares – specifically, unless a much smaller fraction of their energy release goes into the acceleration of nuclei, or unless there are hitherto-unobserved low-energy populations of accelerated nuclei (< 1 MeV) or electrons (< 25 keV). A similar conclusion has recently been reached in a more direct manner ny T. T. Lee and V. Petrosian (1992, private communication) using hard X-ray fluences measured by ISEE-3/ICE and GOES soft X-ray fluxes.

4.3. Production of Tritium at the Solar Surface

The SMM upper limit on overall 2.223 MeV line emission can be used to estimate an upper limit on the continuous rate of production of ^{3}H at the solar surface by neutrons from weak flares (or a continuous acceleration process). The main nuclear reaction competing with $^1\mathrm{H}(n, \gamma)^2\mathrm{H}$ for the neutrons produced in flares is $^3\mathrm{He}(n, p)^3\mathrm{H}$ (Wang and Ramaty, 1974). It follows that the production rates of 2.223 MeV line photons (Q_{2223}) and of tritium (Q_T) are in the ratio

$$\frac{Q_{2223}}{Q_T} = \frac{N(^1\mathrm{H})\sigma(^1\mathrm{H})}{N(^3\mathrm{He})\sigma(^3\mathrm{He})}\,, \tag{3}$$

where N represents the abundance and σ the reaction cross section as indicated.

The ratio of the two cross sections in Equation (3) is known experimentally to be 5.95×10^{-5} (Wang and Ramaty, 1974). The abundance ratio $N(^3\mathrm{He})/N(^1\mathrm{H})$ in the solar photosphere has been measured by Hua and Lingenfelter (1987b) from the time-dependence of the 2.223 MeV line intensity in flares to be $2.3 \pm 1.2 \times 10^{-5}$. Equation (3) therefore implies $Q_{2223}/Q_T = 2.6^{+2.8}_{-0.9}$; to be conservative, we will express this as $Q_{2223}/Q_T \geq 1.7$. Since the total neutron production rate Q_n is obviously greater than Q_{2223}, it follows that $Q_T < Q_n/1.7$.

The neutron production rate is related to the observed flux ϕ_{2223} by taking the time derivative of Equation (13) of Ramaty (1986):

$$Q_n f = 4\pi r^2 \phi_{2223}\,, \tag{4}$$

where r is 1 AU and f is the efficiency of conversion of neutrons into line photons which escape the Sun. As discussed in Section 3.3, f was calculated by Hua and Lingenfelter (1987a) as a function of the heliocentric angle θ between Earth and the flare; under the assumptions adopted in Sections 3.3 and 4.2 (horizontal beam interacting with a thick target) they found $f(0°) \simeq 0.16$, varying weakly with the Bessel function spectral parameter αT. We saw in Section 3.3 that, for an assumed distribution of quiescent line emission following the distribution of solar active regions, $\langle f(\theta)/f(0°)\rangle \simeq 0.8$ (also weakly dependent on αT). Our measured upper limit of 4.1×10^{-5} γ (cm^2 s)$^{-1}$ there-

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fore gives

$$\frac{f}{\phi_{2223}} = \frac{f(0°)\,\langle f(\theta)/f(0°)\rangle}{\phi_{2223}} > 3.12 \times 10^3$$

to be put in Equation (4). We then obtain an upper limit on the steady rate of production of tritium of

$$Q_T < 5.3 \times 10^{23} \text{ nuclei s}^{-1}\,,$$

which is equal to 9 ^{3}H nuclei cm^{-2} s^{-1} at the solar surface. This may be compared with the upper limit of 80 ^{3}H nuclei cm^{-2} s^{-1} at the solar surface obtained from measurement of the solar wind (Fireman, DeFelice, and D'Amico, 1976). This solar wind loss rate is equal to the production rate if it is assumed that ^{3}H is not lost from the surface by mixing downwards; otherwise, the value would be even larger than 80 nuclei cm^{-2} s^{-1}. We conclude that the limit on the 2.223 MeV line flux provides a much more sensitive limit on the tritium production rate.

4.4. Storage of accelerated particles in active regions

Elliot (1964) proposed a model whereby the accelerated particles which manifest themselves during solar flares are derived from a steady-state population which is trapped in the lower corona by the magnetic fields associated with active regions. He proposed to test this hypothesis by searching for steady emission of the ~ 100 MeV γ-rays from the decay of π^0 produced by very energetic (> 100 MeV) protons. We believe that steady emission of the 2.223 MeV line from the interactions of lower-energy protons with the ambient corona can also be used to test this model. Our test improves upon the preliminary results of Simnett *et al.* (1986), whose analysis involved a search for the 2.223 and 4.44 MeV γ-ray lines in GRS spectra prior to several flares during 1980–1982. They placed a limit of $\simeq 10^{25}$ erg s^{-1} on the power in non-thermal protons above 10 MeV during the $\simeq 2$ hr periods before these flares; for comparison, by applying the arguments of Section 4.2 we obtain an upper limit 1.2×10^{24} erg s^{-1} in protons above 1 MeV during periods of high solar activity.

We may use Equation (4) (Section 4.3) to derive the steady-state abundance of energetic protons which is permitted by our upper limit for the 2.223 MeV line flux during periods of high solar activity. However, the numerical values of the quantities in Equation (4) will be different in the context of Elliot's model. Instead of a horizontal beam of particles interacting at the footpoints of the magnetic field with a thick (photospheric) target, we must now assume an approximately isotropic distribution of particles interacting according to the thin-target approximation. Under these circumstances, the efficiency f of conversion of neutrons into 2.223 MeV line photons was calculated by Hua and Lingenfelter (1987a, based on Wang, 1975) to be $\simeq 0.13$, depending weakly on the particle energy spectrum (so long as it was of the form of a Bessel function).

Ramaty (1986) calculated the quantity $Q_n/(n_{\rm H}N_{30})$ in the thin-target approximation, where $n_{\rm H}$ is the number density of hydrogen in the interaction region, and N_{30} is the

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steady-state number of accelerated protons of energy > 30 MeV. Although this quantity varied strongly with the Bessel function spectral index αT, it was found to have a minimum value 2×10^{-16} neutrons cm^3 s^{-1} for $\alpha T \simeq 0.05$. Substituting $Q_n \geq 2 \times 10^{-16}\, n_H N_{30}$ in Equation (4), and assuming a typical coronal density $n_H \simeq 10^8$ protons cm^{-3}, we obtain

$$N_{30} < 1.08 \times 10^{36} \phi_{2223} \text{ protons},$$

where ϕ_{2223} is the upper limit on the steady 2.223 MeV line flux from an active region. From Figure 3 we estimate that, during the 3-day periods of greatest solar activity, the 2.223 MeV line flux was $-1.2 \pm 2.9 \times 10^{-4}\ \gamma\,(\text{cm}^2\,\text{s})^{-1}$, corresponding to a conservative limit $\phi_{2223} < 1 \times 10^{-3}\ \gamma\,(\text{cm}^2\,\text{s})^{-1}$. We thus estimate the typical abundance of protons of > 30 MeV to be $< 1.1 \times 10^{33}$.

In the model of Elliot (1964) this represents the upper limit on the number of protons of > 30 MeV which can appear when the trapped population of accelerated particles is released in a flare. However, Hua and Lingenfelter (1987a) have estimated the numbers of protons of > 30 MeV from the indices αT of 15 rather strong flares (see Section 4.2), finding values between 10^{31} and $\simeq 10^{34}$ protons. It is clear that, within our upper limit on N_{30}, the model of Elliot (1964) cannot provide the numbers of protons of > 30 MeV seen in the strongest of these flares.

This conclusion can be demonstrated quantitatively for the individual flares in the Hua and Lingenfelter (1987a) sample for which SMM data are available. For the 11 flares listed in Table II, we combined the upper limits on the 2.223 MeV line flux for

TABLE II

Solar flare protons of energy > 30 MeV in Elliot's (1964) model

Flare date	Active region 2.223 MeV line flux[a] $\gamma\,(\text{cm}^2\,\text{s})^{-1}$	N_{30}	
		Model	Measured[b]
1980 June 4	$<1.4 \times 10^{-3}$	$<1.5 \times 10^{33}$	9.6×10^{30}
1980 June 7	$<7.3 \times 10^{-4}$	$<7.9 \times 10^{32}$	$9.3 \pm 2.4 \times 10^{31}$
1980 June 21	$<9.5 \times 10^{-4}$	$<1.0 \times 10^{33}$	$3.9 \pm 0.3 \times 10^{32}$
1980 July 1	$<8.5 \times 10^{-4}$	$<9.2 \times 10^{32}$	$2.2 \pm 0.8 \times 10^{31}$
1980 Nov. 6	$<1.1 \times 10^{-3}$	$<1.2 \times 10^{33}$	$1.5 \pm 0.3 \times 10^{32}$
1981 Apr. 10	$<7.2 \times 10^{-4}$	$<7.8 \times 10^{32}$	$2.1 \pm 0.2 \times 10^{32}$
1981 Apr. 27	$<7.3 \times 10^{-4}$	$<7.9 \times 10^{32}$	$6.8 \pm 2.1 \times 10^{32}$
1982 Feb. 8	$<7.9 \times 10^{-4}$	$<8.6 \times 10^{32}$	$1.5 \pm 1.2 \times 10^{32}$
1982 June 3	$<6.9 \times 10^{-4}$	$<7.5 \times 10^{32}$	$3.5 \pm 0.2 \times 10^{33}$
1982 July 9[c]	$<9.2 \times 10^{-4}$	$<9.9 \times 10^{32}$	3.2×10^{32}

[a] Obtained from the mean intensity of the 2.223 MeV line measured by SMM during all 3-day intervals between the appearance round the east limb of the active region and the occurrence of the listed flare; or between the last prior γ-ray flare from the active region and the listed flare, assuming that the prior flare depleted the stored accelerated protons.

[b] From Hua and Lingenfelter (1987a).

[c] Two flares on same day from same active region combined.

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all the preceding 3-day periods during which the responsible active region was visible on the solar disk. From these upper limits ϕ_{2223} we calculated the number N_{30} of protons of > 30 MeV for comparison with the number measured by Hua and Lingenfelter. We find that Elliot's (1964) model failed to produce the number seen in the strongest flare, that of 1982 June 3.

The Oriented Scintillation Spectrometer Experiment (OSSE) on board the Gamma Ray Observatory is well equipped to pursue this test of Elliot's (1964) hypothesis. Matz, Share, and Kurfess (1989) describe OSSE observations of the Sun to be made over periods of several days during periods of high solar activity. In this mode, OSSE's sensitivity to 2.223 MeV line emission should be about a factor of 6 better than that of the SMM GRS.

5. Conclusions

The upper limits for continuous 2.223 MeV γ-ray line emission from the active and inactive Sun, as established in the present work, are about two orders of magnitude less than previously published results. An upper limit on the solar tritium abundance may be obtained from the 2.223 MeV γ-ray line which is a factor 9 lower than that obtained from solar wind measurements. Our results for inactive periods also suggest that small flares (or a continuous acceleration mechanism) are unlikely to be the source of the heating of the quiet solar corona; more precisely, we conclude:

(a) that the power in accelerated nuclei during inactive periods falls short of the coronal heating requirement by about four orders of magnitude *unless there is a large and as yet unobserved population of nuclei at energies below 1 MeV*;

(b) that energy release in other forms associated with the acceleration process falls short of the heating requirement by about two orders of magnitude *if this energy release is in the same proportion to the power in accelerated nuclei as is estimated from observed flares*. Since this proportion is not well-known, this conclusion must be regarded as tentative.

We have also obtained an upper limit on the strength of the 2.223 MeV line during periods of high solar activity (but outside the times of flares), which is about a factor 2 above the most optimistic expectation of the flux in small flares from a downward extrapolation of the fluence distribution of observed γ-ray flares. We find no correlation between the activity of the Sun (as measured by 2800 MHz radio emission) and the 2.223 MeV line strength over 3-day periods of high activity. Our upper limit falls below the level of 2.223 MeV line emission implied for the strongest flares by Elliot's (1964) model, whereby accelerated nuclei are stored in an active region before the occurrence of a flare.

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References

Canfield, R. C., Bely-Dubau, E., Brown, J. C., and 13 co-authors: 1966, in M. R. Kundu and B. Woodgate (eds.), *Energetic Phenomena on the Sun,* NASA CP-2439, p. 3.

Chupp, E. L.: 1982, in R. E. Lingenfelder, H. S. Hudson, and D. M. Worrall (eds.), *Gamma Ray Transients and Related Astrophysical Phenomena,* AIP, New York, p. 363.

Chupp, E. L., Lavakare, P. J., and Sarkady, A. A.: 1968, *Phys. Rev.* **166**, 1299.

Chupp, E. L., Debrunner, H., Flückiger, E., Forrest, D. J., Golliez, F., Kanbach, G., Vestrand, W. T., Cooper, J., and Share, G. H.: 1987, *Astrophys. J.* **318**, 913.

Elliot, H.: 1964, *Planetary Space Sci.* **12**, 657.

Fireman, E. L., DeFelice, J., and D'Amico, J.: 1976, *Earth Planetary Sci. Letters* **32**, 185.

Forrest, D. J., Chupp, E. L., and 11 co-authors: 1980, *Solar Phys.* **65**, 15.

Fowler, W. A., Caughlan, G. R., and Zimmerman, B. A.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 525.

Golub, L., Krieger, A. S., Silk, J. K., Timothy, A. F., and Vaiana, G. S.: 1974, *Astrophys. J.* **189**, L93.

Harris, M. J. and Share, G. H.: 1991, *Astrophys. J.* **381**, 439.

Harris, M. J., Share, G. H., Leising, M. D., Kinzer, R. L., and Messina, D. C.: 1990, *Astrophys. J.* **362**, 135.

Hua, X.-M. and Lingenfelter, R. E.: 1987a, *Solar Phys.* **107**, 351.

Hua, X.-M. and Lingenfelter, R. E.: 1987b, *Astrophys. J.* **319**, 555.

Hudson, H. S.: 1989, in W. N. Johnson (ed.), *Proc. Gamma Ray Observatory Science Workshop,* GSFC, Greenbelt MD, pp. 4–351.

Letaw, J. R., Share, G. H., Kinzer, R. L., Silberberg, R., Chupp, E. L., Forrest, D. J., and Rieger, E.: 1989, *J. Geophys. Res.* **94**, 1211.

Lin, R. P. and Hudson, H. S.: 1976, *Solar Phys.* **50**, 153.

Lin, R. P., Schwartz, R. A., Kane, S. R., Pelling, R. M., and Hurley, K. C.: 1984, *Astrophys. J.* **283**, 421.

MacKinnon, A. L.: 1989, *Astron. Astrophys.* **226**, 284.

Matz, S. M., Share, G. H., and Kurfess, J. D.: 1989, in W. N. Johnson (ed.), *Proc. Gamma Ray Observatory Science Workshop,* GSFC, Greenbelt MD, pp. 4–381.

Metzger, A. E., Anderson, E. C., Van Dilla, M. A., and Arnold, J. R.: 1964, *Nature* **204**, 766.

Murphy, R. J. and Ramaty, R.: 1985, *Adv. Space Res.* **4**(7), 127.

Narain, U. and Ulmschneider, P.: 1990, *Space Sci. Rev.* **54**, 377.

Porter, J. G., Moore, R. L., Reichmann, E. J., Engvold, O., and Harvey, K. L.: 1987, *Astrophys. J.* **323**, 380.

Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T.: 1986, *Numerical Recipes,* Cambridge University Press, Cambridge, p. 537.

Ramaty, R.: 1979, in J. Arons, C. Max, and C. McKee (eds.), *Particle Acceleration Mechanisms in Astrophysics,* AIP, New York, p. 135.

Ramaty, R.: 1986, in P. A. Sturrock, T. E. Holzer, D. Mihalas, and R. K. Ulrich (eds.), *Physics of the Sun,* Vol. 2, D. Reidel Publ. Co., Dordrecht, Holland, p. 291.

Ramaty, R. and Murphy, R. J.: 1987, *Space Sci. Rev.* **45**, 213.

Share, G. H., Forrest, D. J., Chupp, E. L., Rieger, E., Reppin, C., and Kanbach, G.: 1983, *Bull. Am. Astron. Soc.* **15**, 912.

Share, G. H., Kinzer, R. L., Leising, M. D., Messina, D. C., and Harris, M. J.: 1992, in preparation.

Simnett, G. M., Share, G. H., Messina, D. C., Chupp, E. L., Forrest, D. J., and Rieger, E.: 1986, *Adv. Space Res.* **6**(6), 105.

Wang, H. T.: 1975, Ph.D. Dissertation, University of Maryland.

Wang, H. T. and Ramaty, R.: 1974, *Solar Phys.* **36**, 129.

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