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The Origin and Implications of Gamma Rays from Solar Flares*

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The principal aim of gamma-ray astronomy is the study of the origin, distributions and interactions of energetic particles in the cosmos. While energetic electrons reveal their existence by radiating a variety of electromagnetic emissions, energetic nuclei radiate almost exclusively in the gamma-ray region.

Solar flares accelerate both electrons and nuclei. But until the advent of solar gamma-ray astronomy, observations in the radio and x-ray bands revealed the existence of only the electronic component in the flare region itself.

Solar gamma-ray astronomy was established as an observational science in 1972. The first gamma-ray lines from solar flares were observed in that year, when an instrument designed at the University of New Hampshire and flown in the wheel of the seventh orbiting solar observatory (OSO-7) detected gamma rays from the large (3B) flares of August 4 and 7, 1972. Hard photons from these flares ranged in energy up to almost 10^7eV, and consisted of both emission lines and continuum. Detailed theoretical work, carried out both before and after the observations supports the conclusion that the observed lines at 0.51, 2.2, 4.4 and 6.2 MeV are due to positron annihilation, neutron capture on hydrogen, and deexcitation of nuclear levels in carbon, nitrogen, and oxygen, and that the continuum is most likely bremsstrahlung (braking radiation) of relativistic electrons. We discuss now how these gamma rays are formed, what their properties are, and how they contribute to the understanding of the physics of flares.

The basic mechanism for the production of gamma rays in solar flares are interactions between accelerated charged particles and the ambient solar atmosphere. These interactions excite nuclear levels which decay by emitting high-energy photons, they generate neutrons, they produce π mesons and radioactive nuclei which emit gamma rays and positrons, and they produce bremsstrahlung which extends into the gamma-ray region provided that the accelerated particles have sufficiently high energies.

Gamma-ray lines from excited nuclei such as the line at 4.4 MeV from ^{12}C may be considered as prompt emissions because the excited levels decay in time intervals which are much shorter than any of the characteristic times of the flare. They serve, therefore, as excellent tracers of the time dependence of the nuclear reaction rates. These rates are directly proportional to the instantaneous numbers of accelerated particles in the interaction region, which, in turn, are determined by the acceleration mechanism and the losses suffered by the particles. The very important question of whether protons and electrons are accelerated by the same mechanism can be best studied by observing simultaneously gamma-ray lines and continuum. The presently available observations, however, are not sufficiently accurate to provide clear-cut answers and hence more measurements are needed.

The production of the lines at 2.2 MeV and 0.5 MeV lines involves the more complex processes of neutron capture and positron annihilation.

Neutrons in solar flares result mainly from the dissintegration of ^{4}He nuclei in proton-alpha particle interactions. These interactions take place in the chromosphere or lower corona and they produce neutrons with energies from about 10^{6}eV to 10^{8}eV. Because the neutrons do not interact with magnetic fields, an initially upward moving neutron escapes from the Sun. Some of these escaping neutrons, especially those with high energies, may be detected near Earth. An experiment to detect solar neutrons in the interplanetary medium, however, has not yet been successfully carried out. A fraction of the downward moving neutrons can also escape after being backscattered elastically by ambient protons, but most of these neutrons either are captured or decay at the Sun. But because the probability for elastic scattering is much larger than the capture probability, the majority of the neutrons are thermalized before they get captured. This thermalization erases the effects that possible directional anisotropies of the charged particles may have on the 2.2 MeV line. It also leads to the conclusion that this line has an extremely narrow width of only about 100eV. The energy of the 2.2 MeV line has been measured in the laboratory and is 2223.351 ± 0.046 keV.

Neutrons in the photosphere are captured by protons or ^{3}He nuclei, or they decay. Only capture by protons, however, produces gamma rays, since capture by ^{3}He results in tritium without emitting photons. The latter process has, nevertheless, considerable astrophysical importance because it can place an upper limit on the photospheric ^{3}He abundance. This is achieved in the following manner: The detection of line emission at 2.2 MeV implies that not all the neutrons were absorbed by ^{3}He and hence the photospheric ^{3}He abundance cannot be arbitrarily large. When reasonable values are used for the other parameters of the accelerated particles, the upper limit on the photospheric ^{3}He abundance is of the same order as the measured abundance in the solar wind. Neutron capture is at present the only method for assessing the abundance of ^{3}He in the photosphere. This abundance is of considerable importance for the problem of solar neutrino emission and the question of element synthesis in the big bang or primeval fireball that started the evolution of the universe.

From the comparison of the observed and calculated intensities of the lines at 4.4 MeV and 2.2 MeV it is possible to obtain information on the energy spectrum of accelerated nuclei in flares. This follows from the fact that excited states in nuclei are produced on the average by protons of lower energies than those which produce neutrons; hence the ratio of the two lines depends quite strongly on the proton energy spectrum. This method gives information on protons of energies from about 10^7 to 10^8eV. Spectral information at higher energies could be best obtained by observing the products of high-energy interactions such as photons from π° decay and high energy neutrons that survive during transit from the Sun to Earth.

From the absolute intensity of gamma-ray lines it is possible to deduce the total energy deposited by the accelerated nuclei in the flare region. For the 1972, August 4 flare, the protons which are responsible for gamma-ray emission produce only a few percent of the energy generated by the electrons which make the implusive hard x-rays. Nevertheless, protons could deposit their energy in regions which are not accessible to electrons because they have a longer stopping range in the ambient medium than the electrons.

Positrons in solar flares result from the decay of π^+ mesons and various radioactive nuclei produced by the nuclear reactions. The half lives of these positron emitters range from values less than 1 second to about 20 minutes and they produce positrons of energies from a few times 10^5eV to about 10^8eV. After their production, the positrons are decelerated to energies less than 10^3eV where they can annihilate. This deceleration is achieved by interactions with the ambient solar atmosphere, and hence the deceleration time depends on the density and magnetic field of the medium in which the positrons annihilate. A fraction of the positrons may escape from the flare region and could be detected in the interplanetary medium as relativistic particles. (No such measurements have yet been made.) The annihilation process itself is quite complicated. The positrons can annihilate with free electrons to produce two 0.51 MeV gamma rays per annihilation, or they may form a positronium atom. This atom is similar to the hydrogen atom except that the proton is replaced by a positron. Positronium atoms also annihilate into gamma rays: annihilation from the singlet spin state produces two 0.51 MeV photons, and the triplet state annihilates into three photons of energies less than 0.51 MeV. It appears that future gamma-ray detectors with good energy resolution may resolve radiation from positronium annihilation and thereby detect the existence of this exotic atomic species in solar flares.

As a result of the finite capture time of the neutrons in the photosphere, and the half lives of the positron emitters and deceleration times of the positrons, both the 2.2 MeV and 0.51 MeV lines are considerably delayed with respect to the prompt nuclear deexcitation lines. This result is verified by observational data from the flare of

August 7, 1972: at a time when all prompt emissions were very small, the 2.2 MeV and 0.51 MeV lines were still observable.

Thus, both the 2.2 MeV and 0.51 MeV lines from solar flares present time dependences which reflect not only the histories of the charged particles but also the physical conditions of the gamma-ray producing regions. These conditions could be best studied by simultaneously observing a prompt gamma-ray line such as the line at 4.4 MeV from ^{12}C and the delayed 2.2 MeV and 0.51 MeV lines. The former would unambiguously determine the time history of the accelerated nuclei, while the latter would provide valuable information on the physics of neutrons and positrons in solar flares, and on the physical conditions of the gamma-ray producing regions.

The possibility for detecting gamma-ray lines from an astronomical source depends not only on the strength of the lines but also on their widths. The narrower the line the easier it can be resolved from background provided that the detector has good energy resolution.

Line broadening is caused by the Doppler effect which shifts the energy of a photon emitted by a moving source, upward or downward in energy depending on whether the source moves toward or away from the observer. There are two kinds of Doppler broadening of gamma-ray lines from solar flares. Thermal broadening which influences mainly the positron-annihilation and neutron-capture radiations, and kinematical broadening which affects the nuclear excitation lines.

Because positrons and neutrons thermalize before they produce gamma rays, the widths of the 0.51 and 2.2 MeV lines depend on the temperature of the particles before annihilation or capture. It turns out that the width of the 0.51 MeV line is a very sensitive thermometer of the ambient medium in the annihilation region. While the presently available measurement can only set upper limits (at about 10^7 degrees kelvin), future measurements may be able to measure temperatures as low as 2×10^4 degrees.

Because the 2.2 MeV line is formed in the photosphere where the temperature is known, its width can be calculated. It is found that the 2.2 MeV line has a width of only 100eV, a value much smaller than the width of any other gamma-ray line from solar flares. This result, coupled with the fact that the 2.2 MeV line is the most intense line from flares, implies that this line could be observable with high resolution detectors not only from major events such as those in August, 1972, but also from smaller flares.

Kinematical broadening is due to the fact that nuclear gamma rays are produced by fast particles which not only excite the levels but also impart kinetic energy to the nuclei. The gamma rays are therefore emitted by moving sources whose velocities tend to reflect the velocity distribution of the fast particles.

The kinematical width of the 4.4 MeV nuclear excitation line from ^{12}C is about 100 keV. The width of the 0.85 MeV line from ^{56}Fe (not yet detected) is only a few keV, because this nucleus is so massive that it acquires only a very small velocity when it is excited by a fast proton. Thus, eventhough iron is much less abundant than carbon in the solar atmosphere, its lines may be relatively easy to observe with a high resolution detector. The large kinematical Doppler shift of the 4.4 MeV line, however, may be used to detect anisotropies in the angular distribution of protons in solar flares.

In summary, solar flares may be studied in the gamma-ray region, and this study can provide essential information on accelerated nuclei that can be obtained in no other way. A multitude of physical processes, such as particle acceleration, nuclear reactions, positron and neutron physics, and kinematical line broadening, come into consideration at gamma-ray energies. Gamma-ray observations are complementary to hard x-ray observations since both provide information on accelerated particles. But it appears that only in the gamma-ray region do these particles produce distinct spectral lines.

All the presently available observational data on solar gamma rays has come from only two large flares. It is hoped that more data will be forthcoming during the next solar maximum.

The first observations of gamma-ray lines from solar flares were reported by Chupp, E. L., Forrest, D. J., Higbie, P. R., Suri, A. N., Tsai, C. and Dunphy, P. P. 1973, Nature <u>241</u>, 333.

Various aspects of the theory of solar gamma rays were treated by Lingenfelter, R. E. and Ramaty, R. 1967, High Energy Nuclear Reactions in Astrophysics, edited by B.S.P. Shen (W. A. Benjamin, New York), p. 99. Ramaty, R., Kozlovsky, B., Lingenfelter, R. E. 1975, Space Science Review, in press.