1.0 INTRODUCTION

Until now, solar γ-ray and neutron emissions have only been detected during times of intense solar activity, specifically, during solar flares. These emissions arise from the interaction of accelerated charged particles with the ambient solar material. However, there are several mechanisms that might result in γ–ray and/or neutron emission during times when there is no significant solar activity. These include: 1) interactions of accelerated particles produced by coronal heating processes; 2) emission from long–lived radioactive isotopes produced in recent solar flares; 3) precipitation of downstream shock-accelerated ions back to the solar surface from coronal mass ejections not be associated with a visible solar flare; 4) interactions of high energy cosmic rays in the solar atmosphere; 5) the radiative decay of massive solar neutrinos. We have been using COMPTEL data to investigate whether such processes are capable of producing detectable γ–ray emissions in the 0.75–30 MeV energy range (Young et al. 1996; McConnell et al. 1997a,b). To date, we have concentrated on γ–ray emissions of the type that might be related to coronal heating. Our results leave open the possibility that coronal heating may be attributable to sub-MeV protons accelerated, for example, by quasi-continuous microflares. Here, we review the status of these efforts and propose additional actions to further investigate quiet-time solar emissions. *Although our analysis has yet to show any evidence for measurable flux levels, we have not yet fully exploited the available data.* The latest analysis includes only those data for which the Sun was at high galactic latitudes, well away from sources of galactic emission. The inclusion of additional low-latitude data, although difficult, would effectively triple the available data. We also anticipate that we can improve our sensitivity to line emissions by perhaps a factor of two using specialized line-imaging techniques. Finally, we would extend our analysis to include additional energy bands that are more appropriate for other emission processes (e.g., neutrino decay) that have not yet been considered. In addition to the data analysis efforts, *we propose an additional two weeks of COMPTEL γ-ray observations during cycle 7*. These measurements would help to ensure a continuous set of γ-ray data throughout the solar cycle. For these observations, we also propose to maximize our sensitivity by collecting these data at times when the Sun is at high galactic latitudes. This constraint will be especially important during cycle 7, given the increased orbital background of COMPTEL. *In addition to the γ-ray observations, we propose one week of solar observations with COMPTEL in solar neutron mode.* This mode has only ever been operated during times of solar activity. These data would be used to search for quiet-time levels of solar neutrons, a study which can best be undertaken with new data.

2.0 "QUIET TIME" PARTICLE ACCELERATION

One hypothesis which has been put forth to explain the heating of the solar corona is that the necessary energy comes from a quasi-continuous succession of “microflares” (e.g., Lin et al. 1984; Porter et al. 1987; Biesecker, 1995). In both cases, it was suggested that the energy content of the microflares may be sufficient to explain the coronal heating requirements. Although it is not known whether these less energetic flares involve non-thermal processes (i.e., particle acceleration) or whether they are basically a thermal phenomena, there is at least some indication that particle acceleration may be taking place (Lin et al., 1984). If particle acceleration (especially ion acceleration) is an integral part of the microflare phenomena, this leads directly to the possibility of a quiescent level of γ–ray and neutron emissions.

If ions are accelerated in microflares, it is difficult to say anything about the nature of the resultant ion spectrum. In observed γ–ray flares, the total energy in accelerated nuclei is roughly proportional to the total 2.2 MeV line fluence. Assuming that the microflare phenomena is analogous to a typical solar flare, one would expect that measurements of the 2.2 MeV line would provide an estimate of the total energy content of the accelerated ion population in microflares. Harris et al. (1992) used 9 years of SMM data to set an upper limit on the 2.2 MeV emission (corrected for limb-darkening effects) of 5.1×10^{-5} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. By assuming that the microflares are similar to observed γ–ray flares in terms of their accelerated ion spectrum and the fraction of total energy imparted to the ions, it was argued that microflares are insufficient to heat the quiet-time solar corona. However, the fraction of total flare energy carried by the ions in an observable flare is poorly known, so it is difficult to estimate the total energy content of the ion population with any degree of certainty. Furthermore, it is not yet known to what extent these two types of flares are similar. It may be that the microflares impart a much smaller fraction of their total energy in the energetic ion population, in which case the SMM observations may not rule out microflares as a coronal heating mechanism.

The γ–ray lines that are normally produced in solar flares yield information only on protons of energy > 10 MeV. The total energy content of the accelerated protons, dominated by the form of the distribution at lower energies, is uncertain by orders of magnitude (MacKinnon 1989). *It is entirely conceivable, and maybe even likely,* *that the accelerated ion spectrum is very soft, with large numbers of protons having energies below 1 MeV.* Although certain observed γ–ray lines (such as the 1.634 MeV line from ^{20}Ne) have a lower energy threshold than others (Share & Murphy 1995), a very soft ion spectrum would be far more difficult to detect. MacKinnon (1989) has pointed out, however, the possible importance of radiative capture reactions involving protons of energy in the range 0.1–1.0 MeV. These reactions lead to line emissions which may be observable. Such lines include those resulting from proton capture on ^{12}C (2.37 MeV), ^{13}C (8.07 MeV), ^{14}N (7.56 MeV) and ^{15}N (12.44 MeV). Although the cross-sections for these reactions are quite small, this would be offset by the number of protons required for such a population to be energetically important.

Another possible mechanism for generating non-flare solar γ–ray emission involves the storage of accelerated particles in active regions (Elliot, 1964). In this model, a reservoir of accelerated particles is generated and stored (via magnetic confinement) in the lower corona. The release of these particles, and their subsequent interaction in the chromosphere, is then responsible for what we observe as a solar flare. It is possible, however, that the interactions of such a particle population within the lower corona (i.e., within the storage region) might also lead to some level of pre-flare γ–ray emission (Simnett et al. 1986; Harris et al. 1992; Ryan and Simnett, 1989). This model would generally predict a γ–ray precursor (possibly extending over several days) to a conventional solar flare.

3.0 LONG–LIVED RADIOACTIVE ISOTOPES

Several radioactive isotopes which are likely to be produced in solar flares (e.g., Kuzhevskii 1982) have half-lifes ranging from several weeks to months. Some of these isotopes could, in principle, result in detectable levels of emission well after the flare itself. Of particular interest are the decays of ^{56}Co (emitting photons at 0.847 and 1.238 MeV with a half-life of 77 days) and ^{22}Na (emitting photons at 0.511 MeV and 1.275 MeV with a half-life of 2.58 years). Predicted average flux levels for these particular line emissions range from 10^{-5} to 10^{-8} cm^{-2} sec^{-1}. The upper end of this range is within reach of COMPTEL, suggesting that COMPTEL may be able to place useful constraints on the magnitude of these emissions. Note, however, that these are *average* flux values; these levels can be expected to vary as a function of solar cycle and could therefore be more easily detected around the time of solar maximum.

4.0 SHOCK-ACCELERATED PROTON PRECIPITATION

One of the solar physics highlights of the Compton mission is the measurement of so-called long–duration high-energy γ–ray flares. These events are characterized by prolonged emission of γ–rays from high-energy protons, taking place hours after the impulsive phase. Trapping and prolonged acceleration of protons have been put forth as explanations for the phenomenon, but another candidate is the precipitation of protons downstream from blast wave shocks or coronal mass ejections (CME). The downstream protons can, in principle, diffuse back to the solar surface and produce γ–rays for hours. The telling measurement would be one in which a significant coronal mass ejection occurs without an accompanying flare. This often take the form of filament lifting off the solar surface with no X-ray flare. If γ–rays are observed after such a CME, then one has clear evidence that shock-accelerated protons from the CME contribute to the phenomenon of long–duration high-energy flares. We have searched for a correspondence between high flux levels of 10 MeV protons at 1 AU and the availability of COMPTEL solar data. The only such events which took place for which COMPTEL data are available were during the June 1991 solar ToO. Although we plan to search these data for a CME / γ-ray correlation, this may be a difficult task given the very active state of the Sun at the time. Ideally, we would like to look for correlations between flare-less CMEs and γ-ray emission; unfortunately, we do not as yet have any such correlated data available. It is possible that such a flare-less CME could occur during the observations which we propose for cycle 7. In any case, a good background measurement of the Sun during solar minimum would provide a reference for other measurements made during solar maximum.

5.0 RADIATIVE DECAY OF MASSIVE SOLAR NEUTRINOS

If a massive neutrino species exists, then it is reasonable to hypothesize that it may be unstable and decay. A radiative decay is the simplest two-body decay mode available for a massive neutrino within the framework of the Standard Model of particle physics. To date the most sensitive attempt to measure the characteristic γ-ray signature of radiative neutrino decay involved COMPTEL observations of type-II supernovae (Miller, Ryan & Svoboda 1996). Although no evidence of radiative decay was found, observations of SN1987A and SN1993J were used to improve the neutrino mass/lifetime limits by up to 5 orders of magnitude. Neutrinos produced in the core of the sun are believed to be ν_e, but observations of continue to indicate a deficit of such neutrinos. Mixing of neutrino flavors (i.e, oscillations from ν_e to ν_μ and/or ν_τ) has been suggested as a solution to the observed deficit, but this can occur only if a massive neutrino species exists. Bahcall (1989) has pointed out that for a neutrino lifetime of ~500 seconds, oscillations and decay (although not specifically radiative decay) can explain the observed neutrino deficit. Measurements of hard X-rays and γ-rays from the Sun can be used to investigate radiative neutrino decay, since the predicted spectrum lies predominantly in the 0.1–10 MeV energy range. Cowsik (1977) and Raffelt (1985) used early hard X-ray and γ-ray data to derive constraints on the radiative lifetime of solar neutrinos. Assuming that no ν-decay emission is observed, the limits obtained from an analysis of COMPTEL data will be complementary to those obtained from the COMPTEL supernovae observations. As with the supernova analysis, the search for neutrino decay emission will be optimized by using PSFs tailored to the expected form of the decay spectrum. The proposed analysis will be sensitive to neutrino masses 10^3 times lighter than the COMPTEL supernova observations, as well as placing significant constraints on the radiative lifetime and the radiative branching ratio (Miller 1995). The proposed effort will allow for a direct test of a potential solution to the “solar neutrino problem,” and provide an opportunity to study fundamental particle physics at a scale unobtainable in terrestrial laboratories.

6.0 COSMIC RAY ALBEDO EMISSION

A study on the effects of incident cosmic rays in the solar atmosphere has been carried out by Seckel, Stanev and Gaisser (1991). This albedo flux would be dependent on the phase of the solar cycle (Hudson, 1989), being strongest near the time of solar minimum, when instellar cosmic rays would more readily reach the Sun. In principle ameasurement of the expected continuum spectrum could provide useful constraints on the nature of the interplanetary diffusion in the inner heliosphere. The predicted flux values for the albedo γ–ray emission (from Seckel, Stanev and Gaisser, 1991) suggest that even the most optimistic predictions may not be within the sensitivity limits of COMPTEL. These predictions do show that a measurement of the solar albedo flux would more likely be within the reach of EGRET. Recent results from EGRET, however, show no evidence for quiet-time solar emissions at energies above 100 MeV (Thompson et al. 1997). It is therefore unlikely, that COMPTEL would detect any cosmic ray albedo flux from the Sun.

7.0 RECENT PROGRESS

The latest analysis of COMPTEL γ-ray data (Young et al. 1996; McConnell et al. 1997a,b) covers the first five years of the CGRO mission (through VP 523.0). The analysis is restricted to observations away from the galactic plane and to those time periods well removed from the solar activity of 1991. The final set of selected data covered a total of 24 days (CGRO viewing periods 320.0, 513.0, and 514.0). Sun-centered image data was generated separately for each day and subsequently co-added. Such data have now been compiled for four separate energy bands: 1–10 MeV (searching for general nuclear line emissions), 1.50–1.75 MeV (for the 1.63 MeV line from ^{20}Ne), 2.110–2.336 MeV (for 2.22 MeV neutron capture line) and 7.80–8.35 MeV (for the 8.07 MeV from proton capture on ^{13}C). Separate maximum likelihood maps were generated from each set of co-added data using a standard analysis. The resulting likelihood maps were used to search for evidence of time-integrated solar emission. We found no detectable flux in any of these energy bands. The 2σ upper limits derived from these data are: 2.2×10^{-5} cm^{-2} s^{-1} MeV^{-1} in the 1–10 MeV, 6.3×10^{-5} cm^{-2} s^{-1} at 1.63 MeV, 4.1×10^{-5} cm^{-2} s^{-1} at 2.22 MeV, and 1.9×10^{-5} cm^{-2} s^{-1} at 8.07 MeV.

Assuming a fixed ratio between the 2.22 MeV line flux and the total power input (as in Harris et al. 1992), the COMPTEL limit on the 2.22 MeV flux implies a continuous power input of $< 4 \times 10^{23}$ ergs s^{-1} for accelerated nuclei with E > 10 MeV. This is far below the level of ~10^{28} ergs s^{-1} required to heat the solar corona. The limit on the 8.07 MeV line flux, on the other hand, allows us to place a constraint on the power input of nonthermal ions down to ~0.5 MeV/nucleon (MacKinnon 1989). The COMPTEL limit implies that the total power input must be < 2×10^{30} ergs s^{-1}. Based on these data alone, we can rule out energetic ions (> 10 MeV/nucleon) as the source of coronal heating, but *we cannot rule out the possibility of a significant contribution from low energy ions (< 1 MeV/nucleon) as a source of coronal heating.*

8.0 PROPOSED INVESTIGATIONS

For cycle 7, we propose to continue with our on-going efforts in the analysis of available COMPTEL solar data. These data will be used not only to search for continuum emissions (such as that which might be expected from radiative neutrino decay), but also to search for evidence of specific solar line emissions. Of particular interest are those lines at 2.2 MeV, 1.6 MeV and 8.07 MeV. Some (but not all) of the proposed effort is an extension of work already completed. However, the work that has been done so far was based on a standard COMPTEL analysis method, that is sensitive to the combined line and continuum emissions. Other techniques are available which can achieve somewhat better line flux sensitivity. More specifically, we would employ a technique (Knödlseder et al. 1996) pioneered in studies of the galactic 1.8 MeV emission from ^{26}Al (Diehl et al. 1995) and also used in an all-sky survey at 2.2 MeV (McConnell et al. 1997). The analysis can also be improved by incorporating more of the available data. This will require using data collected when the Sun was near the galactic plane. The analysis in this case will require more detailed spatial modeling of the galactic plane emissions. These actions alone should provide a sensitivity increase by as much as a factor of three over the results already derived. A further effort to correlate the analysis with observed microflares (in conjunction with an on-going microflare program at UNH; e.g., Biesecker, 1994; Arndt et al. 1997) will be used to investigate the possibility of emissions directly from microflares.

We also propose to acquire two additional weeks of COMPTEL solar γ-ray data during cycle 7. For reasonable exposures, the Sun should be positioned within 25° of the COMPTEL (CGRO) z-axis. These observations should also be made at times when the Sun is located at high galactic latitudes ($b>25°$) in order to reduce effects from the presence of emissions (from both diffuse and point sources) along the galactic plane. This is especially important for cycle 7, given the much higher instrumental background which will be encountered as the result of a higher orbit. (This high-latitude constraint corresponds to observation times from Feb 1 to May 1 and from Aug 1 to Nov 1.)

Although COMPTEL is capable of making sensitive 10–150 MeV neutron measurements, only very limited neutron data is returned during the normal operating mode of COMPTEL. A more effective solar neutron mode is typically activated only upon the receipt of a special solar trigger from BATSE. On only one occasion (during the solar ToO of June 1991) was COMPTEL placed in solar neutron mode for an extended period. *In order to obtain a high quality measurement of the quiescent solar neutron emissions, we propose a one-week solar observation in solar neutron mode.* (These data need not be constrained to high galactic latitudes.) This same set of data may also be useful in a more detailed study of atmospheric albedo neutrons covering a broad range of geomagnetic parameters. Some of this time (~1 day) could also be used as an opportunity by the COMPTEL team to fine-tune the instrument settings which define the solar neutron mode in advance of the upcoming solar maximum. This may be especially important, given the very different character of the present COMPTEL background from that of 1991.

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