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COMPTEL solar flare measurements

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COMPTEL Solar Flare Measurements

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We review some of the highlights of the COMPTEL measurements of solar flares. These include images of the Sun in γ rays and neutrons. One of the important features of the COMPTEL instrument is its capability to measure weak fluxes of γ rays and neutrons in the extended phase of flares. These data complement the spectra taken with the COMPTEL burst spectrometer and the telescope during the impulsive phase of flares. We focus our attention on some of these general capabilities of the instrument and the latest results of two long-duration γ-ray flares, i.e., 11 and 15 June 1991.

INTRODUCTION

One of the original purposes of double-scatter (now more commonly known as Compton telescopes) was to measure the flux of neutrons arising from the earth's atmosphere as well as the flux of neutrons coming from the Sun. Either or both of these fluxes was postulated to be the origin of the energetic neutron-decay protons in the earth's radiation belts. A series of balloon flights with instruments of this type confirmed that the earth-albedo neutrons could populate the earth's radiation belts. Quiet-Sun measurements of the solar-neutron flux proved negative. Balloon-platform experiments have only short exposures to the Sun, so measuring the active-Sun neutron flux is consequently more difficult than with the same instrument on a spacecraft. However, with the launch of the Compton Gamma Ray Observatory, COMPTEL—a new generation double-scatter telescope—was now capable of fulfilling one of the original objectives of double-scatter telescopes, that of measuring the active-Sun emissions, including both γ rays and energetic neutrons. This review of COMPTEL solar data highlights these observations and measurements. A recent review of general high-energy solar-flare phenomena is provided by Hudson and Ryan (1).

Energetic electrons, protons and heavier ions are some of the significant products of the solar-flare process. They can account not only for emissions in generally quiet bands of the electromagnetic spectrum, i.e., microwaves, γ rays and

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X rays, but can also account for a significant fraction of the flare energy. The solar-flare photon emission above 500 keV is particularly revealing. This part of the spectrum contains not only a host of nuclear lines but also the bremsstrahlung emission from relativistic electrons. Beyond 10 MeV lies the part of the spectrum containing radiation from ultrarelativistic electrons and π^0-decay photons at 68 MeV. The decay of charged π mesons yields electrons and positrons that in turn radiate. We consider these to be secondary radiations, much like 511 keV annihilation γ rays. COMPTEL is sensitive to much of this rich spectrum. In its bulk spectrometer mode it has measured solar γ rays from 600 keV to 10 MeV (2), while in its telescope mode it has measured γ rays from approximately 800 keV to 30 MeV (3). These measurements complement the concurrent measurements of BATSE (4) and OSSE (generally at lower energies) (5) and EGRET (generally at higher energies) (6,7). Unique to COMPTEL are the measurements of solar flare neutrons—a harkening to its heritage. These neutron measurements further complement the γ-ray measurements. Together they form a comprehensive set of solar measurements.

The data sample a wide range of the accelerated-particle population in a flare. Nuclear lines are produced by the energetic-proton spectrum in the range of 10–40 MeV, whereas the π^0-decay γ rays originate from the proton (or ion) spectrum above about 300 MeV. Neutrons in the range of 10–100 MeV, on the other hand, sample the proton spectrum at energies slightly higher than the neutrons themselves. The nuclear line at 2.223 MeV from the capture of free neutrons on hydrogen serves as an integral measure of the proton spectrum at all energies above the nuclear binding energy. It is useful as a crude measure of the total energy of the proton population but its origin for any given flare or any moment within a flare is uncertain. The free neutrons could be produced by protons that are also responsible for the nuclear lines but could also be produced by protons that are responsible for the π^0-decay γ rays—entirely different parts of the proton spectrum.

This review highlights some of the features and findings of the COMPTEL measurements of solar flares. We illustrate some of the technical properties of the instrument with measurements of so-called long-duration high-energy flares. Some of the more interesting phenomena are associated with these events. The remainder of the paper addresses these relatively rare events and the COMPTEL measurements of them. First, though, we briefly describe the COMPTEL instrument and its features that make it unique in solar-flare studies.

THE COMPTEL INSTRUMENT

The COMPTEL instrument is described by Schönfelder et al. (8). It is comprised of two detecting systems, D1 and D2. In the detection and measurements of photons, the γ rays Compton scatter in D1 and are ideally fully

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absorbed in D2. The locations of the interactions in the detector systems, the energy measurements and the Compton-scatter kinematics restrict the incident γ-ray direction to be on a circle in the sky that may pass through the location of the Sun. If it does, the measured energy is the full photon energy. A time-of-flight measurement between D1 and D2 serves to greatly improve the signal-to-noise ratio. This time-of-flight measurement is employed in the measurement of neutrons in the range of 10–100 MeV. Instead of Compton scattering in D1, the neutron elastically scatters off hydrogen in the scintillator material in D1. The scattered neutron—now with less energy—is detected in D2. The time-of-flight measurement is equivalent to measuring the scattered neutron energy. The sum of the two energies then represents the full neutron energy. Kinematics similar to the Compton scatter process also restrict the neutron incident direction to be on a circle in the sky, and this circle may also pass through the location of the Sun. There are many other complicating reactions, particularly for neutrons, that do not yield accurate energies or incident directions. The reader is referred to the instrument description by Schönfelder et al. (8) for more details.

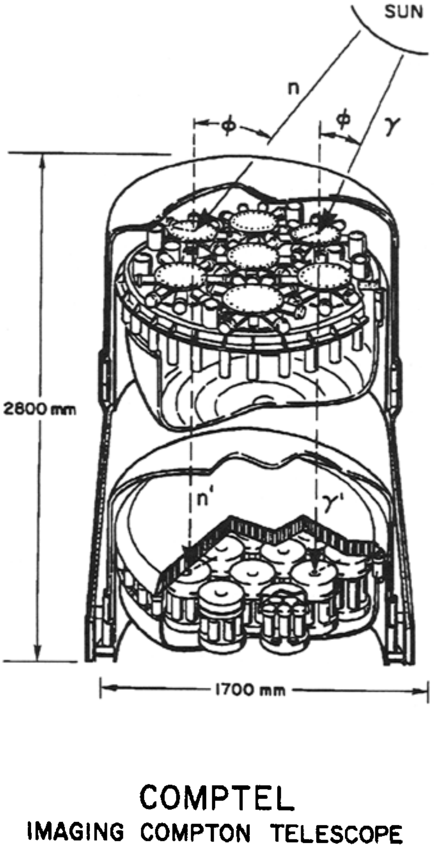

Figure 1. COMPTEL schematic.

OBSERVATIONS

γ-ray and Neutron Images

In general, the process of imaging greatly improves an instrument's signal-to-noise ratio, thereby enabling it to detect weaker signals and measure smaller fluxes. Such is the case with the COMPTEL. Exclusive of the science behind the flares that the Sun provides, the major feature of the COMPTEL solar-flare measurements is their sensitivity, best illustrated with the observations of the 15 June 1991 solar flare. The image displayed in Figure 2 is that of the Sun in the time following the

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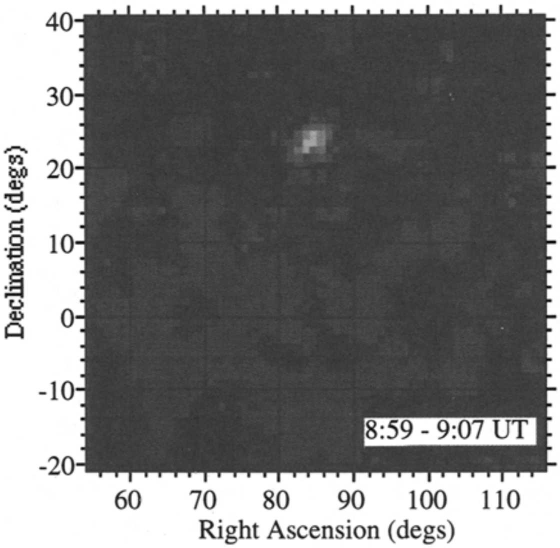

Figure 2. Gamma-ray image of the Sun from 0.8–8 MeV.

impulsive phase of a flare on 1991 June 15 (9). The image was obtained from only 9 minutes of data starting 30 minutes after the impulsive phase. Unfortunately, the resolution of the telescope does not permit resolving features smaller than ~ 1°—twice the diameter of the Sun. The Observatory missed the impulsive phase of the flare during an occulted part of the orbit. However, the lingering low-level MeV radiation was still detectable primarily because of the imaging properties of COMPTEL.

The Sun also emitted neutrons during this flare and these particles were detected and measured by COMPTEL concurrent with the γ-ray measurements. Since 10–100 MeV neutrons are subrelativistic these neutrons arose from earlier epochs of the flare. The γ-ray imaging procedures were applied to the neutron data resulting in a neutron image of the Sun (Figure 3). The neutron flux from this flare was 30× smaller than that of the 3 June 1982 flare (10). We will return to this flare because it exhibits what we now call long-duration γ-ray emission, that is γ-ray emission persisting for ~ 1 hour or more after the impulsive phase of a flare.

Neutron Measurements

The long-sought-after ability to perform neutron spectroscopy has yielded new information that is difficult or impossible to obtain with γ-ray measurements. Long-duration high-energy flares have been a poorly measured and understood phenomenon before the Compton Observatory. One of the simplest of such flares to observe and measure was that of 9 June 1991. Here, the impulsive phase

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was observed near the beginning of a sunlit portion of a spacecraft orbit, enabling uninterrupted γ-ray and neutron measurements for more than 40 minutes after the impulsive phase. The subrelativistic nature of the 10–100 MeV neutrons makes them arrive at the instrument mostly after the intense γ-ray flux has subsided. By measuring the energy of each registered neutron, we are able to trace the neutron back to its emission time at the Sun. A background-corrected and velocity-corrected intensity-time profile of these measured neutrons is shown in Figure 4. This 4 σ signal peaks well after the impulsive phase indicating that neutron emission is either delayed or of longer duration than that of the γ rays. This conclusion is supported by the EGRET detection of > 50 MeV γ-ray emission at this time or later (6). Whereas the flux of MeV photons is declining monotonically after the impulsive phase, the neutron flux stays at an elevated level for at least 5 minutes. The evidence points to a clear hardening of the proton spectrum over the course of 5 minutes. This phenomenon was observed again two days later with the flare on 11 June 1991.

As mentioned above, the impulsive phase of the 15 June 1991 flare was unobservable with the Compton Observatory because of earth eclipse and SAA transit. However, again because of the subrelativistic nature of the sub-100 MeV neutrons, the neutron measurements provide information about the flare high-energy emissions in the occulted and blacked-out time periods. Debrunner et al. (10) concluded that the neutron emission was consistent with the high-energy γ-ray measurements made with the GAMMA-1 instrument (11,12) that had more observing time on the Sun after the impulsive phase. The GAMMA-1 data show an exponentially declining flux of > 100 MeV γ rays after the impulsive phase, similar to what was measured by COMPTEL in γ rays (9).

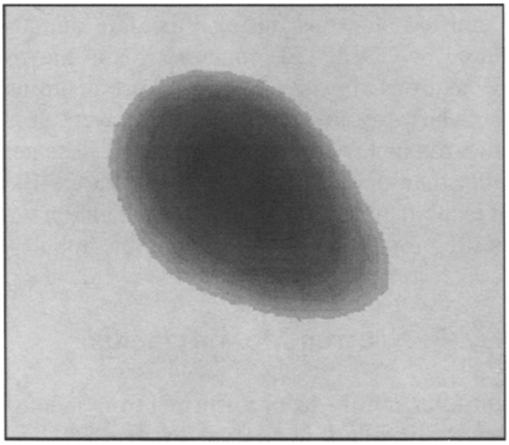

Figure 3. The Sun as it appears in neutron radiation. The image is ~ 10° in diameter and its asymmetrical shape is due to inaccuracies in the instrument point-spread function—the equivalent of optical distortion.

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Because COMPTEL has different types and areas of detecting elements it is capable of performing measurements at different epochs of the flare that have greatly different emission rates. In particular, the burst spectrometer can handle greater fluxes without encountering dead time effects, while the telescope can measure weaker fluxes later in a flare. Such is the case for the 11 June 1991 long-duration, high-energy flare. In the impulsive phase of the flare the intense thermal X-ray flux and the limited telemetry of the telescope limited the number of registered photons. However, the burst spectrometer measured the 0.6–10 MeV spectrum every 12 s (2). Later in the flare after the flux subsided, no significant measurements in the nuclear-line region were possible with the burst spectrometer while the telescope was collecting data at its maximum rate.

The 11 June 1991 solar flare is a bellweather event in solar high-energy physics. Its γ-ray emission > 50 MeV persisted for more than 8 hours after the impulsive phase (13). Schneid et al. (6) also reported photon emission above 50 MeV minutes after the impulsive phase. The flare has attracted much attention since it tests our understanding of particle acceleration and transport. Opposing models of the particle behavior can be classified as to whether they revolve around the trapping of previously accelerated particles (14,15) or the continuous acceleration of particles (16,17). Distinguishing between these models is difficult with little more to go on than the γ-ray measurements.

COMPTEL measurements of the prolonged nuclear-line emission have been reported by Rank et al. (18) in these proceedings. The decay of the nuclear-line emission with respect to the emissions in the 2.223 MeV line and the 8–30 MeV band provides a clue into the nature of the particle populations late in this event.

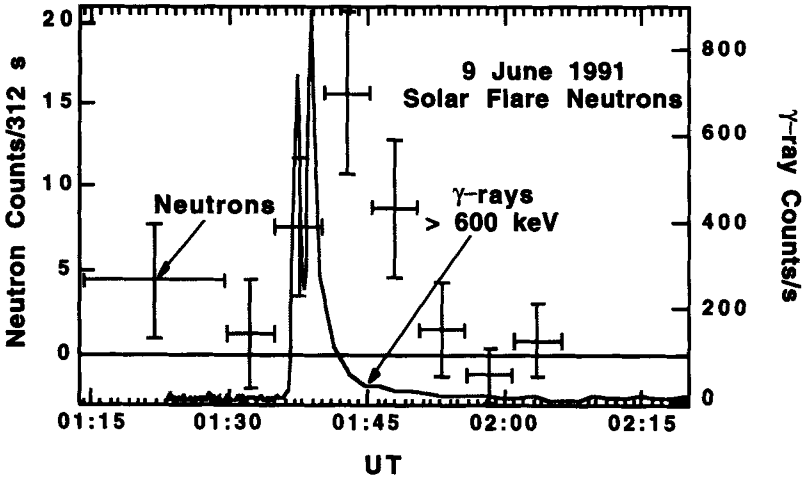

Figure 4. The velocity-corrected neutron emission from the 9 June 1991 flare.

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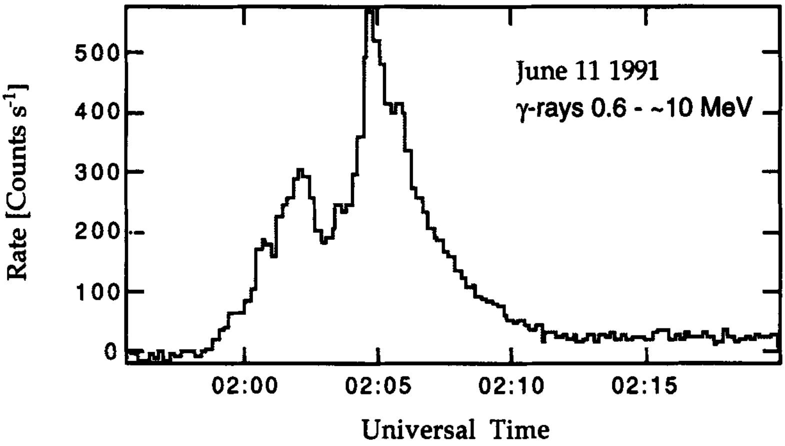

Figure 5. The background-corrected COMPTEL burst spectrometer count rate during the impulsive phase of the 11 June 1991 solar flare.

Rank et al. find that the behavior of these emission bands agree within statistics, supporting the hypothesis that the entire extended emission derives from protons, and that because of the constancy of the spectrum, the long lifetime of the proton population is due to prolonged acceleration rather than trapping. In the extended phase of the flare, the decay of all forms of γ-ray emission follows a double exponential decay—the first fast and the second much slower. The fast decay is on the order of 10 minutes and the slow decay is on the order of 100 minutes (13,18).

The situation differs during the *impulsive* phase of the 11 June 1991 flare. Figure 5 shows the count rate of the COMPTEL burst spectrometer. The burst spectrometer accumulated 256 channel spectra every 12 s during the impulsive phase. The flare consisted of an impulsive phase that included two large bursts starting at approximately 0158 UT and lasting for about 10 minutes. After about 0208 UT the flare as seen in γ rays showed little structure—only a simple exponential decay after a possible local minimum occurring at 0212 UT. This change in tempo suggests that some fundamental change in the nature of the flare was taking place at this time and this may be reflected in the spectrum and species of particles being accelerated and the photons that those particles would subsequently produce. We can investigate this putative change with the COMPTEL burst spectrometer data.

A simple but useful measure of the general spectral shape of the protons responsible for the γ-ray emission is the ratio of the time-integrated flux of the 2.223 MeV line to that of the nuclear-line region of 4–7 MeV (19). With some care this ratio can be constructed for different phases of the flare (20). The difficulty in this analysis stems from the fact that the 2.223 MeV deuterium formation line has a prolonged nature. The neutrons created by the energetic proton reactions require ~ 100 s (density and ^{3}He dependent) to capture on

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hydrogen, resulting in an exponential decay of the 2.223 MeV flux. The instantaneous 2.223 MeV flux is thus due to the integrated effect of all neutron production prior to that moment.

One can see in Fig. 5 that after 0210 UT the count rate does not return to background. This excess is statistically significant and is mostly in the 2.223 MeV line. We interpret this as the start of the extended emission phase. We can compare the 2.223 MeV/4–7 MeV flux ratio during the impulsive phase to that during the beginning of the extended phase to detect any change in the proton spectrum. Suleiman et al. (20) arbitrarily defined the interval 0158–0207 UT as the impulsive phase and the period 0210–0220 UT as the so-called tail phase or the beginning of the extended phase of the flare. The gap between these intervals was excluded to reduce 2.223 MeV cross-talk between the intervals. In the gap the 2.223 MeV flux appears to be declining exponentially in magnitude. Interpolating this decay allows one to estimate the 2.223 MeV flux lost from the impulsive phase interval and the excess flux introduced into the tail phase. (The corrections are both on the order of 30%. The lines in the 4–7 MeV range are prompt and one can directly account for all their emission by simply integrating the flux over time.) Doing this and combining with the time-integrated fluxes in the range of 4–7 MeV yields a 2.223 MeV/4–7 MeV flux ratio of 0.83±0.12 for the impulsive phase and 4.7±2.0 for the tail phase. The ratio in the tail phase could be larger than indicated by the error bars because so little flux is detected in the 4–7 MeV range. These ratios imply that the proton spectrum changes its shape significantly between the impulsive and tail phases of the flare. If the spectrum is of the form of a Bessel function, the hardness parameter αT changes from 0.02 to 0.12, or if the spectrum is power law in shape the spectral index changes from –3.6 to –2.3 (21). Stated either way, the change represents a marked hardening of the proton spectrum responsible for the γ-ray emission. The major evolution of the occurs sometime around or before 0210 UT when the proton spectrum hardens. Our value for the power-law index for the impulsive phase agrees with the value of –3.5 reported by Ramaty and Mandzhavidze (14), but our value for the tail phase represents a spectrum harder than what they concluded for the extended phase based solely on the high-energy spectrum hours after the impulsive phase. This disagreement in the extended or tail phases may not be significant because the two measures of the spectrum, i.e., the flux ratio and the shape of the photon spectrum > 100 MeV, span such a wide range of energy and different reaction channels that these simple measures may not be precise enough for such a comparison.

The 15 June 1991 solar flare in many ways resembles the 11 June 1991 flare. The two flares erupted in the same active region and both had prolonged high-energy photon radiation. Unfortunately, as mentioned above, the impulsive phase of the flare was unobservable to the Compton Observatory and the GAMMA-1 spacecraft as well. The similarity of the two flares may be more than just coincidental. Having originated in the same active region, they also may carry the

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signatures of the geometry and the topology of the region in their intensity-time profiles. Both models of prolonged γ-ray emission—trapping and continuous acceleration—are sensitive to the topology and dimensions of the magnetic structures containing the energetic particles. The time scales of the photon flux decay both follow the size of the active region, or more specifically, the size of the magnetic loops confining the particles. Rank et al. (18) have shown with the COMPTEL data that the time scales of the 2.223 MeV emissions have within uncertainties the same long and short exponential decays. This suggests that the long-duration flare scenario played out in two events four days apart. Although the impulsive phases may have been different, the particle populations, or more specifically protons, that produced the prolonged emission both resided in the same loops or, at least, loops of approximately the same dimensions.

CONCLUSIONS

Although of considerable importance and interest, our measurements of long-duration high-energy solar flares are largely based upon events stemming from a single active region in 1991. The specifics, as we saw, may depend on the details of the topology and dimensions of the particular region in which the flares occurred. Additional observations of flares in other active regions, supported by observations in other wavelength bands would broaden our knowledge base of this phenomenon. We must await the next solar maximum to study this further. The Compton Observatory and COMPTEL are both capable of operating and making good measurements in the next solar maximum. It is important that the mission be extended through the next maximum. Our experience in both solar physics and the operation of the instrument and some cooperation of the Sun will certainly yield data of the highest quality, thereby broadening our understanding of the enigmatic behavior of energetic particles in solar flares.

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