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FINAL REPORT

Title of Investigation: Analysis of γ -Ray Data from Solar Flares in Cycles 21 and 22

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One of our primary accomplishments under grant NAGW-35381 was the systematic derivation and compilation, for the first time, of physical parameters for all gamma-ray flares detected by the SMM GRS during its ten year lifetime. The flare parameters derived from the gamma-ray spectra include: bremsstrahlung fluence and best-fit power-law parameters, narrow nuclear line fluence, positron annihilation line fluence, neutron capture line fluence, and an indication of whether or not greater than 10 MeV emissions were present. We combined this compilation of flare parameters with our plots of counting rate time histories and flare spectra to construct an atlas of gamma-ray flare characteristics. The atlas time histories display four energy bands: 56-199 keV, 298526 keV, 4-8 MeV, and 10-25 MeV. These energy bands respectively measure nonrelativistic bremsstrahlung, trans-relativistic bremsstrahlung, nuclear de-excitation, and ultra-relativistic bremsstrahlung. The atlas spectra show the integrated high-energy spectra measured for all GRS flares and dissects them into electron bremsstrahlung, positron annihilation and nuclear emission components. The atlas has been accepted for publication in the *Astrophysical Journal Supplements* and is currently in press. The atlas materials were also supplied to the Solar Data Analysis Center at Goddard Space Flight Center and were made available through a web site at the University of New Hampshire. Since a uniform methodology was adopted for deriving the flare parameters, this atlas will be very useful for future statistical and correlative studies of solar flares—three independent groups are presently using it to correlate interplanetary energetic particle measurements with our gamma-ray measurements.

A better model for the response of the GRS instrument to high energy radiation was also developed. A refined response model was needed because the old model was not adequate for predicting the first and second escape peaks associated with strong nuclear lines nor could it accurately describe the Compton continuum shape. The new response was developed using a GEANT based simulation code and tested against preflight calibration data. The refinement of the response model and the removal of systematic errors now allow more detailed spectral studies of the GRS gamma-ray measurements. This refined response function was supplied to the Solar DAC at Goddard and was also made available

via a web site at the University of New Hampshire.

A very important scientific result was our discovery of a spatially extended component of gamma rays from solar flares. Our analysis of SMM/GRS measurements for a giant solar flare that occurred beyond the western solar limb on 1989 September 29 revealed a neutron capture line that is much stronger than predicted by limb-darkening curves that fit measurements for flares on the visible hemisphere. We were able to show that this strong neutron capture line emission can be explained if, in addition to the compact impulsive phase component that normally dominates the total fluence, there is a spatially extended component. For the 1989 September 29 flare we found that the spatially extended region must subtend more than $\sim 30^\circ$ on the solar surface. We concluded that the extended component is probably powered by particles that diffuse into the lower solar atmosphere from a large-scale acceleration site. Papers presenting these results were published in the *Astrophysical Journal Letters* and in conference proceedings. The results have important implications for the HESSI mission.

We wrote a comprehensive review of high energy observations made by the GRS and HXRBS instruments aboard SMM that will appear as a chapter in the SMM Multigraph—"The Many Faces of the Sun" that is being published by Springer-Verlag. The chapter examines our current understanding of particle acceleration by solar flares and focuses on how SMM observations changed the paradigm from particle acceleration as a special property of giant flares to a common process that occurs in all flares.

We completed a study of gamma-ray directivity from flares using the entire SMM GRS database. We found that the ratio of electron bremsstrahlung fluence to nuclear line fluence exhibits a center-to-limb dependence that is consistent with predictions inferred from our earlier studies of bremsstrahlung directivity. This new result strongly supports the idea that >300 keV bremsstrahlung emission is radiated anisotropically by flares. Another interesting result is that the complete data set, unlike cycle 21 subsample, contains a number of disk events that were detected above 10 MeV. Since the bremsstrahlung cross-sections are strongly beamed in the forward direction at energies above 10 MeV, the emission had to be generated by electrons moving away from the sun or by pion-decay secondary electrons. Our work on the spectra of the 9 Sep 1989 and 10 Mar 1989 disk

flares indicates that the latter possibility. This result indicates that the transport of high energy particles in flare loops plays an important role in regulating the flare radiation pattern.

Publications supported in whole or part by NAGW-35384:

“Evidence for a Spatially Extended Component of Gamma Rays from Solar Flares”, W.T. Vestrand and D.J. Forrest, *Ap. J. Letters*, 409, L69, (1993).

“Gamma-Rays from an ‘Over-the-Limb’ Flare”, W.T. Vestrand and D.J. Forrest, in *High Energy Solar Phenomena-A New Era of Spacecraft Measurements*, eds. J.M. Ryan and W.T. Vestrand (New York:AIP), p. 143, (1994).

“OSSE Observations of Solar Flares”, R.J. Murphy et al., in *Compton Gamma-Ray Observatory*, eds. M. Friedlander et al. (New York:AIP), p. 619, (1993).

“On the Origin of Gamma-Ray Emission from the Behind-the-Limb Flare on 29 September 1989”, Cliver, E.W., Kahler, S.W., and Vestrand, W.T., *Proc. of 23rd International Cosmic Ray Conference*, vol. 3, p. 91, (1993).

“Hard X-Ray Polarimetry of Solar Flares”, M. McConnell, D. Forrest, W.T. Vestrand, and M. Finger, in *High Energy Solar Physics*, eds. R. Ramaty et al. (New York:AIP), p. 368.

“Particle Acceleration during Solar Flares”, W.T. Vestrand and J.A. Miller, in *The Many Faces of the Sun: The Scientific Results of the Solar Maximum Mission*, (Springer-Verlag), in press.

“The Solar Maximum Mission Atlas of Gamma Ray Flares” W.T. Vestrand et al., *Ap. J. Supplements*, in press.