Solar Flares: Gamma Rays

In press: Encyclopedia for Astronomy (Macmillan)

OVERVIEW

Electromagnetic radiation extends over a very broad range of wavelengths, from gamma rays at the shortest wavelengths to radio waves at the long-wavelength end of the spectrum. In terms of photon energies, gamma rays are at the high end of the spectrum, starting at a few tenths of an MeV. This unit of energy (1 MeV = 1.6 × 10^-13 joule) is used throughout this article. In solar flares, as at many other astrophysical sites, gamma-ray emission results from interactions of fast particles with an underlying ambient medium. These fast particles, protons, α particles, heavier nuclei and electrons, are accelerated from the ambient plasma by the electric fields associated with the complex and varying magnetic fields in the flaring solar atmosphere. Thus, solar flare gamma rays can teach us about the mechanisms that accelerate the particles, in particular those which yield particles with energies in excess of about 1 MeV, the minimum energy needed to produce gamma rays. This is quite important for the understanding of flare mechanisms, because such protons and α particles, along with lower energy electrons, contain the bulk of the energy released in flares. In addition, the solar flare gamma-ray emission exhibits characteristic spectral lines which provide information on the elemental composition of the ambient solar atmosphere.

Gamma-ray production mechanisms

Solar flare gamma-ray emission exhibits both lines and continuum (Fig. 1). This theoretical spectrum extends over the entire energy range in which gamma rays from flares were observed. The lines appear at energies from about 0.5 to 8 MeV, whereas the continuum extends up to at least 1000 MeV. Up to about 1 MeV, and again from about 10 to 50 MeV, the continuum is dominated by bremsstrahlung produced by the braking of the accelerated electrons in the Coulomb fields of the ambient nuclei and electrons. The bremsstrahlung produced by ultrarelativistic electrons is strongly collimated along the direction of motion of the electrons. The lines result from the deexcitation of nuclei, from the capture of neutrons, and from the annihilation of positrons. The relevant nuclear cross sections are available from accelerator measurements. Deexcitation lines are either narrow or broad. Narrow lines result from the bombarding of ambient nuclei by accelerated protons and α particles, while broad lines result from the inverse reactions in which accelerated C and heavier nuclei collide with ambient H and He. The strongest narrow deexcitation lines are at 6.129 MeV from 16O, 4.438 MeV from 12C, 1.779 MeV from 28Si, 1.634 MeV from 20Ne, 1.369 MeV from 24Mg and 0.847 MeV from 56Fe. The broad lines merge into a quasi-continuum above the bremsstrahlung between about 1 and 8 MeV. The broadening of the deexcitation lines is the consequence of the Doppler shifting of the essentially monochromatic radiation produced in the rest frame of the excited nuclei. In the case of the narrow lines the broadening is due to the recoil velocity of the excited nuclei which is quite small. The widths of the broad lines are much larger because the excited nuclei continue to move rapidly after their excitation.

The strong, very narrow line at 2.223 MeV is due to neutron capture. All accelerated ions (protons and heavier nuclei) produce neutrons. The dominant neutron production mode in solar flares is the breakup of He nuclei, both in the accelerated particles and the ambient medium. Along with the deexcitation lines, the neutrons are produced at sites most likely located in the chromospheric portions of magnetic loops. The neutrons propagate both upward, away from the Sun, and downward into the photosphere where they are first thermalized by elastic collisions with protons and subsequently captured mostly by protons to produce deuterium and essentially monoenergetic photons at 2.223 MeV, the binding energy of deuterium. The neutrons moving away from the Sun can reach Earth where they were detected with ground-based and Earth-orbiting instruments. The protons resulting from neutron decay in the interplanetary medium were also detected.

The 2.223 MeV neutron capture line is very narrow
Figure 2: Time dependencies. The upper panel exhibits the impulsive nature of the gamma-ray emission, along with the associated high frequency radio emission. In contrast, the lower shows gamma-ray emission extending over many hours.

because it is broadened by only the relatively low photospheric temperature of about 6000 K. Because the production site of the 2.223 MeV line is situated much deeper than that of the nuclear deexcitation lines, the 2.223 MeV line can be attenuated resulting in limb darkening. This means that for flares located at or near the solar limb, the intensity of the line is much weaker than that of the deexcitation lines, in contrast with disk flares located far from the limb for which the 2.223 MeV line is the strongest. A competing mode of neutron capture in the photosphere is that on \(^3\)He. This has been used to obtain information on the photospheric \(^3\)He abundance.

Another strong narrow line is that at 0.511 MeV from positron annihilation (Fig. 1). The positrons result mainly from the decay of various short lived radioactive nuclei, for example \(^{11}\)C, \(^{13}\)N and \(^{15}\)O, which are also produced by interactions of the accelerated ions. The positrons subsequently either annihilate directly into 0.511 MeV gamma rays, or form positronium (an atom analogous to hydrogen with the nuclear proton replaced by a positron), which also annihilates into gamma rays. Positronium annihilation leads to both line emission at 0.511 MeV and continuum below this energy. The positronium continuum (denoted by Ps) can be seen in Fig. 1 at energies just below the \(e^+\) (0.511 MeV) line. The width of this line is very sensitive to the temperature of the medium in which the positrons annihilate. For the calculations of Fig. 1 it was assumed that the positrons annihilate in the chromosphere.

Two strong lines result from the interactions of \(\alpha\) particles with He. Fast and ambient \(^4\)He nuclei fuse into \(^7\)Li and \(^7\)Be which are born either in their ground states or in their respective excited states at 0.429 and 0.478 MeV. Because of Doppler broadening, the ensuing deexcitations produce a relatively broad emission feature centered around 0.45 MeV (except under conditions of strong accelerated particle anisotropy when the two lines are narrowed into separate distinguishable features). The combined feature, generally referred to as the \(\alpha\alpha\) line, can be seen in Fig. 1, superposed on the Ps and bremsstrahlung continua. Along with the \(\alpha\alpha\) line, there are several other lines which can only be excited by accelerated \(\alpha\) particles, as well as lines which are excited exclusively by accelerated \(^3\)He nuclei. The latter are of interest because of the very large \(^3\)He abundances observed in accelerated particles from impulsive flares (see below). The lines in question are at 1.00, 1.05 and 1.19 MeV, and at 0.937, 1.04 and 1.08 MeV, from \(\alpha\) particle and \(^3\)He induced reactions, respectively.

At high energies the continuum in some flares is dominated by pion decay radiation. Neutral and charged pions are produced mostly in high energy (greater than hundreds of MeV) proton-proton, proton-\(\alpha\) particle and \(\alpha\)-\(\alpha\) interactions. Neutral pions decay directly into two photons, while charged pions decay (via muons) into secondary electrons and positrons which produce gamma rays via bremsstrahlung and annihilation in flight. The combined pion decay radiation is shown in Fig. 1.

The data and their implications

Gamma-ray lines from solar flares were first observed in 1972 with a detector flown on spacecraft. But it was not until 1980 that routine observations of gamma-ray lines and continuum became possible with the much more sensitive spectrometer on the Solar Maximum Mission (SMM), a spacecraft that carried out successful solar observations for almost a decade. During that period, gamma-ray observations were also carried out with a smaller instrument on the Japanese spacecraft HINOTORI. During the 1990’s, solar flare gamma rays have been detected with instruments on the COMPTON GAMMA RAY OBSERVATORY (CGRO). This observatory was launched in 1991, and it is expected that it will continue to operate well into the first decade of the
21st century. Additional solar gamma-ray observations during this period were carried out with instruments on the GRANAT and GAMMA-1 spacecraft, which are no longer operational, as well as with a small detector on the YOHKOH spacecraft which continues functioning. Starting in 2000, a new spacecraft, the High Energy Solar Spectroscopic Imager (HESSI), will carry out solar flare X-ray and gamma-ray observations. The main implications of the already available data are the following:

Flare energy release

Hard X-ray observations of solar flares demonstrated that a major fraction of the released flare energy resides in sub-relativistic electrons of energies above 0.02 MeV. This, together with the observed impulsiveness of the hard X-rays, strongly suggested that electron acceleration to these subrelativistic energies is closely associated with the process that releases the flare energy initially stored in magnetic fields. But prior to the availability of gamma-ray data, the accepted paradigm was that ion acceleration is only a secondary manifestation of the flare energy release process. The gamma-ray emission, however, turned out also to be very impulsive. Moreover, recent studies based on the relative intensities of gamma-ray lines (in particular the $^{20}$Ne line at 1.634 MeV) provided new information on the energy distribution of the accelerated ions, requiring very large particle fluxes near 1 MeV. It was shown that the energy contained in such ions is comparable to that contained in the subrelativistic electrons. It thus appears that a large fraction of the released flare energy (approximately $10^{32}$ ergs for large flares) is indeed in accelerated particles, but equipartitioned between ions and electrons. The top panel in Fig. 2 shows the impulsive time profile of gamma-ray emission produced by ions and electrons of MeV energies compared with very high frequency radio emission produced by electrons of similar energies gyrating in solar magnetic fields of hundreds of gauss.

Particle acceleration and transport at the Sun

Particles accelerated at or near the Sun are also observed by detectors on spacecraft in interplanetary space. These observations have led to the identification of two classes of acceleration events, impulsive and gradual. Among the various characteristics of the two classes, the composition of the accelerated particles is perhaps the most important. The impulsive events exhibit large enhancements of relativistic electrons relative to MeV protons, of $^3$He relative to $^4$He, and of heavy ions (particularly Fe) relative to the C and O. In contrast, the gradual events have smaller electron-to-proton ratios ($e/p$), and their heavy ion abundances and $^3$He-to-$^4$He ratios are similar to coronal values. The strong association of the gradual events with coronal mass ejections (CME) suggest that the particles in these events are accelerated by CME driven shocks. On the other hand, the electron, $^3$He and heavy ion enrichments in impulsive events require selective acceleration which is most likely achieved by gyroresonant interactions with plasma waves.

The gamma-ray observations have independently revealed the characteristics of impulsive acceleration. In particular, high $e/p$ ratios are required by the observed continuum to line flux ratios, high $^3$He abundances are suggested both by the 2.223 MeV line observations, which require enhanced neutron production, and very recent findings in SMM data of $^3$He induced lines. In addition, there is evidence in the GRANAT data for highly enhanced heavy ion abundances based on broad lines from Ne, Mg, Si and Fe.

The increased sensitivity of the CGRO detectors, and the occurrence of large flares while these instruments were observing the Sun, have shown that flares can produce gamma rays for very long periods of time. The data, showing gamma ray emission lasting for up to 8 hours after the impulsive phase of the flare, can be seen in the bottom panel of Fig. 2. It is still not known whether the particles were accelerated in the impulsive phase of the flare and subsequently trapped in magnetic loops at the Sun or accelerated continuously over the duration of the emission.

Additional information on accelerated particle transport at the Sun was obtained from observations of the 2.223 MeV line and electron bremsstrahlung above 10 MeV. The limb darkening of the 2.223 MeV was observed from many solar flares, and it was demonstrated most dramatically by gamma-ray observations of a flare located 10° behind the limb for which the 2.223 MeV line was absent while the deexcitation lines were still seen. Evidently, a considerable fraction of the interactions occurred in the corona, at a site which was visible from earth orbit while the neutron capture site in the photosphere was occulted. On the other hand, there is one observation of a behind-the-limb flare from which the 2.223 MeV line was seen. Because of the very strong expected attenuation, the observed 2.223 MeV line must have been produced by charged particles interacting on the visible hemisphere of the Sun. These particles were either accelerated by a coronal shock over a large volume, thereby producing an extended gamma-ray emitting region, or accelerated locally at the flare site whence they propagated along large loops to the visible hemisphere.

In contrast to the limb darkening of the 2.223 MeV line emission, the bremsstrahlung above 10 MeV was observed to be limb brightened. This means that the flares from which such emission was observed were preferentially located close to the solar limb. This effect is
most likely the consequence of particle motion in magnetic loops which converge toward the footpoints with the particles radiating most efficiently when they move parallel to the photosphere near the mirror points.

Ambient medium abundances

SMM and CGRO data on narrow gamma-ray lines have provided information on solar atmospheric elemental abundances. While the C-to-O abundance ratio was found to be consistent with both photospheric and coronal values, the Mg-to-O, Si-to-O and Fe-to-O ratios turned out to be enhanced relative to the photospheric abundances but consistent with those of the corona. The first ionization potentials (FIP) of Mg, Si and Fe are lower than those of C and O. The enhancement of the abundances of low FIP elements in the corona relative to the photosphere has been known from both atomic spectroscopy and particle observations of gradual events, but the origin of this fractionation is still only poorly understood. The gamma-ray results, and the fact that the gamma-ray lines are most likely produced in the chromosphere, indicate that the FIP bias sets in already at relatively low heights in the solar atmosphere. Ongoing research on the \(\alpha\) line indicates that in the gamma-ray production region either the \(\alpha\) particle or the ambient He abundances is enhanced, exceeding the standard He/H value of 0.1.

The early development of the field is summarized in the reviews of Chupp, and Ramaty and Murphy. Much of the recent observations and theory, the relationship of the gamma-ray studies to other solar flare investigations, as well as a detailed historical review (by Chupp), are given in the HESP conference proceeding edited by Ramaty, Mandzhavidze and Hua. The Murphy et al. paper provides details on ongoing research.

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