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A SEARCH FOR MEV GAMMA-RAY EMISSION FROM THE QUIET-TIME SUN

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ABSTRACT

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 solar particles (both electrons and ions) with the ambient solar material. However, there are several reasons to expect that γ-ray emission might also be detectable at times when there is no significant solar activity. We report on the first results of an effort to measure quiet-time γ-ray emissions using data from the COMPTEL experiment on the *Compton Gamma-Ray Observatory* (*CGRO*).

INTRODUCTION

Several mechanisms have been proposed which might be capable of producing detectable levels of γ-ray emission during periods of low solar activity. These include:

1) Processes related to the general problem of coronal heating may accelerate particles to non-thermal energies, in which case their interactions with the ambient solar material may lead to γ-ray and neutron emission.
2) The decay of long-lived radioactive isotopes produced in flares (Ramaty Kozlovsky & Lingenfelter 1979), may lead to detectable emission long after the flare itself. Of particular interest in this regard are the decays of ^{56}Co (emission at 0.847 and 1.238 MeV with a half-life of 77 days) and ^{54}Mn (emission at 0.835 MeV with a half-life of 303 days).
3) The precipitation of downstream shock-accelerated ions back to the solar surface from coronal mass ejections (e.g., Vestrand & Forrest 1993). Such coronal-mass ejections may or may not be associated with a visible solar flare.
4) The interaction of high energy cosmic rays with the solar atmosphere is expected to produce γ-ray and neutron emissions much like those generated by similar processes in the Earth's atmosphere (Seckel, Stanev & Gaisser 1991).
5) Some models involving the radiative decay of massive neutrinos imply that solar neutrino decay might result in the generation of MeV γ-rays in a region just outside the solar surface (Miller 1995).

We have been using data from the *COMPTEL* experiment on *CGRO* to search for quiet-time solar emissions. *COMPTEL* is a wide FoV instrument operating in the energy range of 0.75–30.0 MeV, precisely the energy range where many of these processes may be expected to operate. The wide FoV of *COMPTEL* implies that the solar pointing requirements are not too severe. Most of the available solar data comes from serendipitous observations. Furthermore, the imaging nature of each instrument improves the signal-to-noise relative to earlier solar γ-ray experiments (such as *SMM*), that provided only very broad ($\sim 2\pi$ sr) collimation. The results presented can be used for testing models of quiet-time acceleration processes.

QUIET-TIME PARTICLE ACCELERATION

One hypothesis that 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. These microflares have been observed at hard X-ray (Lin et al. 1984; Biesecker, 1995) as well as ultraviolet (Porter et al. 1987) wavelengths. 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 phenomenon, there is at least some indication that particle acceleration may be taking place (Lin et al., 1984). If indeed non-thermal 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.

In observed γ-ray flares, the total energy in accelerated nuclei of energies > 10 MeV/nucleon 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 *SMM-GRS* data to search for a quiescent level of 2.2 MeV line emission. No detectable level of 2.2 MeV emission was observed. An upper limit on the 2.2 MeV emission, obtained from the entire 9 year database of *SMM* observations, was given as 5.1×10^{-5} cm^{-2} s^{-1}. By assuming that the microflares are similar to observed γ-ray flares in terms of their accelerated ion spectrum and in terms of the fraction of total flare energy imparted to the accelerated ions, it was argued that microflares are insufficient to heat the quiet-time solar corona. However, the fraction of total flare energy carried by accelerated ions in an observable flare is poorly known, so it is difficult to estimate the total energy content of the accelerated 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.

If ions are accelerated in microflares, it is difficult to say anything about the nature of the resultant ion spectrum. One can assume (as did Harris et al.) that the ion spectral shape follows that of observable γ-ray flares, but there is no observational evidence to support this assumption. Moreover, the γ-ray lines which 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 below 1 MeV. These reactions lead to γ-ray line emission which might well 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 is offset by the number of protons which would be present if such a population were energetically important.

Another consideration regarding the importance of ion acceleration in microflares is the extent of the energy deposit. Since the observed X-ray emission from microflares is largely a thermal process, it requires that the flare energy deposit be limited over a relatively small spatial region. If, on the other hand, the energy deposit is spread out over a fairly large spatial region, then the X-ray component may become much weaker as a result of the lower overall plasma temperature. In either case, the γ-ray line component (if any) would remain relatively unchanged. So it is conceivable that microflares that are not visible in X-rays may still produce energetic ions which lead to γ-ray emission.

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). This model would generally predict a γ-ray precursor (possibly extending over several days) to a conventional solar flare. Pre-flare ion acceleration has also been postulated to enhance the γ-ray efficiency of small flares (Ryan and Simnett, 1989).

OBSERVATIONS AND DATA ANALYSIS

The present analysis covers the first five years of the *CGRO* mission. Only those observations were included in which the sun was within 30° of the *COMPTEL* viewing axis and in which the viewing direction was well away from the galactic plane. In addition, we restricted the analysis to periods far removed from any solar activity, especially the very active periods in 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. This resulted in a single integrated dataset centered on the Sun. Such datasets have now been generated for four separate energy bands: 1–10 MeV (for integrated nuclear line emission), 1.50–1.75 MeV (for the 1.63 MeV line from ^{20}Ne), 2.110–2.336 MeV (for the 2.22 MeV neutron capture line) and 7.80–8.35 MeV (for the 8.07 MeV line from proton capture on ^{13}C).

Separate maximum likelihood maps generated from each set of image data were used to search for evidence of emission in each energy band. There was no detectable flux in any of these energy bands. The 2σ upper limits derived from these data are: 2.1×10^{-5} cm^{-2} sec^{-1} MeV^{-1} in the 1–10 MeV range, 6.3×10^{-5} cm^{-2} sec^{-1} for the 1.63 MeV line, 4.1×10^{-5} cm^{-2} sec^{-1} for the 2.22 MeV line, and 1.9×10^{-5} cm^{-2} sec^{-1} for the 8.07 MeV line.

DISCUSSION

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 sec^{-1} for accelerated nuclei with $E > 10$ MeV. This is far below the level of $\sim 10^{28}$ ergs sec^{-1} required to heat the solar corona. Clearly, the quasi-continuous acceleration of > 10 MeV nuclei is not a viable mechanism for heating the solar corona.

The limit on the 8.07 MeV line flux, on the other hand, allows us to place constraints on the power input of nonthermal ions down to energies of ~ 0.5 MeV/nucleon (Mackinnon 1989). Because the energy loss rate of protons in the source, and thus their lifetime, depends on ambient temperature, constraints on total proton energy are similarly temperature-dependent (Figure 1). The observed upper limit on the 8.07 MeV flux implies an energy input rate for low-energy protons of $< 2 \times 10^{30}$ ergs sec^{-1}. Based on these data alone, we cannot rule out the possibility of coronal heating by low energy protons.

On-going efforts are presently focused on improving these limits by incorporating more of the available *COMPTEL* data and by using potentially more sensitive imaging methods. Being able to use more of the available data, for example, will require incorporating models for the galactic diffuse emission. Improvements in sensitivity may be obtained by using imaging algorithms that have been specifically developed for line emission. In this regard, the procedures developed by the *COMPTEL* team for use in imaging the 1.8 MeV line from ^{26}Al (Diehl et al. 1995) may be especially useful. We have already used this technique for imaging the full sky at 2.2 MeV (McConnell et al. 1997). It would be a straightforward effort to perform the same analysis with the solar data. In addition, time resolved studies will allow us to set limits on the emission as a function of solar cycle. Additional

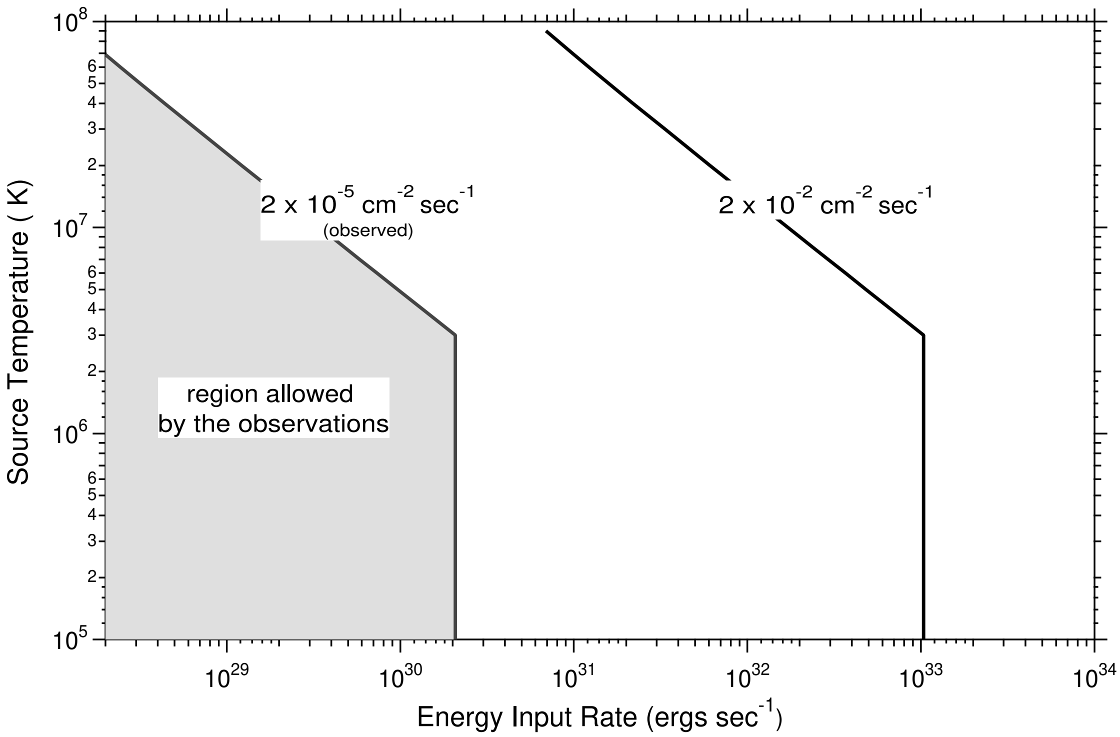

Fig. 1: Constraints on the coronal heating by protons of energies above 0.555 MeV, based on observations of the 8.07 MeV line flux. Higher ambient temperatures result in a greater rate of proton energy loss. This leads to a temperature-dependent constraint (MacKinnon 1989).

COMPTEL data will also be incorporated into these studies as they are collected during the next few years.

ACKNOWLEDGEMENTS

The *COMPTEL* project is supported by NASA under contract NAS5-26645, by the Deutsche Agentur für Raumfahrtgelenheiten (DARA) under grant 50 QV90968 and by the Netherlands Organization for Scientific Research NWO.

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