The High Energy Solar Spectroscopic Imager (HESSI) Mission

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Abstract. The primary scientific objective of the High Energy Solar Spectroscopic Imager (HESSI) Small Explorer mission selected by NASA is to investigate the physics of particle acceleration and energy release in solar flares. The HESSI instrument utilizes Fourier-transform imaging with 9 bi-grid rotating modulation collimators and cooled germanium detectors to make observations of X-rays and γ-rays from ~3 keV to ~17 MeV. It will provide the first imaging spectroscopy in hard X-rays, with ~2 arcsec angular resolution, time resolution of 2s for full image (tens of ms for crude image), and ~1 keV energy resolution; the first solar γ-ray line spectroscopy with ~1-5 keV energy resolution; and the first solar γ-ray line and continuum imaging, with ~36-arcsec angular resolution. The instrument is mounted on a Sun-pointed spin-stabilized spacecraft, and is planned to be launched in July 2000 into a 600 km-altitude, 38° inclination orbit. HESSI will provide detailed information on the energetic particle populations at the Sun, for comparison to measurements of solar energetic particles by ACE, WIND, and other interplanetary spacecraft.

INTRODUCTION

The Sun is the most powerful particle accelerator in the solar system. Both solar flares and fast Coronal Mass Ejections (CMEs) appear to accelerate ions up to tens of GeV and electrons to hundreds of MeV. Solar flares release up to 10^{32}-10^{33} ergs in 10^2-10^3 s with accelerated 10-100 keV electrons (and possibly >1 MeV ions) containing a significant fraction, perhaps the bulk, of this energy. How the Sun releases this energy, presumably stored in the magnetic fields of the corona, and how it rapidly accelerates electrons and ions with such high efficiency, and to such high energies, is presently unknown. CMEs involve the ejection of up to ~10^{15}-10^{16} gms of solar material, also with total energy release of ~10^{32}-10^{33} ergs. It is believed that Large Solar Energetic Particle (LSEP) events seen at 1 A.U. are due to acceleration by the shock waves driven by fast CMEs as they travel through the corona.

High-energy emissions are the most direct signature of energetic particles near the Sun. Hard X-ray/γ-ray continuum is produced as bremsstrahlung by energetic electrons. Nuclear collisions of energetic protons and heavier ions with the ambient solar atmosphere result in a complex spectrum of narrow and broad γ-ray lines that contain unique information on not only the accelerated ions but also the ambient solar atmosphere.

It is not known how the electrons and ions that produce the X-ray and gamma-ray emissions in solar flares are related to solar energetic particles observed in the interplanetary medium.[1] Gamma-ray flare events have similarly large e/p ratios as impulsive (so-called because the soft X-ray imaging burst is < 10 minutes duration) SEP events, and may have similar enrichments of ^{3}He and heavy ions.[2] On the other hand, there is evidence indicating that LSEP events may be predicted by flare hard X-ray bursts which exhibit systematic hardening of the spectrum through the event.[3] HESSI hard X-ray and γ-ray spectroscopy and imaging, together with observations of coronal shocks, SEPs, and CMEs by other spacecraft such as ACE, WIND, etc., are needed to understand the relationship of the various acceleration processes.

[1] See Acknowledgements

CP528, *Acceleration and Transport of Energetic Particles Observed in the Heliosphere: ACE 2000 Symposium,* edited by Richard A. Mewaldt, et al.

Electron Acceleration and Energy Release

Bursts of hard (>20 keV) X-rays are the most common signature of the impulsive phase of a solar flare (Fig. 1). These X-rays are bremsstrahlung produced by accelerated electrons colliding with the ambient solar atmosphere. The Yohkoh Hard X-ray Telescope (HXT) often observes double footpoint structures, with the two footpoints brightening simultaneously to within a fraction of a second.[4] These coincide, spatially and temporally, with H_α and white-light brightenings, implying the X-ray emitting electrons have energy $E>kT$ of the ambient gas. Then the energy lost by the electrons to bremsstrahlung is only $\sim 10^{-5}$ of their energy lost to Coulomb collisions with ambient thermal electrons. This inefficiency means that, for many flares, the energy in accelerated >20 keV electrons must be comparable to the total flare radiative and mechanical output.[5] Thus, the acceleration of electrons to tens of keV may be the most direct consequence of the basic flare-energy release process.

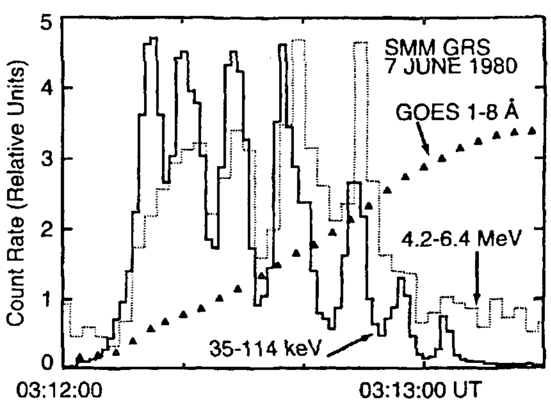

Figure 1. Time profiles for a flare[6] showing near-coincident impulsive peaks in 35-114 keV hard X-rays (from energetic electrons) and 4.2-6.4 MeV γ-rays (from energetic ions).

For some flares occurring near the solar limb, HXT has detected a co-temporal, weaker, hard X-ray source in the corona[7] above the soft X-ray loop linking the hard X-ray footpoints. This source has been interpreted as evidence for energy release by magnetic reconnection in a region above the soft X-ray loop.

HESSI's hard X-ray imaging spectroscopy allows the photon spectrum in each spatial and temporal element to be directly inverted to obtain N(E, **r**, t), the X-ray producing electron number density, as a function of energy (E), and position (**r**), and time (t). Context observation by the fleet of spacecraft (SOHO, Wind, ACE, Ulysses, TRACE, GOES, Yohkoh, SAMPEX, CGRO, etc.) that will already be in place, and by ground based instruments, will provide information on the ambient density, magnetic field strength and topology, etc. Then the electron loss processes can be directly evaluated, and with transport calculations (using a spatially dependent continuity equation including loss processes), the spatially and temporally resolved *accelerated* electron source distribution, F(E, **r**, t), can be obtained. This can be used to test detailed quantitative models of the acceleration, energy release, and energy propagation.

Ion Acceleration

Nuclear collisions of accelerated nuclei with the ambient solar atmosphere result in a rich spectrum of gamma-ray lines.[8] γ-ray line emission has been observed from many solar flares.[9,10] Energetic protons and α-particles colliding with carbon and heavier nuclei produce narrow de-excitation lines (widths of ~few keV to ~100 keV), while energetic heavy nuclei colliding with ambient hydrogen and helium produce much broader lines (widths of a few hundreds keV to an MeV). Neutron capture on hydrogen and positron annihilation produce narrow lines (at 2.223 MeV and 0.511 MeV, respectively) which are delayed.

The bulk of the γ-ray line emission is produced by ions with energies of 10-100 MeV/nucleon that contain only a small fraction of the energy in the >20 keV electrons. However, systematic study of SMM γ-ray line flares[10] shows that the 1.634 MeV ^{20}Ne line is unexpectedly enhanced. Because the cross section for ^{20}Ne has an unusually low energy threshold (~2.5 MeV), this effect may be due to large fluxes of low-energy ions with a total energy content comparable to that in accelerated electrons.[11] HESSI's high spectral resolution allows the identification of accelerated ^{3}He induced lines[12] in the broad group of lines around 1 MeV. It also provides high sensitivity measurements of the narrow neutron capture lines and detailed line shapes (a measure of the energetic particle anisotropy) for the α-α lines around 400 keV.[13]

HESSI will provide the first localizations of solar γ-rays and the most precise imaging ever achieved in γ-ray astronomy. For large flares, HESSI should be able to image in narrow γ-ray lines, e.g. the 2.223 MeV neutron capture and 0.511 MeV positron annihilation lines, where line counts dominate over the background. Although γ-ray lines have never been directly imaged, the 2.223 MeV line was once detected in a behind-the-limb flare.[14] This line is formed when thermalized neutrons are captured by ambient protons in the photosphere, so the neutrons must have been produced by charged particles interacting on the visible hemisphere of the Sun. Thus, either the acceleration site was far removed from the optical flare site, or the charged particles were transported over large distances.

INSTRUMENTATION

The HESSI scientific objectives will be achieved with a single instrument consisting of an Imaging System and a Spectrometer.[15] The Imaging System is made up of nine Rotating Modulation Collimators (RMCs), each consisting of a pair of widely separated identical grids in front of an X-ray/γ-ray detector (Fig. 2), mounted on a rotating spacecraft. Each grid consists of a planar array of equally-spaced, X-ray-opaque slats separated by transparent slits. The transmission through the grid pair depends on the direction of the incident X-rays. For slits and slats of equal width, the transmission is modulated from zero to 50% and back to zero for a change in source angle to collimator axis (orthogonal to the slits) of p/L where p is the pitch and L is the separation between grids. The angular resolution is then defined as p/(2L).

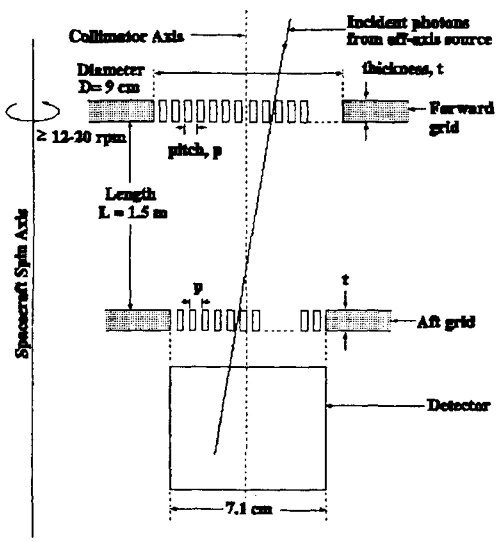

Figure 2. Schematic showing the instrument parameters that define the imaging capability.[15]

For a parallel incident beam, the modulated waveform generated by a smoothly rotating spacecraft has a distinctive quasi-triangular shape whose amplitude is proportional to the intensity of the beam and whose phase and frequency depend on the direction of incidence. For complex sources, and over small rotation angles, the amplitude and phase of the waveform provide a direct measurement of a single Fourier component of the angular distribution of the source.[16] Different Fourier components are measured at different rotation angles and with grids of different pitches.

For HESSI, the separation between grids in each RMC is L = 1.5 m and the grid pitches range from 34 μm to 2.75 mm in steps of √3. This gives angular resolutions that are spaced logarithmically from 2.3 arcsec to ~3 arcmin, allowing sources to be imaged over a wide range of angular scales. The chosen grid thicknesses provide imaging from 3 keV to ~100 keV with ~2 arcsec resolution, up to several hundred keV with 20 arcsec, and > 10 MeV with 36 arcsec.

The detector records the arrival time and energy of individual photons, allowing the modulated counting rate to be determined as a function of rotation angle. HESSI uses hyperpure (n-type) closed end coaxial germanium detectors (GeDs), cooled to provide high spectral resolution (~1-5 keV FWHM). The inner electrode is segmented into two contacts that collect charge from two electrically independent detector segments. The front segment thickness of ~1.5 cm is chosen to stop photons up to ~150 keV, where photoelectric absorption dominates. Photons with energies from ~150 keV to ~20 MeV, including all nuclear γ-ray lines, stop primarily in the thick rear segment The intense 3-150 keV X-ray fluxes that usually accompany large γ-ray line flares are absorbed by the front segment, so the rear segment will always count at moderate rates to provide optimal spectral resolution and high throughput for γ-ray line measurements. The GeDs are cooled on-orbit to ~75 K by a single Sunpower Inc. single stage, integral (counterbalanced) Stirling cycle mechanical cooler.

In a half rotation (2 s) the 9 RMCs measure amplitudes and phases of ~1100 Fourier components compared to 32 for the Yohkoh HXT. Detailed simulations show that HESSI can obtain accurate images with a dynamic range (defined as the ratio of the brightest to the dimmest feature reliably seen in an image) of up to 100:1 compared to ~10:1 for Yohkoh HXT. High-resolution X-ray spectra can be obtained for each location in the image, thus providing true high-resolution imaging spectroscopy.

The Solar Aspect System (SAS) provides six precise measurements of the solar limb every 10 ms, yielding Sun center position to ~1.5 arcsec. A star scanner Roll Angle System (RAS) samples the roll orientation at least once per rotation.

Spacecraft and Mission

The instrument field of view (~1°) is much larger than the Sun (0.5°) so spacecraft pointing is relaxed (within ~0.2° of Sun center). The energy and arrival time of every photon, together with SAS and RAS aspect data, are recorded in the spacecraft's on-board 4-Gbyte solid-state memory and telemetered when the spacecraft goes over the ground station. All of the photon data for the largest flare can be stored in the spacecraft memory and downlinked in <~48 hours, so flare data will rarely, if ever, be lost. Consequently, HESSI is planned for an automated store-and-dump operation, with normally no real-time access.

The HESSI spacecraft weighs a total of ~290 kg, uses ~280 watts, is passively spin-stabilized at 15 rpm, and points continuously at the Sun. It will be launched into a 600 km circular, 38° inclination orbit with a Pegasus XL rocket. A single 11-meter dish ground station at Berkeley provides the required data downlink rate and command uplink.

The complete data output of the HESSI mission will be made available promptly to the scientific community, without restriction, together with a fully documented analysis package, consisting of the same software used by the PI team.

HESSI is planned, and presently on schedule for, launch in mid-2000 near the predicted next solar maximum. A two-year nominal mission (a third year is highly desirable) will provide observations of tens of thousands of microflares, thousands of hard X-ray flares, and of order a hundred γ-ray line flares.

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