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FINAL TECHNICAL REPORT
NASA GRANT NAG 5-945
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DETERMINATION OF SOLAR FLARE ACCELERATED ION ANGULAR DISTRIBUTIONS FROM SMM GAMMA RAY AND NEUTRON MEASUREMENTS

AND

DETERMINATION OF THE ^{3}He/H RATIO IN THE SOLAR PHOTOSPHERE FROM SMM GAMMA-RAY MEASUREMENTS

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1. FLARE ACCELERATED ION ANGULAR DISTRIBUTIONS

Comparisons of Solar Maximum Mission (SMM) observations of gamma-ray line and neutron emission with theoretical calculations of their expected production by flare accelerated ion interactions in the solar atmosphere have led to significant advances in our understanding of solar flare particle acceleration and interaction, as well as the flare process itself. These comparisons have enabled us to determine (Hua and Lingenfelter 1987a), not only the total number and energy spectrum of accelerated ions trapped at the Sun, but also to make the first qualitative determination (Hua and Lingenfelter 1987b) of the ion angular distribution as they interact in the solar atmosphere, showing that they may be highly anisotropic with a mirroring-like distribution. These comparisons have also enabled us to make the first direct determination (Hua and Lingenfelter 1987c) of the photospheric ^{3}He ratio, which strongly affects the time dependence of the neutron capture line emission.

More detailed calculations are essential, however, for an understanding of the angular dependence of the SMM gamma ray and neutron measurements, and of the accelerated ions that produce them. Thus we have modified our Monte Carlo program to include in the calculations of ion trajectories the effects both of mirroring in converging magnetic fields and of pitch angle scattering. For ions with various initial angular distributions at their acceleration site in the upper atmosphere of the Sun, we have calculated their energy losses, pitch angle scattering, nuclear interactions and magnetic mirroring on converging magnetic field lines in the lower atmosphere, together with their expected neutron and gamma ray line emission as a function of observing angle. Comparing the results of these calculations with the SMM observations of gamma-ray lines from flares at different heliocentric longitudes, we can thus determine not only the angular distribution of the interacting ions but also the initial angular distribution of the ions at acceleration and quantitatively study the effects of pitch angle scattering and mirroring in the converging magnetic field.

In particular, we consider a magnetic flux tube model consisting of a semicircular coronal portion of half-length L_c having a uniform circular cross section of radius a_c, and two straight portions parallel to a solar radius extending from the ends of the coronal portion (at the transition region), through the chromosphere and into the photosphere. We assume the gas to be completely ionized in the corona and neutral below the transition region. For the density profile below the transition region we use a sunspot active region model (Avrett 1981) at depths -1800 km $< h <$ 120 km merged with a photospheric model (Allen 1963) at depths $>$ 120 km. Zero height is the point where the optical depth for the 500 nm continuum radiation is unity and $h = -1800$ km is the location of the transition region. Below the transition region, we take B proportional to a power δ of the pressure (Zweibel and Haber 1983), $B(h) = B_c[P(h)/P_c]^{\delta}$, while in the corona we take the magnetic field B_c to be constant. We assume a constant coronal pressure P_c and density n_c, and the pressure $P(h)$ below the transition region is given by the models above. The convergence parameter δ can be calculated by specifying the photospheric magnetic field $B_p = B(h{=}0)$; thus $\delta = \ln(B_p/B_c)/\ln(P_p/P_c)$, where we take $P_p = P(h{=}0) = 1.53\mathrm{x}10^5$ dyne cm^{-2}. We assume local galactic abundances (Meyer 1985) for the ambient gas composition throughout the loop.

We assume that the acceleration takes place in the corona, primarily because of the requirement for pitch-angle scattering by MHD turbulence for stochastic acceleration and diffusive shock acceleration (Forman, Ramaty and Zweibel 1986). Such turbulence could be produced by the flare energy release mechanism and could exist in the ionized corona, but is expected to be quickly damped (Melrose 1980, p. 27) by neutral hydrogen in the chromosphere. The energy spectrum, angular distribution, and time profile of the accelerated particles depend on the acceleration process. Energy spectra were considered for stochastic acceleration and shock acceleration. There are no detailed studies of the expected angular distributions; however, for stochastic acceleration the distribution is probably isotropic.

In the Monte-Carlo simulations, we release energetic particles in the coronal segment with a given energy spectrum, angular distribution, time dependence, and spatial distribution. The ions subsequently lose energy through Coulomb interactions and are removed by nuclear interactions. We employ the guiding center approximation to determine the particle's motion in the magnetic field. Although in the presence of energy losses, $(p\times\sin\alpha)^2/B$ is not conserved, as long as the force corresponding to these losses is antiparallel to the particle's direction of motion, $(1 - \cos^2\alpha)/B$ = constant (Northrop 1987); where, α and p are the particle's pitch angle and momentum. The loss processes, considered here, obey this condition.

In addition to the effect of the converging magnetic field, the pitch angle can also be changed by scattering on MHD turbulence. As mentioned above, such turbulence is expected to exist in the corona but not below the transition region. Alfven turbulence can scatter ions if $\gamma\beta \gg \beta_a$, where γ and $c\beta$ are the Lorentz factor and speed of the particle and $c\beta_a$ is the Alfven speed (Melrose 1974). This condition is easily satisfied by ions with energies greater than the gamma-ray production thresholds.

Pitch-angle scattering is described by the diffusion coefficient $D_{\mu\mu} = (1 - \mu^2)$ $D_{\alpha\alpha}$, where $\mu = \cos\alpha$. For protons resonating with Alfven turbulence with a Kolmogorov spectrum $D_{\alpha\alpha} = 100\ \mathrm{sec}^{-1}\ [(W_a/1\mathrm{erg\ cm}^{-3})/(B/100\mathrm{G})]\ \gamma^{-1}(\mu\gamma\beta)^{2/3}$, where W_a is the total energy density of the Alfven turbulence, derived from an expression by Melrose (1974) with a low wave number cutoff on the spectral density equal to the resonant wave number for a 10 GeV proton in a magnetic field of 100 G. Hence, for $W_a = 1$ erg cm^{-3} and $B = 100$ G, the scattering rate (defined as $D_{\alpha\alpha}(\mu = 1)$) is approximately 50 sec^{-1} for 30 MeV protons. The value of W_a is not known. But even this relatively low value (less than 1% of the energy density in the ambient magnetic field) would suffice to practically isotropize the particles in the corona, as a typical particle transit time is ~ 0.5 sec. Pitch-angle scattering will affect the time profile of the interactions primarily by scattering particles in the corona from large to small pitch angles, thus enabling them to lose energy faster below the transition region. As shown below, even a W_a of $\sim 2\text{x}10^{-4}$ erg cm^{-3} has a significant effect on the time profile of nuclear line emission. This coronal scattering, however, will not destroy anisotropic gamma-ray production in the converging magnetic field below the transition region.

Having made these modification to our Monte Carlo program, as we proposed, we calculated the nuclear line production in magnetic loops by energetic ions with various pitch angle distributions and energy spectra.

A comparison of our calculations of the time-dependent 4.438 MeV line emission with SMM measurements (Chupp et al. 1987) of the time history of the 4 – 7 MeV emission of the 1982 June 3 flare is shown in Figure 1. This time history should be proportional to that of the 4.438 MeV time profile, as it is expected to be dominated by nuclear deexcitation lines. In these calculations, we assumed a loop with $L_c = 10^9$ cm, $a_c = 10^8$ cm, $n_c = 2.5\text{x}10^9$ H cm^{-3}, $P_c = 0.16$ dyne cm^{-2}, $B_c = 100$ G, and convergence parameter $\delta = 1/5$ and $1/20$, and we injected the ions isotropically at the top of the coronal loop at $t = 0$, with an energy spectrum proportional to the modified Bessel function K_2 characterized by $\alpha T = 0.03$ (e.g. Forman, Ramaty and Zweibel 1986).

As can be seen in Figure 1, the calculated the time-dependent production rate of the 4.438 MeV line is not consistent with the measurements if there is no pitch-angle scattering. However, if we include MHD pitch-angle scattering (Palmer and Jokipii 1981) with a scattering mean-free path $\lambda = 1800 L_c$, which corresponds to $W_a = 2\text{x}10^{-4}$ erg cm^{-3} for a Kolmogorov spectrum, the we see that the calculated time dependence is in good agreement with the measurements. This shows that scattering by even a low level of turbulence can cause a much more rapid repopulating of the loss cone increasing the number of ions interacting at early times and decreasing the number at late times.

Thus if the ions are accelerated stochastically with an isotropic distribution, then MHD pitch-angle scattering in the corona is the dominant mechanism for injecting the bulk of the ions into the denser regions of the chromosphere and photosphere where they react rapidly and produce the impulsive gamma-ray time profiles.

These results were presented at the meeting on "Nuclear Spectroscopy of Astrophysical Sources" in Washington D.C. in December of 1987 and are being published in the proceedings as part of a general review (Ramaty, Miller, Hua and Lingenfelter 1988) of models of gamma-ray production in solar flares. Full details of the calculations and results have been published in the *Astrophysical Journal* (Hua, Ramaty and Lingenfelter 1989). Copies of these two papers are attached.

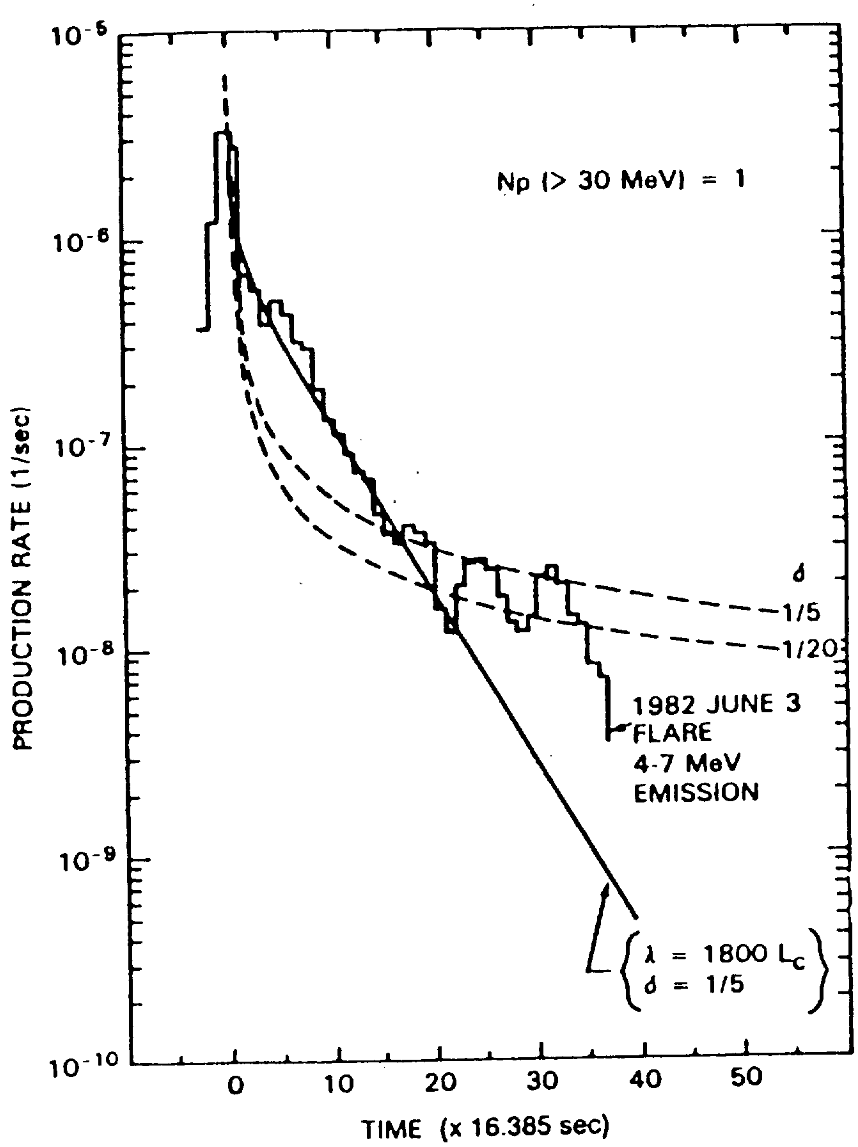

Figure 1. Comparison of calculated time dependences of 4.438 MeV line production in a converging magnetic field loop with SMM measurements of 4 – 7 MeV flux from Chupp et al. (1987), showing that pitch angle scattering in the corona is needed to account for the observed time dependent flux if the ions are accelerated isotropically.

2. THE ^{3}He/H RATIO IN THE SOLAR PHOTOSPHERE

The reliable determination of the solar photospheric ^{3}He abundance is of great importance for our understanding of nucleosynthesis in the early universe and its implications for cosmology, as well as for the study of the evolution of the sun. It is also essential for determinations of the spectrum and total number of flare accelerated ions from the SMM/GRS gamma-ray line measurements. A sensitive measure of the ^{3}He abundance can be made from SMM/GRS measurements of the time-dependent rate of 2.223 MeV gamma-ray line emission, resulting from radiative capture in photospheric hydrogen of neutrons produced by flare-accelerated ions, because that rate depends strongly on the nonradiative capture by ^{3}He.

We have made systematic Monte Carlo calculations (Hua and Lingenfelter 1987a,b,c,d,e) of this time dependence as a function of the ^{3}He abundance and other variables. Comparing the results of these calculations with the SMM/GRS measurements (Prince et al. 1983) of the time dependent 2.223 MeV line emission observed for nearly 1000 seconds from the large flare of 3 June 1982, we found a photospheric ^{3}He/H ratio of $(2.3 \pm 1.2) \times 10^{-5}$. This determination of the solar ^{3}He/H ratio must still be regarded only as a preliminary one, however, because it relies on the analysis of just one flare. Studies of additional flares are needed to test the reliability of the determination and its sensitivity to other variables. Thus, we are making a similar analysis of the SMM/GRS measurements of the time-dependent 2.223 MeV flux of comparable duration (Chupp 1988) from a second large flare, that of 24 April 1984, at a heliocentric longitude of 45°E and a latitude of 11°S. This provides an independent measure of the ^{3}He/H ratio and enables us to test the reliability of the technique and to study the effects of uncertainties in the accelerated ion energy and angular distributions, the neutron production time dependence, and the assumed atmospheric model. These uncertainties are also constrained by comparing other SMM/GRS measurements with the results of related studies, which we have carried out (Hua, Ramaty and Lingenfelter 1989, Ramaty, Miller, Hua, and Lingenfelter 1988) as a part of this investigation.

We have completed a new series of calculations of the time-dependent flux of 2.223 MeV neutron capture line emission and the ratio of the time-integrated flux, or fluence, in the 2.223 MeV line to that in the 4.1-6.4 MeV nuclear deexcitation band, expected as a result of the accelerated ion interactions in the solar atmosphere. These have been calculated for an observing angle of 46°, corresponding to that of the 24 April 1984 flare, as was previously done for an angle of 72° for the 3 June 1982 flare. These calculations were made for a range of photospheric ^{3}He/H ratios and accelerated ion energy spectra, assuming a Bessel function spectrum and a mirroring distribution for the interacting ions.

The data reduction of the time-dependent gamma-ray line measurements for this flare is presently being carried out by the SMM/GRS investigators (Forrest 1989) and we are now awaiting its completion. As soon as it is available, we can compare the calculated time-dependent 2.223 MeV flux for this flare with the SMM/GRS measurements to make a second determination of the ^{3}He/H ratio. We will make two separate best-fit comparisons of the calculations and measurements to determine both the $^3He/H$ ratio and the spectral index αT. We will determine the best-fit values of $^3He/H$, as a function of the assumed spectral index αT, using χ-square tests of the fit of the measured and expected time dependence of the 2.223 MeV flux. And we will determine the best-fit values of spectral index αT, as a function of the assumed $^3He/H$, using χ-square tests of the fit of the measured and expected ratios of the 2.223 MeV to 4.1-6.4 MeV fluences. From these two comparisons, as was done for the 3 June 1982 flare, we can then determine the combined best-fit values of the spectral index αT and the $^3He/H$ ratio.

These two independent determinations of the photospheric $^3He/H$ ratio from the 3 June 1982 and 24 April 1984 flares at different observing angles, allow us to critically test the reliability of the technique, since we would not expect variations in the $^3He/H$ ratio from flare to flare. By combining the two determinations, we obtain a better value of $^3He/H$ with a statistical uncertainty reduced by a factor of $\sqrt{2}$. These two separate determinations will also enable us to study the systematic uncertainties, associated with the ion energy and angular distributions, the neutron production time dependence and the assumed atmospheric model.

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