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ABUNDANCES FROM SOLAR FLARE LINE SPECTROSCOPY

Final Report

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ABSTRACT

The work performed during the six-month contract period is summarized. Most of this work was devoted to updating and improving the computer codes used in the abundance analyses of solar-flare gamma-ray data. These modifications are itemized in detail. The abundance analysis technique was then applied to data obtained by the Gamma-Ray Spectrometer (GRS)of the Solar Maximun Mission (SMM) spacecraft for the 27 April 1981 solar flare to set constraints on the interacting-particle angular distribution. The results are presented and a copy of the article submitted to the Astrophysical Journal is included. In addition, research in several other areas was performed during the contract period and they are discussed.

INTRODUCTION

The technique that has been developed for the determination of abundances using solar-flare gamma-ray data consists primarily of two computer codes. One code calculates theoretical gamma-ray spectra expected from solar flares and the other uses observed gamma-ray data to determine the best-fitting intensities of the individual components which have been identified to constitute gamma-ray spectra. Substantial improvements to these two codes have been accomplished and are detailed in the first two following sections.

The improved codes were then applied to the data obtained by the SMM/GRS from the 27 April 1981 solar flare to set constraints on the angular distribution of the interacting accelerated particles. Both idealized distributions and distributions resulting from a magnetic-loop propagation model incorporating converging magnetic fields and MHD pitch-angle scattering were investigated. The results are discussed and a copy of the paper submitted to the Astrophysical Journal is included.

Research in three other areas of gamma-ray astrophysics was performed (two of which were solar and one galactic) and the results and/or progress of each is discussed. These were: (1)A statistical study of a large number of solar flares was initiated using data existing in the SMM/GRS data base. The focus is on the flare-to-flare variation of the electrons and nuclei which produce the gamma rays. As the next solar maximum developes, new data will be constantly added to the data base until the spacecraft (whose orbit is, unfortunately, decaying) finally loses attitude control. (2)The abundance analysis technique was used to determine the fraction of the 2.223 MeV neutron-capture line radiation present in the 3 June 1982 solar flare was Compton scattered in the solar atmosphere. This work is in support of work initiated at the University of New Hampshire by Tom Vestrand. (3)The flux in the 4.44 MeV ^{12}C line and the ~5.2 MeV ^{16}O spallation lines resulting from a relativistic proton beam from a pulsar impinging on a Wolf-Rayet companion star was calculated.

GAMMA-RAY PRODUCTION COMPUTER CODE

The fundamental theoretical tool used in abundance analyses of solar-flare gamma-ray spectral observations is a computer code which calculates the detailed gamma-ray spectrum expected from a flare. This code was developed previously and incorporates a number of assumptions and approximations. Laboratory data exists which can be used to improve this calculation. The first effort under the Guest Investigator Program was therefore to incorporate this data and to check the assumptions. The following three specific areas were addressed:

1. Previously, the angular distribution of the recoil nucleus in inelastic excitation reactions involving nuclei heavier than oxygen was assumed to be similar to that of carbon. Laboratory data on this distribution for several excited states of neon, magnesium and silicon at several incident proton energies is available. This data has been used to improve the modeling of the distribution from such heavy nuclei.

2. The energy and angular distribution of the recoil nucleus in spallation reactions was calculated using a very simplistic model. This model has been significantly improved by assuming that the recoil angular distribution is isotropic and its energy distribution is given by a phase-space distribution for three particles.

3. A previous, model-independent analysis of the 27 April 1981 solar flare showed that the derived values for the narrow-line parameters were very sensitive to the assumed shape of

the underlying continuum. A dominant component of this continuum is the large number of unresolvable, narrow, relatively weak lines from nuclei heavier than oxygen. The modeling of this "continuum" has been improved using laboratory data of the gamma-ray spectrum produced by the bombardment of various target nuclei by protons of several incident energies.

Further improvements in this computer code were undertaken. Previously, the angular distribution of the recoil nucleus in inelastic excitation reactions involving nuclei heavier than oxygen was assumed to be similar to that of the J=2 excited state of 12C which is peaked in the backward direction. Heavier elements have many excited states which, through cscades, populate the upper level of the transition giving rise to a particular gamma-ray. These excited states (with spin J>2) are produced with angular distributions that are much more isotropic than that of J=2. This isotropic distribution in the center of mass can give rise to higher recoil velocities in the laboratory system which may affect the line width. To incorporate the contribution of these higher levels, we have constructed representative angular distributions composed of equal contributions from scattering to the J=2 and J=4 excited states. Three energy ranges were established and distributions were constructed using several sources of laboratory data.

SPECTRAL-FITTING COMPUTER CODE

The other fundamental theoretical tool used the determination of ambient solar abundances from solar-flare gamma-ray data is a computer code that determines the best fit amplitudes of the several components which have been indentified to constitute flare spectra. The total gamma-ray spectrum is the sum of these components and the code determines the relative amplitudes of these components which best reproduce an observed spectrum. Since the total spectrum is linear in the amplitudes, the fitting procedure is exact in that it involves a matrix manipulation rather than an explicit search. One of the spectral components is a power law which approximates the electron bremsstrahlung spectrum. The power-law index is then another parameter which must be adjusted along with the amplitudes but its dependence is not linear. Previously, a specific index was assumed, a fit was obtained, then the index changed and a new fit was obtained. This was repeated until a good fit to the data was achieved. This process was time consuming and yielded a fit whose goodness was limited by the size of the increment chosen for the index. A new code was written in which the index is automatically found to arbitrary precision using a parabolic search technique.

When the weighted least-squares fitting technique is used to determine ambient abundances, the library of gamma-ray spectral files consists, in part, of 12 elemental files: the gamma-ray spectra resulting from interactions of a population of accelerated particles (of assumed composition) with each of the 12 most-abundant elements in the ambient solar atmosphere (H, He, C, N, O, Ne, Mg, Al, Si, S, Ca and Fe). The resulting relative best-fit amplitudes of these spectra should represent the corresponding relative ambient abundances. For those ambient elements heavier than He, the spectra are produced primarily by accelerated protons and α particles only since heavy-heavy interactions are negligible, their abundances being smaller than that of the protons by a factor of about 10^4. Furthermore, since the α-to-p ratio of solar material is generally less than 0.10, these spectra are generated almost exclusively by the protons only. It is for this reason that the resulting best-fit abundances of these heavy ambient elements relative to each other are essentially independent of the assumed accelerated-particle composition.

This is not true for ambient H and He. For He, the spectrum consists of three lines resulting from α-He fusion interactions producing ^{6}Li, ^{7}Li and ^{7}Be and a large number of very broad lines resulting from deexcitations of accelerated particles heavier than He interacting with ambient He. (There are no excited states of He which relax via gamma-ray emission so there are no deexcitation gamma rays from He itself.) Similarly, since there are no excited states of H, the ambient H spectra consists only of very broad lines resulting from deexcitations of accelerated particles heavier than He interacting with ambient H. As a result, the ambient H and He spectra both are produced exclusively by accelerated particles heavier than protons. Therefore, the derived abundances of ambient H and He relative to those of the heavier ambient elements do depend on the assumed proton-to-heavier element composition ratio assumed for the accelerated particles. This dependence of the derived H and He abundances relative to the heavier abundances is an unavoidable systematic uncertainty since the accelerated-particle composition for a given flare is unknown. The derived ambient H and He abundances relative to each other and relative to the heavier elements have no useful significance.

However, with some modification to the library, some useful information can be obtained. We have now separated the two ambient H and He spectra into the following eight components: the spectrum resulting from interactions of accelerated α particles with ambient He and the seven spectra resulting from interactions of each of the 7 accelerated-particle elemental nuclei (C, N, O, Ne, Mg, Si and Fe) interacting with ambient H and He. The ambient He-to-H ratio is, of course, not known but, since it is most probably less than 0.10, the spectra are dominated by interactions with H. A photospheric ratio of 0.067 was assumed. Since the gamma-ray yields from S, Al and Ca are quite weak, the spectrum resulting from accelerated S was combined with that of accelerated C with a photospheric [S]/[C] composition ratio and those of accelerated Al and Ca were combined with that of accelerated Fe with photosperic [Al]/[Fe] and [Ca]/[Fe] composition ratios. The choices of combination these particular were based on first-ionization potential considerations. These eight spectra include all of the gamma-ray interactions which were present in the original two ambient H and He spectra.

The elemental part of the spectral library now contains 18 spectra in 3 sets: ten spectra consisting of accelerated p-α interactions with ambient C, N, O, Ne, Mg, Al, Si, S, Ca and Fe, seven spectra consisting of accelerated C, N, O, Ne, Mg, Si, and Fe interacting with ambient H-He, and the spectrum consisting of the three lines from α-He interactions. The derived abundances of the ambient elements relative to each other and of the accelerated elements relative to each other are essentially independent of compositional assumptions. The overall relative abundances of the 3 sets, however, are not. In particular, the α-He "abundance" is now useful only as a measure of the best-fit fluences in the α-He fusion lines. Including the positron-annihilation, the neutron-capture and the electron-bremsstrahlung power-law spectra, the total number of adjustable parameters is now 21 (for the individual spectra) plus one (for the power-law index).

The new library was used to reanalyze the gamma-ray spectrum obtained from the 27 April 1981 solar flare. With the increased number of adjustable parameters, χ^2 necessarily decreased (from 507.5 to 462.6). What is more important, the confidence in the fit increased from <1% to 12%, even though the number of degrees of freedom decreased. The essential result of the previous analysis of 27 April remained intact: the suppression of ambient C and O by factors of 3 to 4 relative to Ne, Mg, Si and Fe. A further improvement in the fitting confidence was achieved when the energy range over which the fit was attempted was reduced. Previously, the fit was obtained from 0.3 to 8.5 MeV. It could be seen that the bulk of the contribution to χ^2 was coming from the lowest-energy channels. The reason for this may be due to inaccuracies in the numerical model of the SMM/GRS detector response used to convert trial gamma-ray spectra into pulse-height spectra for comparison with observations. The only spectral features at these low energies of any importance are the ~0.45 MeV α-He fusion lines and the 0.511 MeV positron-annihilation line. Since the derived α-He "abundance" is useless and since the positron annihilation line cannot be adequately resolved from the α-He feature, the lower limit to the fitting region was changed to 0.7 MeV. Since there are no significant spectral features above ~7 MeV, the upper limit was changed to 7.1 MeV. As a result, χ^2 decreased to 341.5 corresponding to a 33% confidence level. The essential ambient-element result was again obtained and the derived accelerated-particle abundances showed a similar supression of C and O, although the associated uncertainties are much larger.

ACCELERATED-PARTICLE ANGULAR DISTRIBUTION

The gamma-ray spectrum obtained by the Solar Maxixmum Mission spectrometer from the solar flare that occurred on 27 April 1981 was particularly rich in nuclear gamma-ray lines. We used this data previously in the first determination of solar abundances using gamma-ray spectrometry. In a recent paper, we have calculated in detail the profiles of the two gamma-ray lines resulting from interactions of accelerated alpha particles with ambient He. These profiles were found to be quite sensitive to the angular distribution of the interacting accelerated particles. Using the spectral-fitting code discussed above, we have reanalyzed the data from the 27 April flare to determine whether constraints could be placed on this distribution.

Using the least-squares fitting procedure developed for abundance determinations, data from the 27 April 1981 limb flare was compared with calculations for three angular distributions of the accelerated α particles: isotropic, downward beam and fan beam (parallel to the solar surface). (The latter distribution results from α-particle propagation in a converging magnetic loop.) First, it was established for the first time that the α-He lines have, in fact, been observed from a solar flare, as predicted in 1974 by Kozlovsky and Ramaty. Furthermore, it was found that the isotopic and fan-beam models gave acceptable fits (confidence levels of 53 and 51%, respectively) but the downward-beam model did not (12%). For limb flares, the gamma-ray spectra resulting from isotropic and fan-beam distributions are essentially indistinguishable but are quite distinct from that from a downward-beam distribution. However, for disc-centered flares, the fan-beam spectrum is identical to that from the downward-beam on the limb, while the isotropic spectrum is, of course, the same (see Murphy, Kozlovsky and Ramaty 1988). Therefore, an analysis of a disc-centered flare with counting statistics similar to the 27 April limb flare will be able to distinguish between the isotropic and fan-beam distributions.

Recent calculations by R. Ramaty and X.-M. Hua concerning the depth and angular distributions of interacting α particles in converging magnetic loops with and without pitch-angle scattering have been used to generate more realistic gamma-ray line profiles than those obtained from the idealized angular distributions. It was found that, while the data was of sufficient quality to distinguish limb-flare models from disc-flare models, it was not sufficient to distinguish between models incorporating pitch-angle scattering and models without. Again, it is expected that this can be done using high-quality data from a disc-centered flare.

The paper is complete and has been submitted to the Astrophysical Journal for publication. The results were presented at the Gamma-Ray Observatory Workshop held at Goddard Space Flight Center in April and at the May APS meeting in Baltimore. A copy is included.

STATISTICAL STUDIES OF SOLAR FLARES

Gerry Share has provided background-subtracted gamma-ray spectra of 33 flares observed with the SMM gamma-ray spectrometer. Initial analysis has begun using a Gaussian-fitting procedure developed during my NRC post-doctoral appointment at NRL. This technique will allow, at the very least, the comparison of the total gamma-ray production due electrons with that due to nuclei and the determination of the best-fit spectra of the electron bremsstrahlung, all parameterized by flare location on the solar disc. Preliminary results indicate that the dependence of the bermsstrahlung-to-nuclear fluence ratio expected from anisotropic electron distributions is present in the data. Also, the expected spectral hardening of the electrom emission is present. Further analysis is required to establish the absence of any systematic biasing that may be present in the procedure. Additional analysis will include abundance determinations for those flares for which the statistical significance of the data is adequate.

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As required by the SMM/GRS team publication policy, Tom Vestrand of the University of New Hampshire circulated among the team members a notification of intended research using SMM solar-flare data. This policy keeps the other team members informed of current research topics and thus allows them to become involved when they believe they can contribute to a particular research topic. Tom planned to calculate the expected spectrum of the Compton-scattered continuum from the 2.223 MeV neutron-capture line and then the ratio of the fluence in the 1.0-to-2.223 Mev portion of that continuum to the fluence in the 2.223 MeV line itself, parameterized by the accelerated-particle kinetic-energy spectrum and angular distribution, the depth of produc-tion, and flare position. This ratio should be quite sensitive to the amount of material the escaping gamma rays must traverse. He would then compare his calculations to SMM data obtained after the impulsive phase of the large solar flare which occurred on 3 June 1982. (After the impulsive phase, the 2.223 MeV line and its continuum is still strong, while nuclear gamma-ray emission is reduced.) Critical to such a comparison is determining what fraction of the gamma-ray spectrum observed between 1 and 2.223 MeV is to be attributed to Compton-scattered photons and what fraction to gamma rays from other nuclear-reaction sources. We believe that, with the abundance-determining technique we have developed, we could make an important contribution to this latter aspect. The least-squares fitting procedure was modified appropriately and applied to the 3 June data, the fit being optimized over the energy range 1.0 to 7.2 MeV. We found that the data was consistent with a Compton continuum-to-line ratio of 0.55 ± 0.17. This is similar to the value Tom had determined previously. However, when the fit-optimization range lower-limit was lowered from 1.0 to 0.3 MeV, the derived value for the ratio decreased to 0.34 ± 0.10, suggesting considerable sensitivity to the fitting-range chosen. The results were reported to Tom.

GAMMA-RAY PRODUCTION BY PULSARS

I was invited by Rein Silberberg to contribute to a paper concerning gamma-ray production by relativistic pulsar beams impinging on a companion Wolf-Rayet star. With some modifications, the gamma-ray production code developed previously is well-suited for such a study. The gamma-ray production from a pulsar-generated beam of protons impinging on the hydrogen-depleted atmosphere of the companion star was calculated for several angles of observation. It was determined that the resulting fluxes were marginally observable by the GRO if the source is located at a distance of 1 kpc. The paper was presented at the Gamma-Ray Observatory Workshop and will be included in the workshop proceedings. A copy is included.