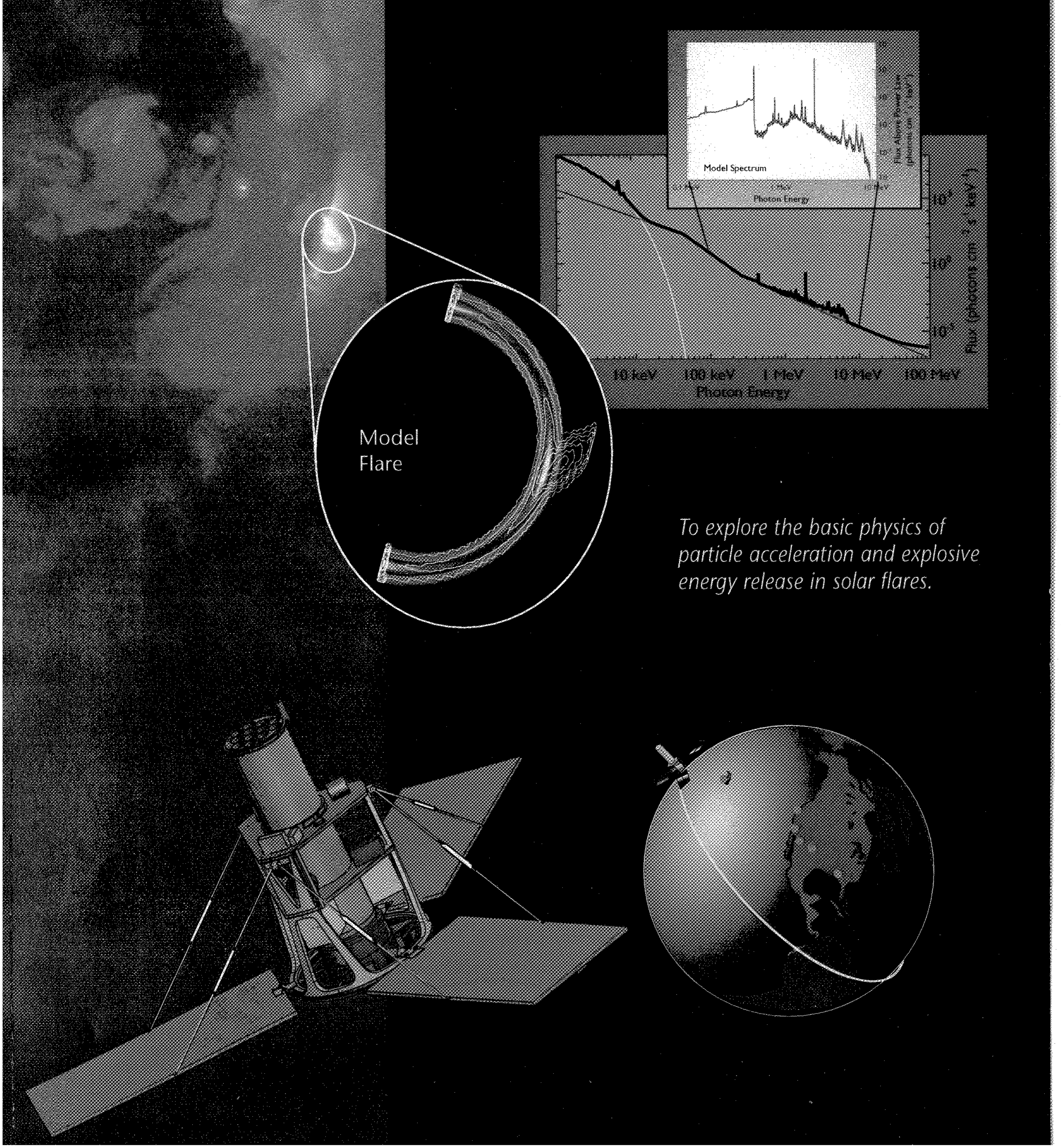
THE HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER

HESSI



To explore the basic physics of particle acceleration and explosive energy release in solar flares.

UNIVERSITY OF CALIFORNIA, BERKELEY

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

OFFICE OF THE VICE CHANCELLOR FOR RESEARCH
TELEPHONE: (510) 642-7540
FACSIMILE: (510) 643-5620

BERKELEY, CALIFORNIA 94720

June 21, 1995

Dr. Wesley T. Huntress, Jr.
Associate Administrator
for Space Science
NASA Headquarters
Washington, D.C. 20546

Dear Dr. Huntress,

On behalf of the University of California at Berkeley, I am pleased to support the "High Energy Solar Spectroscopic Imager (HESSI)" investigation proposed by Professor Robert P. Lin in response to Announcement of Opportunity no. 95-OSS-02.

We look forward to working with NASA on this exciting scientific project.

Sincerely,

Joseph Cerny

Joseph Cerny
Vice Chancellor for Research

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 685

JUN 20 1995

Professor Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Professor Lin:

The Space Sciences and Engineering Directorates of the Goddard Space Flight Center are committed to participating with you at the Space Sciences Laboratory of the University of California, Berkeley, in building the High Energy Solar Spectroscopic Imager (HESSI) within the cost and programmatic constraints of the Medium-class Explorer (MIDEX) program, as specified in the Announcement of Opportunity (AO-95-OSS-02).

Our scientific and technical staff has worked closely with scientists and engineers at Berkeley over the last 5 years to conceive and develop an exceptional high-energy instrument that incorporates the best of the Goddard and Berkeley programs. Our scientific and engineering expertise in solar hard X-ray observations extends from the early Orbiting Solar Observatories in the 1960's and '70's, through the Solar Maximum Mission in the 1980's, and includes, most recently, the balloon flight of the High Energy Imaging Device in 1993, and the fabrication of a Telescope Demonstration Unit that is now undergoing extensive tests. Our theory program led by Drs. Holman and Ramaty is internationally renowned as the finest in the field. In addition, we can offer our outstanding engineering expertise in cryogenics and thermal design that is crucial for the instrumentation being proposed. The combination of scientific and technical abilities at Goddard nicely complements the capabilities of your team at Berkeley. There, you have developed expertise in high resolution solar X-ray and gamma-ray spectroscopy based on your germanium detector technology. You have had many balloon flights of such detectors over the last two decades culminating in three long-duration flights in the Antarctic of your High Resolution Gamma-ray and Hard X-ray Spectrometer, the most recent in January 1995. Thus, by combining Goddard's X-ray imaging and cryogenics talents with your high resolution spectroscopy capabilities, we will produce the best HESSI at the lowest possible cost.

Our ability to work successfully with the scientists and engineers at Berkeley has been amply demonstrated with many missions, including, most recently, the Fast Auroral Snapshot Explorer (FAST) Small Explorer (SMEX) program, all of which have been done within cost and schedule. One difference in our proposed involvement with HESSI compared to previous joint ventures is that, in this case, we have agreed to contribute roughly half of the instrument development effort with your overall HESSI management residing at Berkeley. We believe that this is the efficient mode of operation given that the Principal Investigator is also located at Berkeley. We look forward to participating in this mode and will provide you with the necessary support to ensure the success of the endeavor at the lowest possible cost.

We strongly endorse the participation of our astrophysicists - Drs. Crannell, Davila, Dennis, Desai, Holman, Orwig, Ramaty, Tueller, and von Rosenvinge - as Co-Investigators and Associated Scientists on this proposal. In addition, we will provide a work location at Goddard for non-government Associated Scientists that you fund as part of your HESSI team. Currently, these scientists are Drs. Aschwanden, Schmahl, Schwartz, and Zarro. We recognize the crucial role of Co-Investigator Dr. Gordon Hurford from the California Institute of Technology, in the design and development of the imaging part of HESSI, and we will welcome his full-time participation at Goddard for the duration of the HESSI program.

In addition to the scientific personnel listed above, we will fully support the Goddard management and engineering team necessary to meet our obligations as outlined in the proposal. The required personnel and facilities are available and will be committed to HESSI if and when this proposal is accepted.

With the combined expertise of the Goddard Space Flight Center and the University of California, Berkeley, we are very excited about the prospect of building a superb X-ray and gamma-ray imaging spectrometer. We look forward, with keen anticipation, to the time when that instrument will make high fidelity X-ray and gamma-ray movies of solar flares that will both excite the general public and provide a deeper scientific understanding of the largest explosions in our solar system.

Sincerely,

Stephen S. Holt
Director of Space Sciences

for Allan Sherman
Director of Engineering

Approval:

Joseph H. Rothenberg
Acting Director

6-20-95.
Date

Proposal #
NASA Use Only

Medium - Class Explorer (MIDEX)

Investigation Summary Form

PRINCIPAL INVESTIGATOR
Prof. Robert P. Lin

INSTITUTION
University of California, Berkeley

DEPARTMENT
Space Sciences Laboratory

ADDRESS / STREET
Centennial Drive at Grizzly Peak Boulevard

CITY / TOWN Berkeley	STATE CA	ZIP / POSTAL CODE 94720-7450	COUNTRY U.S.A.
TELEPHONE (510) 642-1149	FAX (510) 643-8302	E-MAIL ADDRESS boblin@sunspot.ssl.berkeley.edu	

INVESTIGATION TITLE

HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER (HESSI)

INVESTIGATION ABSTRACT HESSI will investigate the physics of particle acceleration and energy release in solar flares. Observations will be made of X-rays and gamma rays from 2 keV to 20 MeV with an unprecedented combination of high resolution imaging and spectroscopy. It uses Fourier-transform imaging with 12 bi-grid modulation collimators and cooled germanium and silicon detectors mounted on a Sun-pointed spin-stabilized spacecraft in a low-altitude equatorial orbit. HESSI will carry out the first imaging spectroscopy in hard X-rays with 2 arcseconds angular resolution, time resolution to tens of ms, and <1 keV energy resolution; the first gamma-ray line spectroscopy from a spacecraft with 1 keV energy resolution; and the first gamma-ray line and continuum imaging with 20 arcseconds angular resolution. HESSI must be launched by the year 2000, in time to detect the thousands of flares expected during the next solar maximum.

DISCIPLINE AREA (CHECK AS APPLY)

[x] SPACE PHYSICS
- [ ] IONOSPHERIC
- [ ] THERMOSPHERIC
- [ ] MAGNETOSPHERIC
- [ ] HELIOSPHERIC
- [ ] MESOSPHERIC
- [ ] COSMIC
- [x] SOLAR

[ ] ASTROPHYSICS
- [ ] RADIO
- [ ] SUBMILLIMETER
- [ ] ULTRAVIOLET
- [ ] GAMMA-RAY
- [ ] INFRARED
- [ ] OPTICAL
- [ ] X-RAY
- [ ] GRAVITY

SPACECRAFT MODE (CHECK ONE)
[x] NASA-PROVIDED
[ ] PI-MODE

TOTAL BUDGET AMOUNT (EXCLUDING MO&DA)
$ 39.4M

TOTAL MO & DA BUDGET
$ 15.0M

Proposal #
NASA Use Only

PRINCIPAL INVESTIGATOR
Prof. Robert P. Lin

INVESTIGATION TITLE
HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER (HESSI)

LIST OF CO-INVESTIGATORS at Other Institutions

NAME	INSTITUTION
Dr. Brian R. Dennis	NASA Goddard Space Flight Center
Dr. Carol Jo Crannell	NASA Goddard Space Flight Center
Dr. Gordon D. Holman	NASA Goddard Space Flight Center
Dr. Reuven Ramaty	NASA Goddard Space Flight Center
Dr. Tycho T. von Rosenvinge	NASA Goddard Space Flight Center
Prof. Richard C. Canfield	University of Hawaii at Manoa
Dr. Hugh S. Hudson	University of Hawaii at Manoa
Dr. James C. Ling	Jet Propulsion Laboratory
Prof. A. Gordon Emslie	University of Alabama in Huntsville
Dr. Patricia L. Bornmann	National Oceanic and Atmospheric Administration
Mr. Norman W. Madden	Lawrence Berkeley Laboratory
Dr. Gordon J. Hurford	California Institute of Technology*
Prof. Arnold Benz	Institute of Astronomy ETHZ, Switzerland
Prof. John C. Brown	University of Glasgow, Scotland, U.K.
Dr. Shinzo Enome	National Astronomical Observatory, Japan
Dr. Takeo Kosugi	National Astronomical Observatory, Japan
Prof. H. Frank van Beek	Delft University of Technology, Netherlands
Dr. Nicole Vilmer	Observatoire de Paris-Meudon, France

*currently at Caltech; institutional affiliation for project participation to be determined.

INSTITUTIONAL ENDORSEMENT

INSTITUTION NAME
The Regents of the University of California, Berkeley

NAME AND TITLE OF AUTHORIZING OFFICIAL
Joyce B. Freedman
Director, Sponsored Projects Office†

SIGNATURE
Joyce Freedman

DATE
6/21/95

†Sponsored Projects Office, 336 Sproul Hall, University of California, Berkeley, CA 94720-5940.
For NASA matters: tel. (510) 642-8109; fax (510) 642-8236; e-mail pgates@uclink3.berkeley.edu.

Table of Contents

EXECUTIVE SUMMARY

The primary scientific objective of the High Energy Solar Spectroscopic Imager (HESSI) is to understand particle acceleration and explosive energy release in the magnetized plasmas at the Sun. The Sun is the most powerful particle accelerator in the solar system, accelerating ions up to tens of GeV, and electrons to hundreds of MeV. Solar flares are the most powerful explosions, releasing up to 10^{32}-10^{33} ergs in 100-1000 s. The accelerated 10-100 keV electrons (and perhaps $\gtrsim 1$ MeV ions) appear to contain a significant fraction, perhaps the bulk, of this energy, indicating that the particle acceleration and energy release processes are intimately linked. 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.

The hard X-ray/gamma-ray continuum and gamma-ray lines are the most direct signatures of energetic electrons and ions, respectively, at the Sun. **HESSI will provide the first hard X-ray imaging spectroscopy, the first high-resolution spectroscopy of solar gamma-ray lines from a spacecraft, the first imaging above 100 keV, and the first imaging of solar gamma-ray lines.** HESSI combines an imaging system consisting of 12 rotating modulation collimators (RMCs) with high-spectral-resolution, cooled, germanium (Ge) and silicon (Si(Li)) detectors that cover from soft X-rays (~2 keV) to high energy gamma rays (~20 MeV). The spatial and temporal resolution of HESSI's imaging spectroscopy (down to 2 arcsec and tens of ms, respectively) will, for the first time, be commensurate with **the physically relevant scales for energy loss and transport of tens-of-keV electrons.**

It will then be possible, for the first time, to obtain the detailed distribution of the parent X-ray producing electrons in energy, space, and time. With physical context information, provided as an integral part of the HESSI program, the loss processes for these electrons can be evaluated, and the energy spectrum of the *accelerated* electrons as a function of position and time can be obtained. This information is crucial for determining the acceleration mechanism.

HESSI's gamma-ray imaging spectroscopy will provide the first information on the spatial distribution of energetic $\gtrsim 10$ MeV protons, heavy ions, and relativistic electrons, and the first information on the angular distribution of the energetic ions. It will also provide detailed information on elemental abundances for both the accelerated ions and the ambient ions in the interaction region. These HESSI observations are needed for understanding the acceleration of the intense Solar Energetic Particle (SEP) events observed at 1 AU that can affect human endeavors.

HESSI's full-Sun field of view and storage of all information about every photon in a solid-state memory (big enough to hold all the data from the largest flare) mean that flare data will rarely be lost and that mission operations can be automated to minimize cost.

HESSI will utilize spacecraft subsystems from the FAST Small Explorer with only minor modifications, for a simple, reliable, and inexpensive NASA-provided, Sun-pointed spinning spacecraft. A 600-km equatorial orbit minimizes background and radiation damage to the germanium detectors.

The solar activity cycle, predicted to peak in 2000, requires that HESSI be launched no later than the end of 2000, with the end of 1999 ideal. The extensive heritage from the UCB HIREGS and the GSFC HEIDI balloon programs, and the UCB/GSFC FAST SMEX program, will allow HESSI to be built within MIDEX cost and schedule constraints.

A two-year nominal mission life, with a third year highly desirable, will provide detailed observations for tens of thousands of microflares, thousands of hard X-ray flares, and hundreds of gamma-ray line flares.

The HESSI mission includes a combination of space- and ground-based observations to provide the critical context information required for theoretical interpretation and detailed modeling.

Rapid and direct access by the solar scientific community to the HESSI data and analysis software, together with a Guest Investigator program funded from HESSI MO&DA funds, will ensure the maximum scientific return from this comprehensive data set.

The proposed mission concept has been endorsed by numerous advisory groups such as NASA's Space Sciences Advisory Committee (SSAC), and the National Academy of Science's Committee on Solar and Space Plasmas and Solar Terrestrial Research.

With its large array of unshielded germanium detectors, HESSI will also continuously monitor a large fraction of the sky to provide, serendipitously, high spectral resolution observations of transient hard X-ray and gamma-ray sources, including accreting black holes and cosmic gamma-ray bursts. For these, the confirmation and detailed study of possible line features may provide the crucial information for determining their origin. In addition, HESSI will provide hard X-ray imaging of the Crab Nebula with ~2" resolution (a factor of ten better than available previously) to study particle acceleration in that cosmic source.

The HESSI team includes the leading experts in solar high-energy spectroscopy and imaging, with decades of hardware and data analysis experience. The team also has an outstanding record of involving students and teachers, K through 12. We are committed to educational and public outreach, and to the involvement of beginning scientists/engineers and graduate/undergraduate students throughout all phases of the investigation.

1.0 SCIENCE INVESTIGATION

The processes of particle acceleration and impulsive energy release occur in active cosmic plasmas at diverse sites throughout the Universe, ranging from planetary magnetospheres to active galactic nuclei. The detailed understanding of these processes is a major goal of space physics and astrophysics, but we are just beginning to perceive the relevant basic physics. The Sun constitutes an unparalleled laboratory for investigating these processes. Its proximity allows measurements to be made on physically relevant scales; at the same time, the system as a whole can be studied. Furthermore, the complexity of solar magnetic fields and the solar atmosphere leads to a broad range of acceleration phenomena, which mimic the rich diversity of the processes that occur on cosmic scales.

Solar flares are the most prominent of these phenomena. **High-energy emissions are the most direct signature of the acceleration of electrons, protons and heavier ions in solar flares.** The hard X-ray and gamma-ray continuum is produced as bremsstrahlung by energetic electrons. Nuclear collisions of energetic ions with the ambient solar atmosphere result in a complex spectrum of narrow and broad gamma-ray lines that contain unique information on not only the accelerated ions but also the ambient solar atmosphere. HESSI will have sensitivity and dynamic range sufficient to provide meaningful observations from microflares and the earliest emissions in a flare, to the peaks of the largest flares. The high spectral resolution of these observations will permit, for the first time, the deciphering of the rich information encoded in both the gamma-ray lines and the highly structured photon continuum. These high-energy emissions are accompanied by a wealth of longer wavelength emissions whose observation from the ground will provide information on the context in which the high energy processes occur.

1.1 Particle Acceleration & Energy Release

Bursts of hard X-rays ($\gtrsim 20$ keV) are the most common signature of the impulsive phase of solar flares (Fig. 1-1). These X-rays are bremsstrahlung, most likely produced by electrons accelerated to tens of keV interacting with the ambient solar atmosphere. If the hard X-ray-producing electrons are indeed non-thermal (i.e. their energy $E_e >> kT$, the mean thermal energy of the ambient gas where they interact), then the energy lost by the electrons to bremsstrahlung in collisions with ambient ions is only a small fraction ($\sim 10^{-5}$) of the energy lost to Coulomb collisions on ambient thermal electrons. This inefficiency means that, for the largest flares, a total of $\sim 10^{39}$ electrons, containing $\sim 10^{32}$ ergs, must be accelerated in a time period of less than $\sim 10^3$ s. As this energy is comparable to the total radiative and mechanical output of flares, the acceleration of electrons to tens of keV may be the most direct consequence of the basic flare-energy release process.

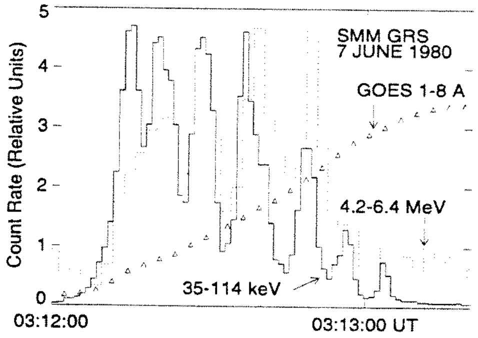


Figure 1-1. Time profiles for flare showing near-coincident impulsive peaks in 35-114 keV hard X-rays (from subrelativistic electrons) and 4.2-6.4 MeV gamma rays (from energetic ions).

It is, however, also possible that at least a fraction of the hard X-rays at tens of keV are quasi-thermal, i.e. produced by a single population of electrons with $E_e \simeq kT$ (with $T \gtrsim 10^8$ K). Then the energy lost by one electron in an electron-electron Coulomb collision simply goes to increase the energy of the other electron. In that case, the principal losses are conduction and convection, which can be considerably less than the collisional losses in non-thermal models. But if the emission is non-thermal, how can so much of the released magnetic energy be converted into accelerated electron kinetic energy? **HESSI will determine the relative contribution of thermal and non-thermal emission to the hard X-ray spectrum.**

The hard X-ray emission from flares is often (perhaps always - the gamma-ray detectors have much lower relative sensitivity) accompanied by nuclear gamma-ray line emission (Fig. 1-1), which is a direct signature of accelerated ion interactions. The bulk of the gamma-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 nonrelativistic electrons. However, there are nuclear reactions that are sensitive to lower energy ions; SMM data that became available recently (Share and Murphy 1995) can be better understood if the ion spectrum is an unbroken power-law in kinetic energy down to at least 1 MeV/nucleon. In this case, the energy content in the ions becomes comparable to that in nonrelativistic electrons.

Some of the accelerated particles themselves can be injected into interplanetary space. In the most intense Solar Energetic Particle (SEP) events, the fluence of protons sufficiently energetic ($\gtrsim 50$ MeV) to penetrate the walls of manned spacecraft is high enough to result in a harmful or even fatal radiation dose to astronauts. Such intense events also degrade electronic components on unmanned spacecraft. SEPs can also penetrate deep into the atmosphere over the Earth's magnetic polar regions and produce increased ionization, lowering the ionosphere and disrupting radio communications.

The $\gtrsim 50$ MeV protons in SEP events generally show a rapid rise in flux, within about the particle travel time from the Sun to 1 AU after the occurrence of a large flare, indicating that the particles were accelerated very close to the Sun at about the time of the flare. Spacecraft observations since then have shown that ions are often accelerated up to many MeV in the interplanetary medium by shock waves driven by fast Coronal Mass Ejections (CMEs). Since the SEP particles show charge states typical of the quiet corona, it is thought that they too may be accelerated by CME shocks, when those shocks are close to the Sun.

The energy release process in flares is clearly capable of accelerating both electrons and ions up to hundreds of MeV or higher on very short time scales (Fig. 1-1). **The nature of the mechanisms that can achieve this rapid acceleration is another fundamental question that will be addressed with HESSI.** It is difficult to see how shocks could accelerate ions to such high energies so rapidly. Furthermore, one of the best present predictors of SEP events is the systematic spectral hardening with time of the flare hard X-ray burst (Kiplinger 1995). **An understanding of the various ion acceleration processes at the Sun and how they are related to flare electron acceleration is therefore needed for the accurate prediction of such events.**

1.1.1 Non-Relativistic Electron Acceleration

The observed spatial, spectral, and temporal properties of the hard X-ray emission are generally consistent with the quantitative predictions of non-thermal thick-target models. In these models, the electrons accelerated in the coronal part of a loop propagate along the magnetic field and deposit their energy predominantly in the lower coronal and chromospheric portions of the loop. There they heat the ambient gas, leading to ablative mass motions of chromospheric material and concomitant radiation in the visible, UV, and soft X-ray bands.

Spatially resolved hard X-ray observations, such as those from the Yohkoh Hard X-ray Telescope (HXT), show a double footpoint structure (Fig. 1-2) typically appearing early in the flare, with the two footpoints brightening simultaneously to within a fraction of a second (Sakao et al. 1994). The hard X-ray centroids are located at progressively lower altitudes for increasing photon energies (Matsushita et al. 1992). They coincide, spatially and temporally, with Hα and white-light brightenings, implying that non-thermal electrons of tens of keV are interacting with a cool ($T<10^5$ K) environment. If the site of the energy release is in the corona, near the tops of flare loops, very rapid transport of energy from the energy release site

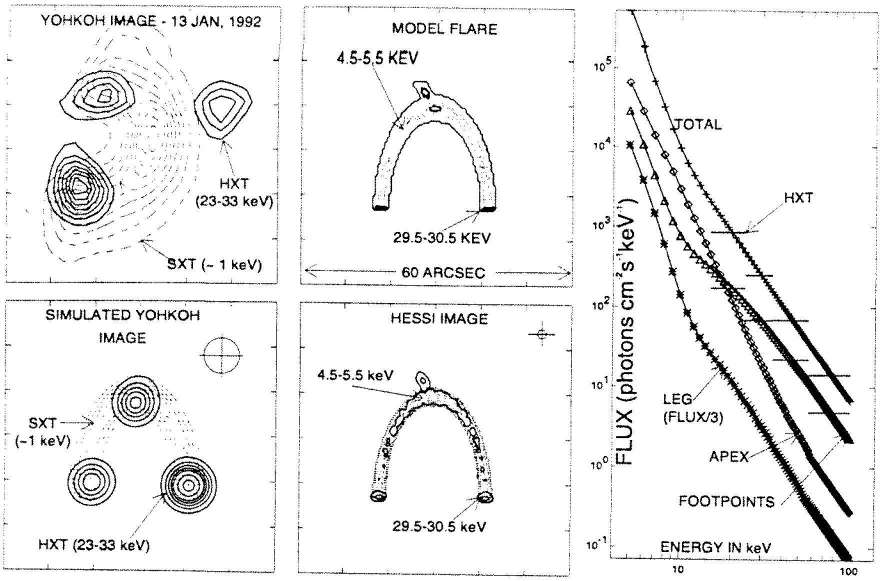


Figure 1-2. The M1 limb flare seen with SXT and HXT *(top left)* with simulation results showing the images and spectra that would be obtained from HESSI and Yohkoh for a model flare ten times more intense. Such a flare *(top right)* is expected to occur once a month, on average. The solid and dotted contours are for hard and soft X-rays, respectively. *Bottom*: Reconstructed images that would be obtained from Yohkoh. and HESSI. The 50% contour of the point-spread functions are shown in the upper right of each box. The spectra on the right are for three different locations in the loop with HESSI's spectral resolution, and with the four HXT energy intervals. Note that HESSI (but not HXT) has sufficient dynamic range capability (up to 100:1) to obtain spectra from the legs of the loop in the presence of the bright footpoints.

to the interaction region is required. This can only be achieved by streaming electrons but it is unclear how the implied huge currents (up to 10^{36} electrons/s or 10^{17} amps) can conform to the global electrodynamic constraints of the flare environment.

For some flares occurring near the solar limb, HXT has detected a co-temporal, but weaker, hard X-ray source in the corona *above* the soft X-ray loop (Masuda et al. 1994) linking the hard X-ray footpoints as seen with the Soft X-ray Telescope (SXT) on Yohkoh (Fig. 1-2). This source has been interpreted as evidence for energy release by magnetic reconnection in a region above the soft X-ray loop. These important observations support the non-thermal thick-target model, but they provide little information about the actual acceleration and energy release processes. As we show below, **high resolution X-ray imaging spectroscopy is the key to understanding these processes.**

Since the bremsstrahlung cross section is accurately known (to about 10% in the hard X-ray range), precise measurements of the solar flare hard X-ray spectrum can, in principle, be inverted to obtain the detailed spectrum of the parent X-ray-producing electrons at the Sun. **The scintillation (NaI or CsI) detectors which have been used for all previous spacecraft solar hard X-ray observations are inadequate for this task** since their FWHM energy resolution is generally larger than the scale of variation of the sharp features in the flare spectrum. In addition, NaI and CsI scintillators have escape peaks (34 keV for iodine) in the middle of the hard X-ray energy range. The resulting broad and complex response function precludes the direct inference of the incoming photon spectrum. Instead, trial spectra must be assumed, a technique which is known to be imprecise, giving acceptable fits for a relatively wide range of spectral shapes (Fenimore et al. 1982). Thus, sharp spectral breaks that are known to exist in the hard X-ray spectrum are essentially missed (see below).

The high spectral resolution of the cooled germanium (Ge) detectors, on the other hand, yields a near delta-function response for continuum measurements above ~10 keV. This makes the direct determination of the X-ray spectrum from the count-rate spectrum possible and eliminates the need to assume an *a priori* spectral shape for the X-rays. The thermal and non-thermal components can be easily and cleanly separated, which is important for determining the low-energy cut-off to the electron spectrum and the total energy in electrons.

The power of such measurements was illustrated by the first (and only) hard X-ray measurement with high-spectral (but no spatial) resolution, which was carried out with a balloon-borne Ge spectrometer for the 1980 June 27 flare. The high spectral resolution immediately led to the discovery of a sharp steepening in the X-ray spectrum below ~30 keV due to thermal bremsstrahlung from a "superhot" ~3.5 × 10^7 K plasma (Lin et al. 1981). It also showed that the non-thermal component does not fit a

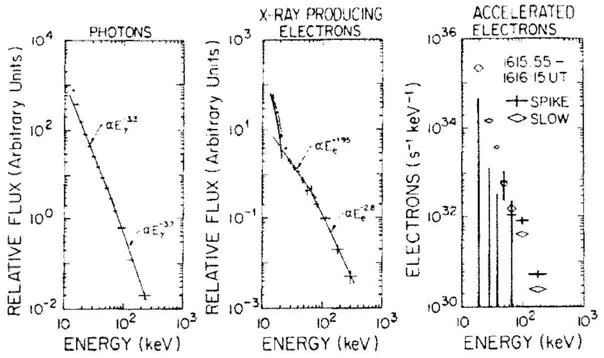


Figure 1-3. High-resolution X-ray spectrum for 27 June 1980 flare *(left)*, together with the derived spectra of the X-ray-producing electrons [N(E), *center*] and the accelerated electrons [F(E), *right*] (from Johns and Lin 1992).

single power law or a single temperature thermal, but rather a double power law with a relatively sharp break at ~50 keV (Fig. 1-3), Such a shape implies a low-energy cutoff or flattening in the X-ray-producing electron spectrum.

A numerical inversion of these data (Johns and Lin 1992) has been used to determine the parent electron spectrum N(E,t) with the same energy resolution and over the same energy range as the X-ray observations (Fig. 1-3).

N(E,t) is the result of modification of the accelerated electron spectrum F(E,t) by electron energy loss, propagation, and escape processes. Assuming that Coulomb collisions dominated these loss processes, Lin and Johns (1993) derived F(E,t) and found that there may be two separate components of accelerated electrons: an impulsive spike component with a spectrum peaked at ~50 keV, plus a slowly varying component with a power-law spectrum extending down to ~20 keV (Fig. 1-3). The integration of F(E,t) over energy and time provided the first accurate assessment of the energy released in accelerated electrons, ~10^{31} ergs above 23 keV, a substantial fraction of the total energy released in this GOES M6 flare.

The peak in the spike electron spectrum suggests acceleration by a DC electric field, with the peak energy corresponding to the total potential drop in the field; such electron spectra are observed in the Earth's auroral zone. A detailed, self-consistent model of the heating and runaway electron acceleration in a DC electric field has been developed for this flare by Benka and Holman (1994). Comparisons with both the observed thermal "superhot" and the non-thermal hard X-ray spectrum allowed determination of the electric-field strength, plasma, density, and temperature in the flare region.

By combining high spatial resolution with high spectral resolution, HESSI will provide the crucial key needed to determine the particle acceleration process, namely the spectral, spatial, and temporal variation of F(E,t), i.e., F(E,r,t). The 2-arcsec and tens-of-millisecond resolutions of HESSI are commensurate with the expected spatial and temporal scales over which the accelerated electrons are expected to lose their energy in the lower corona and upper chromosphere (ambient density $\lesssim 10^{12}$ cm^{-3}). The X-ray emission in each angular and temporal element will be measured with energy resolution $\lesssim$ 1 keV, allowing model-independent determinations of the X-ray spectrum. These measurements will permit the straightforward inversion of the photon spectrum to obtain the X-ray producing electron differential number density as a function of energy (E), position (**r** -- in the plane of the sky), and time (t), N(E,**r**,t).

The evolution of the electron spectrum in space and time, together with information on ambient density, magnetic field strength and topology, will allow the electron loss processes to be directly evaluated. This will decide whether the X-ray emission is thermal or nonthermal, since the energy loss characteristics of the emitting electrons are so different in the two cases. Then, via 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. Once N(E,**r**,t) and F(E,**r**,t) are obtained, detailed quantitative models of the acceleration, energy release, and energy propagation processes can be constructed and tested.

For all of these analyses, knowledge of the physical parameters in the regions of interest are required. **As part of the mission itself, HESSI combines co-temporal space and ground-based observations to determine these parameters both before and during the flare.** Soft X-ray (2-20 keV) imaging spectroscopy by HESSI will reveal the temperature, density, location, and temporal evolution of the flare thermal plasmas, as well as the characteristics of the low energy (<20 keV) accelerated electrons that may contain the bulk of the energy released. Such observations will also allow us to distinguish between plasma directly heated during the energy release process itself or in-directly heated by the thermalization of the accelerated electrons. The Soft X-ray Imager (SXI), to be launched (probably in 1998-9) on the upcoming NOAA GOES spacecraft, will provide SXT-type broadband (6-60Å) images every minute to determine the global and local morphology of coronal features.

Ground-based measurements of magnetic field strengths in the photosphere and corona are critical to understanding the effects of magnetic fields on nonthermal electron transport (e.g., magnetic mirroring), and also provide the plasma beta, an essential parameter in particle acceleration models. Microwave imaging/spectroscopy will provide direct measurements of preflare coronal fields plus thermal and nonthermal electron and field parameters. Vector magnetograms will show the role of evolving magnetic fields (e.g., emerging magnetic flux) in causing magnetic reconnection and magnetohydrodynamic instability, as well as provide maps of electric currents to define their relationship to sites of possible DC electric field acceleration (Canfield et al. 1993). Optical imaging spectra provide velocities in the lower atmosphere, a straightforward measure of the energy that goes into chromospheric evaporation. Multiband optical imaging will provide information on energy release, since the optical continuum emission is thought to be the largest component of the radiative energy budget of flares.

HESSI's imaging spectroscopy is a powerful tool for studying the following phenomena.

Hard X-ray microflares, $\gtrsim 100$ times less intense than normal flares, suggest that the flare process may be a fundamental way by which stored magnetic energy is released in the Sun's corona. During ~2 hours of balloon observations, one microflare was detected every ~5 minutes (Lin et al. 1984). The occurrence frequency varies with peak hard X-ray flux in a way similar to that for normal hard X-ray bursts. Their X-ray spectra measured above 15 keV are power laws with significantly steeper spectral slopes than that measured for the 27 June 1980 flare (Fig. 1-3), and they show no indication of a spectral break. The average rate of energy deposition by $\gtrsim 20$ keV electrons, assuming non-thermal X-ray production, is $\sim 10^{24}$ erg s^{-1} for the observed events, but if the power-law nonthermal electron spectrum extends down to a few keV, the rate would be sufficient to heat the active corona. **HESSI's high sensitivity imaging spectroscopy extending down to ~2 keV will allow the systematic survey of the microflare contribution to coronal heating.** At the same time these "simple" microflares may provide unique insights into the basic flare acceleration and energy release processes.

Hard X-ray emission from the upper corona can occasionally be observed from limb-occulted flares, suggesting that energetic electrons are present high in the corona. In one such event, hard X-ray emission was detected above an occultation height of 160,000 km (Kane et al. 1992). If the emission is non-thermal, 10^{39} electrons above 5 keV with a total energy of 10^{31} ergs are required in a source volume of 10^{30} cm^{-3} or ~1.5 arcmin in angular size. Interplanetary SEP events should also show coronal emission. Clearly, the capabilities of HESSI to obtain N(E,**r**,t) are needed to understand this coronal emission.

Coronal Type III solar radio bursts and soft X-ray jets. Type III bursts are produced by beams of energetic electrons escaping through the corona. An unstable electron beam-plasma interaction produces plasma waves, which, in turn, combine to generate radio waves. How the electron beam can propagate to ≥1 AU distances without losing all its energy to the plasma waves is not known. Soft X-ray jets, recently discovered by Yohkoh (Shibata et al. 1992) turn out to be the dense channels in which some type III bursts propagate (Kundu et al. 1995). Direct observations of the electrons associated with type III bursts in the interplanetary medium generally show steep power-law spectra extending down to ~2 keV. The absence of a low-energy turnover indicates a high coronal origin. Most of these electron events are not associated with flares or chromospheric phenomena, but they show essentially a one-to-one correlation with ^{3}He-rich particle events (Reames et al. 1985). **Comparisons of HESSI's determination of N(E,r,t) at the Sun down to a few keV with soft X-ray images and electron measurements in interplanetary space, will help in understanding the electron acceleration, escape, and radiation processes.**

1.1.2 Relativistic Electron Acceleration

The presence of relativistic electrons in solar flares is revealed by the bremsstrahlung continuum which extends from the hard X-ray region to gamma-ray energies as high as sever-

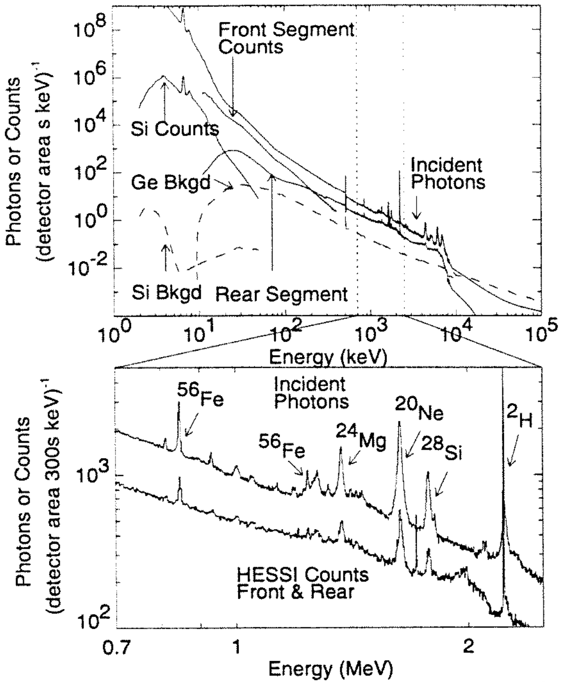


Figure 1-4. **(Top)** Representative photon spectrum for a large X-class flare (such as 4 June 1991) over the full energy range covered by HESSI. Also shown are the corresponding count-rate spectra and the expected background spectra in the HESSI Si(Li) detectors (12 cm^2) and the front and rear germanium segments (475 cm^2). **(Bottom)** Expanded view of the narrow gamma-ray line region.

al hundreds of MeV. At energies of a few hundred keV the spectrum sometimes shows a flattening (Fig. 1-4, top) indicating that different mechanisms may be accelerating the nonrelativistic and relativistic electrons. Electrons of energies from a few hundred keV to several MeV also produce gyrosynchrotron radiation in the microwave region, which is observed with ground-based imaging spectrometers. Because the ratio of the magnetic field to the ambient density is much higher in the coronal part of loops than in the footpoints, it is likely that the centroids of the microwave and soft gamma-ray sources will be spatially distinct. **HESSI will provide the first imaging in this energy range above 100 keV. Comparison of N(E,r,t) obtained by HESSI with the spatial distribution, fluxes, and spectra of the microwaves will provide information on the angular distribution of the electrons, on the magnetic field strength, and on the acceleration, trapping, and precipitation of the electrons in the loop.**

1.1.3 Ion Acceleration

Near the Sun, a rich spectrum of gamma-ray lines (Fig. 1-4) is produced by nuclear collisions of accelerated protons, alpha particles, and heavier nuclei with the ambient solar atmosphere (Ramaty and Murphy 1987). These collisions produce excited nuclei, neutrons, positrons, pions, and other spallation products. Gamma-ray lines result from de-excitations of all the abundant constituents of the solar atmosphere up to iron, as well as from neutron capture and positron annihilation (Table 1-1). Energetic protons and alpha particles colliding with carbon and heavier nuclei produce narrow de-excitation lines (widths of a few keV to about 100 keV) while energetic heavy nuclei colliding with ambient hydrogen and helium produce much broader lines (widths of a few hundreds of keV to an MeV). All of this line emission is superimposed on a bremsstrahlung continuum produced by relativistic electrons. Gamma-ray line emission has been observed from many solar flares, mostly with the Gamma Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) (Chupp 1990). Of all astrophysical sites, the most detailed gamma-ray line spectra have so far been seen from solar flares.

HESSI will perform the first high-resolution spectroscopy of solar flare gamma-ray lines, and the first imaging of solar flare gamma rays. Except for a limited observation of one line with HEAO-3 (Prince et al. 1982), solar flare gamma rays have never been observed with high-resolution Ge detectors. These detectors can spectrally resolve all the expected lines (except the 2.223-MeV line; see Fig. 1-5, the foldout sheet at the end of the proposal); none of these lines have been resolved by the solar gamma-ray detectors flown on spacecraft to date. This will allow the first determination of line shapes, which are direct probes of the angular distribution of the interacting accelerated ions. The derived angular distributions will discriminate between the various transport and acceleration mechanisms. For example, ions which suffer strong pitch-angle scattering into the loss cones due to plasma turbulence in the coronal part of the loops will interact mostly while going downward and produce different line shapes than ions which interact while mirroring near the loop footpoints.

High energy resolution will permit the separation of closely spaced lines. This is particularly important in the crowded 1-2 MeV region populated by many lines produced by protons and alpha-particle excitation of ambient Ne, Mg, Si and Fe (Fig. 1-4, bottom). The

Table 1-1. HESSI response for gamma-ray lines from a large flare (e.g. 4 June 1991), and 3σ sensitivities

			Fluence (photons/cm^2)			Counts in HESSI (300 s)				HESSI Sensitivity 3σ line fluence (photons/cm^2)	
Line Energy (MeV)	Excited Nucleus	Width (keV)	Line	Nuclear Continuum	Total* Continuum	Line	Continuum	Background	Number of σs	100 s	1000 s
Prompt Lines											
~0.45†	^{7}Li-^{7}Be	62	11	179	853	1.5×10^{3}	1.52×10^{5}	1.54×10^{4}	3.6	5.2	16.5
0.478†	^{7}Li	10	5.5	29	123	750	2.45×10^{4}	2.11×10^{3}	4.6	2.1	6.6
0.429†	^{7}Be	5	5.5	14.5	75.5	750	1.22×10^{4}	1.28×10^{3}	6.4	1.5	4.7
0.847	^{56}Fe	6	15	3.3	17.6	1.58×10^{3}	3.83×10^{3}	460	24	1.1	3.4
1.239	^{56}Fe	6	2.7	4.5	10.3	292	2.4×10^{3}	234	5.7	0.8	2.6
1.369	^{24}Mg	18	21.2	14.1	27.7	1.85×10^{3}	6.49×10^{3}	588	22	1.7	5.2
1.634	^{20}Ne	27	63.1	15.1	28.4	4.94×10^{3}	6.59×10^{3}	640	58	1.8	5.8
1.778	^{28}Si	25	23.7	12	22	1.93×10^{3}	5.37×10^{3}	510	25	1.6	5.1
4.439	^{12}C	168	61.1	15.7	23.2	2.1×10^{3}	5.57×10^{3}	670	26	4	12.6
6.129	^{16}O	214	52.2	13.5	18	1.02×10^{3}	4.14×10^{3}	346	15	5.9	18.8
Delayed Lines											
0.511	*e+*	3	198	4.9	28.9	2.68×10^{4}	6.1×10^{3}	6.4×10^{3}	240	1.4 ††	4.6
2.223	^{2}H	3‡	296	1.3	2	2.18×10^{4}	362	44	1083	0.5	1.5

* The total continuum includes both the non-thermal bremsstrahlung continuum and the continuum from the positron and nuclear gamma-ray line components.
† The narrow lines are for a downward beam or a fan beam; the single broad line at ~0.45 MeV is for an isotropic distribution.
†† The sensitivity is computed assuming a narrow (<4 keV) solar 511-keV line.
‡ This line has an intrinsic width of ~0.1 keV, so we used the instrument FWHM resolution (3 keV).

production of the 1.634-MeV ^{20}Ne line is sensitive to protons of very low energy. The detailed study of the ratio of the flux in this line to that in other lines will probe the behavior of the ion energy spectrum at the lowest accessible energies, and thus determine the energy content in the ions down to as low as 1 MeV.

HESSI's high-resolution detectors will be particularly sensitive to narrow lines. For the 2.223-MeV neutron capture line, which is the strongest line from flares but intrinsically very narrow (FWHM < 0.1 keV), HESSI will be at least 10 times more sensitive than was the GRS instrument on SMM. By observing this line from many flares, we will determine the relative frequency of ion and nonrelativistic electron acceleration down to much lower flux thresholds than was done with SMM. Combined with the determination of the energy content in ions for individual flares, we will address the fundamental problem of the partition of the released magnetic energy between ions and electrons.

A very important discovery during Cycle 22 was that of long-duration gamma-ray emission. GeV gamma rays from pion decay were observed with EGRET on CGRO for up to 8 hours after the impulsive phase of the 11 June 1991 flare (Kanbach et al. 1993). Nuclear line emission at 2.223 MeV was also observed with essentially the same time profile (Schönfelder 1994). This strongly suggests that acceleration to GeV energies was ongoing for a very extended period of time. **With its sensitivity, HESSI will be able to observe the 2.223-MeV line for several hours after a flare similar to the 11 June flare.** These observations will address the issue of trapping vs. continuous acceleration in flares.

The 2.223-MeV line is formed when thermalized neutrons are captured by ambient protons in the photosphere at a much greater depth than that at which the nuclear reactions take place. However, in a behind-the-limb flare, the 2.223-MeV line has been seen (Vestrand & Forrest 1993). Because of the very strong expected attenuation, 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.

HESSI has a unique capability to image in narrow gamma-ray lines, since the high spectral resolution of the germanium detectors allows a narrow energy window to be used so that the line counts dominate over the continuum background (Table 1-1). HESSI will be able to locate the neutron capture region by imaging the 2.223-MeV line for many flares. The positron annihilation region can be located by imaging the 0.511 MeV line. Furthermore, by imaging the nuclear continuum above ~1 MeV in flares where that dominates the underlying electron-bremsstrahlung continuum, HESSI will locate the energetic heavy (Z>2) ions, which produce the broad lines that make up that continuum. In a large gamma-ray line flare, where statistics are good, the >10 MeV protons can be located by imaging narrow de-excitation lines (Table 1-1). Imaging of these components should give locations and source sizes to better than ~20 arcsec in large flares. **This will be the first localization of solar flare gamma rays and the most precise imaging ever achieved in gamma-ray astronomy.**

Interplanetary energetic electron-to-proton (e/p) ratio measurements have been used to distinguish two classes of SEP events (Reames 1990) - impulsive and gradual - so-called because of the temporal behavior of the associated flare soft X-ray burst. Acceleration due to gyroresonant interactions with plasma turbulence in impulsive flares is hypothesized to be responsible for the large e/p ratios for such flares. Acceleration by shocks associated with gradual events produce much smaller values of e/p. With gamma-ray observations, the relativistic electron-bremsstrahlung continuum can be compared with the nuclear line emission to investigate the e/p ratio for the interacting particles at the Sun. These indicate that the interacting particles and the interplanetary particles from impulsive flares may have a common origin (Ramaty et al. 1993).

In addition to the e/p ratio, the enrichment of heavy-element (in particular Fe) abundances for the interplanetary particles is another signature of impulsive flares (Reames et al. 1994). HESSI's spectroscopic capabilities will allow the elemental composition of the interacting particles to be investigated in detail, and complementary interplanetary measurements of the composition of SEPs will be provided by the Advanced Composition Explorer (ACE, launch ~1997) for comparison.

Furthermore, HESSI's imaging will allow the determination of the e/p ratio in the MeV region, and proton/heavy (Z>2) ion ratio, as a function of location. Comparisons of the images of the energetic proton, energetic heavy ion, and neutron-capture regions to each other and to the relativistic and non-relativistic electron images, will provide new insight into the relationship of the acceleration of these different species, and as mentioned earlier, this may lead to accurate predictions of SEP events.

The alpha-particle-to-proton ratio is another important diagnostic of acceleration mechanisms. HESSI will determine this from the ratio of the combined 0.429-MeV and 0.478-MeV line flux to the flux in lines at higher energies. These low energy lines are due to de-excitations in ^{7}Be and ^{7}Li that can effectively be produced only by alpha-particle interactions.

The 2.223-MeV line can also be used to determine the unknown ^{3}He abundance in the photosphere (Hua and Lingenfelter 1987). Depending on this abundance, as much as one half of the neutrons can be captured on ^{3}He, so that the ^{3}He abundance significantly affects the flux and time profile of the 2.223-MeV line.

Nuclear reactions also lead to the production of positrons, which annihilate producing the 0.511-MeV line. Because of the low mass of the positron/electron system, the width of the 0.511-MeV line is a sensitive probe of the temperature of the annihilation site. **HESSI's energy resolution at 0.511-MeV is sufficiently good to measure temperatures down to 10^4K,** and it can easily distinguish between annihilation sites located below the transition region, in the corona, or in the hot ~10^7 K flare plasma. The bulk of the annihilations would occur in the corona if the magnetic field traps both the interacting ions and the positrons in this region.

The positronium continuum which accompanies the 0.511-MeV line is sensitive to the density and state of ionization of the ambient medium (Crannell et al. 1976). The positronium continuum is prominent only if the density of the ambient medium is less than about 10^{15} cm^{-3}. Monte Carlo simulations have shown that energetic ions could penetrate to regions of densities as large as 10^{17} cm^{-3} (Hua et al. 1989). Thus, measurements of this continuum with HESSI will provide additional information on the location of the annihilation site.

To understand why, where, and when nuclear line emissions occur, **HESSI's cotemporal ground-based observations of the spatial and temporal distribution and evolution of magnetic fields, electric currents, and plasma flows in and around flares are just as critical for ions as they are for electrons.** The added role they have to play for ions accrues from the sensitivity of optical Hα polarization to low-energy (100 keV) protons. If DC electric fields accelerate the ubiquitous hard-X-ray-producing electrons, then they may also accelerate many 100-keV protons (Holman 1995). Positive detections of Hα polarization in a few flares have been made (Hénoux et al. 1990, Metcalf et al. 1993), but their interpretation is uncertain, and demands cotemporal HESSI energetic ion, electron, and ground-based (Hα polarization) images to open up this new and unexplored range of high-energy solar-flare physics.

1.1.4. Non-Solar Objectives

Although designed as a solar instrument, HESSI provides a combination of high energy resolution, large collecting area, and wide field of view (at 60°-120° to the solar direction) that makes it uniquely suited for investigations of transient astrophysical sources, such as gamma-ray bursts and transient gamma-ray lines from black-hole candidates. Thus, **HESSI is complementary to the European INTEGRAL mission,** which will have a narrow field of view and will not be able to monitor the sky for transients. In addition, the Sun spends a few days a year close enough to the Crab Nebula to allow imaging by HESSI.

The Crab Nebula has long been imaged in radio through UV wavelengths, showing a great deal of structure and a tendency toward smaller sizes at higher energies; this is thought to reflect the loss of energy by synchrotron-producing electrons as they travel out from their region of production near the central pulsar. It has been imaged in soft X-rays by the Einstein observatory and by the ROSAT HRI. The only hard X-ray image to date (Pelling et al. 1987) had only 15 arcsec resolution and two energy bands. **A small offset pointing of HESSI ($\lesssim 1°$), would result in a truly remarkable set of Crab images with unprecedented spatial (2 arcsec) and energy (~1 keV) resolution.** We estimate that a day's observing in a band from 25-35 keV would give about 270,000 source counts for about 380σ of total flux in the map. Maps could be made up to about 200 keV. Fine structures such as the wisps and jets seen at lower energies could be observed for the first time in hard X-rays.

Gamma-Ray Bursts. Although over 1000 gamma-ray bursts have been observed, mostly with BATSE, it is still not certain whether they are remotely extragalactic, distributed in our Galactic halo, or even much nearer. Absorption lines at tens of keV energy, attributed to cyclotron scattering and absorption in $\sim 10^{12}$ G magnetic fields, have been reported from a number of bursts. These lines could not be formed in the extreme conditions that must exist in the source regions if the bursts are at cosmological distances, but could be formed in the magnetic fields characteristic of neutron stars. BATSE has not reported clear observation of any cyclotron absorption features and the statistical consistency of these observations with the most significant positive detections (from Ginga) is strained (Band et al. 1994). **With the largest area by far of any wide field-of-view, high spectral resolution instrument, HESSI will be able to detect such lines easily and unambiguously if they exist.**

Black-Hole Candidates. Line-like emission features at ~0.4 MeV have been observed from a number of sources assumed to be accreting black holes, e.g., Nova Muscae and 1E 1740-2942. In several of these observations, this line was accompanied by another line at ~0.2 MeV. The ~0.4-MeV line may be positron-annihilation radiation gravitationally redshifted by proximity to an accreting black hole; the ~0.2-MeV line could be Compton-backscattering of the annihilation feature from the inner edge of an optically-thick accretion disk (Lingenfelter and Hua 1991). The features could also be due to Compton scattering of continuum radiation in a double-sided jet without the need for positrons (Skibo et al. 1994).

HESSI will provide high resolution, high sensitivity observations to clear up the currently uncertain observational picture. HESSI's 3σ statistical sensitivity for a line at ~0.4 MeV in one day of observation is about 6×10^{-4} photons $cm^{-2}\ s^{-1}$ for a broad line (about 10% of the 1E 1740 and Nova Muscae transients) and 8×10^{-5} photons $cm^{-2}\ s^{-1}$ for a narrow line.

1.2 Investigative Approach

The achievement of these scientific objectives will be based on high resolution imaging and spectroscopy observations in the soft X-ray, hard X-ray, and gamma-ray regimes, with finer angular resolution (up to 2 arcsec) and finer energy resolution (~1 keV) than has previously been possible. HESSI will provide a uniquely powerful combination of the first hard X-ray imaging spectroscopy, the first spacecraft high resolution hard X-ray and gamma-ray spectroscopy up to 20 MeV, and the first imaging at energies above 100 keV up to the gamma-ray line energies. This combination of imaging and spectroscopy is achieved with a set of Rotating Modulation Collimators (RMCs) placed in front of an array of cooled germanium and silicon detectors, as shown in the foldout sheet.

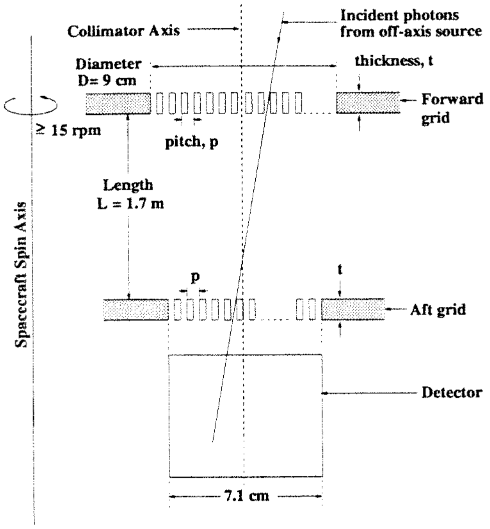


Figure 1-6. Schematic showing the instrument parameters that define the imaging capability.

Imaging Technique. The only viable method of obtaining arcsec-class images in hard X-rays and gamma rays within the MIDEX constraints is to use Fourier-transform imaging. In our implementation of this technique, we use a set of 12 bi-grid collimators, each of which consists of a pair of widely-separated grids in front of an X-ray/gamma-ray detector as shown in Fig. 1-6. Each grid consists of a planar array of equally-spaced, parallel, X-ray-opaque slats separated by transparent slits. If the slits of each grid are parallel to each other, and the pitch (*p* in Fig. 1-6) is identical for the two grids, then the transmission through the grid pair depends on the direction of incidence of the incoming X-rays. For slits and slats of equal width, the transmission varies between zero and 50% depending on whether the shadows of the slats in the top grid fall on the slits or slats of the lower grid. A complete transmission cycle from zero to 50% and back to zero corresponds to a change in source direction that is given by p/L, where L is the separation between grids. The angular resolution is given by $p/(2L)$.

The collimator is mounted fixed on the spacecraft and the transmission is modulated in time as the spacecraft rotates at ≳ 15 rpm about an axis parallel to the collimator axis (Fig. 1-6). The detector records the arrival time and energy of individual photons that have passed through both grids, thus allowing the modulated counting rate to be determined as a function of the rotation angle. Note that **the detector does not need to have any spatial resolution and hence can have the highest possible sensitivity and energy resolution.**

For a parallel incident beam, the modulation waveform generated by the smooth rotation of the spacecraft has a distinctive pseudo-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 fundamental component of the observed waveform provide a direct measurement of a single Fourier component of the angular distribution of the source (e.g., Prince et al. 1988). Different Fourier components are measured by using multiple collimators with grids of different pitches.

For HESSI, the imaging is achieved with a set of 12 such RMCs. The grids are separated by 1.7 m, and have logarithmically spaced pitches ranging from 34 μm to 2 mm resulting in angular resolutions from 2 arcsec to 2 arcmin (see angular coverage plot on foldout sheet). The primary limitation imposed by the 2 arcmin scale of the coarsest grids is that diffuse sources larger than 2 arcmin will not be imaged but the full spectroscopic information will still be available as a function of time. Note, however, that HESSI will be able to image multiple smaller sources regardless of their separation.

To maximize the range of photon energies that are modulated, the grids are fabricated from high density, high-Z materials (gold or tungsten), and made as thick as possible, consistent with a 1° (full-Sun) field of view. Thus, the grid thickness can be up to 57 times the slit width, which implies that the angular resolution is energy dependent, ranging from 2 arcsec at energies below ~200 keV to 20 arcsec above ~1 MeV. The four thickest grids (~2.5 cm) provide ≳ 70% modulation at all energies up to 20 MeV (see modulation amplitude vs. energy on foldout sheet).

The 12 RMCs measure a large number of Fourier components (~1800 uv points for a typical source location, 12 arcmin from the spin axis) in a half rotation (2 s). This compares with 32 uv points for HXT on Yohkoh. An example of the modulated count rates expected for a loop-like source on the Sun is shown in the foldout sheet. A detailed simulation of HESSI's response to an X1 flare similar in structure to that detected by Yohkoh is shown in Fig. 1-2. As indicated, **HESSI can obtain a dynamic range up to 100:1 in the image, and detailed high-resolution spectra can be obtained for each location in the image, thus providing true high-resolution imaging spectroscopy for the first time.**

Although one half rotation is required to measure a full set of Fourier components, useful imaging information can be obtained on the much shorter timescale of the modulation period. Depending on the source location, this can be as short as 1.3 ms for the finest grids. In practice, when count rates are sufficiently high, crude images (from about ten uv points) can be obtained on timescales of tens of milliseconds to permit spatially resolved observations of the rapidly changing emission geometry.

An optical aspect system (described in Section 2.2.1) provides sub-arcsec aspect knowledge at the time of arrival of each photon, using limb sensing of the white-light image of the Sun for pitch and yaw, and a star scanner for roll. Such knowledge allows the X-ray/gamma-ray images to be reconstructed on the ground and accurately located in inertial space for comparison with microwave images. In addition, the solar aspect system is capable of providing sunspot images for use in aligning HESSI's images with ground-based optical data to ~1 arcsec.

X-ray and Gamma-ray Detectors: Behind the RMCs, germanium (Ge) detectors, cooled to ≤85 K by mechanical cryocoolers, cover the entire hard X-ray and gamma-ray-line energy range (10 keV to 20 MeV) with the highest spectral resolution of any presently available detectors. The energy resolution (see the foldout sheet) is sufficient to resolve essentially all the solar gamma-ray lines for the first time, as well as to resolve sharp breaks in the non-thermal continuum and the steep super-hot thermal component of solar flares.

By segmenting the inner (signal) electrode near the top, each germanium crystal is divided by the electric field into two electrically independent detectors (see foldout sheet). The front segment thickness is chosen to stop photons of energies from ~10 to ~150 keV, where photoelectric absorption dominates, while minimizing the active volume for background.

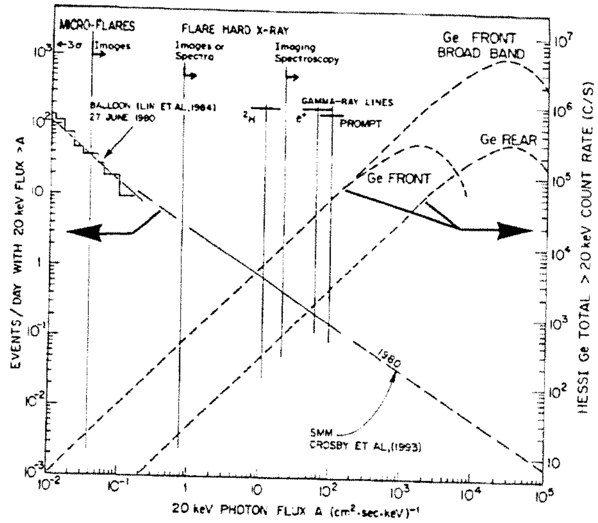


Figure 1-7. Integral flare-size distribution for >20 keV X-rays showing the flares and microflares observed in 1980. Also shown are the corresponding HESSI count rates above 20 keV and count rate ranges over which imaging, spectroscopy, imaging spectroscopy, and the detection of the different gamma-ray lines are possible.

Compton-scattered incident photons and background entering from the rear are rejected by anticoincidence with the rear segment of the detector. In addition, a graded-Z shield around the curved outer surface of the front segment absorbs hard X-rays incident from the side. Therefore, the front-segment-only mode has excellent background rejection properties.

Higher energy (~150 keV to 20 MeV) photons, including nuclear gamma-rays, are detected primarily in the long rear segment. Those that stop in the front segment, those that deposit part of their energy in both the front and rear segments, and those that deposit energy in two or more detectors, also contribute to the total efficiency, and are recorded and tagged accordingly.

The large flares that produce significant gamma-ray line fluxes also produce intense <150 keV X-ray fluxes. Segmentation allows the front segment to absorb these low energy fluxes, so the rear segment will always be able (see Fig. 1-7) to provide gamma-ray line measurements with optimal spectral resolution and high efficiency.

Lithium-drifted silicon Si(Li) semiconductor detectors, cooled to 150-200 K, are placed in front of the germanium detectors to extend the imaging spectroscopy down to 2 keV. Unlike the soft X-ray imaging provided by SXT on Yohkoh, high-spectral-resolution (~0.5

keV) images are obtained over the entire energy range from 2 to 20 keV, and through the same RMCs as the hard X-rays and gamma-rays. Thus, **differences between the soft X-ray and higher energy images will be readily apparent, and all images over three decades of energy are inherently co-aligned**.

Cooling of the Ge detectors to <85 K and the Si(Li) detectors and FETs to 150-200 K (not critical) is provided by **a long-life mechanical cryocooler, similar to those successfully operated for >2 years** on NASA's UARS (ISAMS), and on the European ERS-1 (ATSR).

The **detector electronics** are adapted from the UCB HIREX, HEXAGONE and HIREGS balloon instruments to provide the best available spectral resolution and high-rate performance. For the intense hard X-ray fluxes of very large flares, where the dead time for the front detector spectroscopy channel is large, these electronics are unique in that they can provide imaging in broad-band energy channels at very high count-rates ($\sim 5 \times 10^5$ c/s per detector) (see Fig. 1-7 and Section 2.2.3).

The Instrument Data Processing Unit (IDPU), adapted with minor modification from UCB's FAST SMEX, is equipped with a 16-Gbit solid-state recorder, sized to hold all the data from the largest flare. The telemetry system is designed to downlink $\gtrsim 12$ Gbits in 48 hours to a single ground station near the equator. Since two such large flares have never been observed to occur within a day or two of each other, little or no data should ever be lost.

Spacecraft: A simple Sun-pointed, spin-stabilized spacecraft, utilizing FAST subsystems (described in Appendix B of the AO) with minor changes, is ideal for HESSI. The requirements on spacecraft pointing are minimal since the axes of the RMCs need only to be kept within 0.2° of Sun center. Consequently, HESSI is planned for an automated store-and-dump operation, and no real-time access is required. Thus, **operating costs are low and we have been able to plan and budget for 3 years of operations to maximize the scientific return.**

Orbit: A low altitude (600 km) equatorial orbit (inclination <1°) for HESSI avoids the most intense fluxes of trapped protons in the South Atlantic Anomaly. Solar-flare particles and cosmic rays below 10 GeV are excluded by the Earth's magnetic field. Then, the cumulative radiation dose in a 3-year mission lifetime is low enough to avoid degradation to HESSI's unshielded *n*-type Ge detectors. Moreover, the X-ray and gamma-ray background in an equatorial orbit is low and stable so shielding is not needed for solar-flare observations. Also, non-radiation hardened parts can be used in the electronics, a significant design and cost advantage. Furthermore a single near-equatorial ground station can provide coverage every orbit.

While a greater instrument weight could be put into a higher inclination orbit by the Med-Lite launch vehicle, Monte Carlo calculations show this would necessitate the addition of a thick ($\sim$30-40 g/cm^2) shield around the germanium detectors. If this were an active anticoincidence shield made of BGO or CsI, the sensitivity to gamma-ray lines could be improved by up to a factor of two (orbit average) by reducing the background and by allowing Compton-scattered photons to be rejected. However, such a shield would be very heavy and expensive, and lead to a much heavier spacecraft. The absence of a shield also allows cosmic X-ray and gamma-ray sources to be detected from the side.

Launch Date: A prediction of solar activity is shown in Fig. 1-8 based on the X-ray flare rate observed during the previous two cycles and an assumed period of 10.5 years, the mean value for the last seven cycles. Even with the uncertainty of ±1 year in the predictions, it is clear that a HESSI launch in late 1999 or 2000, with operations lasting for three years, would cover the peak period of activity. Thus, the first of the two MIDEX missions being selected through this AO, with a launch in December 1999, would be ideal for HESSI, with the second mission being still acceptable.

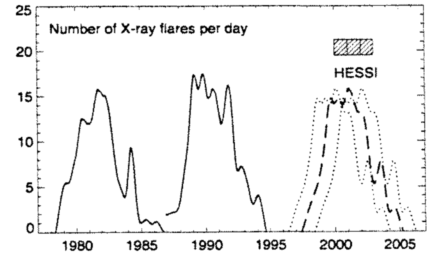


Figure 1-8. Prediction of the flare rate for the next solar cycle (dashed line) based on the observed rates (solid lines) and a period of 10.5 years. An uncertainty of 1 year is indicated (dotted lines). The proposed three years of HESSI operations starting with launch in December 1999 is seen to cover the period of highest expected activity.

Baseline Mission and Expected Results: The baseline HESSI mission is summarized in the foldout sheet. The total effective photopeak area (foldout) and response to a large flare (Fig. 1-4) were obtained with detailed Monte Carlo calculations, using the GEANT code and taking into account the grids and all known materials in the cryostat and detector modules. The orbit-average background (Fig. 1-4) was similarly computed and is consistent with scaling from balloon-borne Ge detector measurements.

The total >20 keV count rates are shown in Fig. 1-7 for the front and rear Ge detector segments. The decrease in the Ge front and rear count rates at high photon fluxes are due to dead-time from the pulse pile-up rejection, which is used to eliminate resolution degradation. Broadband (~10 keV resolution for Ge front and ~3 keV for Si, see Section 2.2) imaging extends the Ge detector dynamic range to cover the largest flares. The largest hard X-ray burst that can be accommodated has a >20 keV hard X-ray flux of $\sim 10^5$ cm^{-2} s^{-1} keV^{-1}, or up to 100 times larger than the 27 April 1981 gamma-ray line flare. Thus, **HESSI is the first solar high energy instrument to have the dynamic range to both detect microflares and make quantitative measurements of the largest flares.**

With the predicted HESSI background, Fig. 1-7 shows that microflares will be detectable above a 20-keV photon flux of $\sim 1 \times 10^{-2}$ photons cm^{-2} s^{-1} keV^{-1}. Since a minimum of about a hundred source counts is needed to form a simple image, the location and spatial size of microflares could be determined for events about three times larger.

For events with $\sim 10^3$ counts s^{-1} above 20 keV, rapid spatial changes of the X-ray sources could be followed with simple images on time scales of 0.1 s. Full-Sun spectroscopic studies with no imaging (e.g., Lin and Johns 1993) could also be carried out to obtain N(E,t). Detailed imaging spectroscopy providing N(E,**r**,t) could be done with images in each of ten energy intervals with ~2-s time resolution for events with 10^4 counts s^{-1} above 20 keV; crude imaging information could be obtained in tens of milliseconds.

Assuming that every flare accelerates ions with fluxes proportional to the hard X-ray flux, the calculated 3-σ detection thresholds for the 2.223-MeV neutron-capture deuterium line, the 0.511-MeV positron-annihilation line, and prompt nuclear de-excitation lines are indicated in Table 1-1. Assuming HESSI observes the Sun ~60% of the time, Fig. 1-7 shows that the 2.223-MeV line should be detected, on average, once every 2 to 3 days, the 0.511-MeV line every 8 days, and prompt de-excitation lines every 10 days.

The source location and size could be obtained once a week for the 2.223-MeV line, and once every month for the 0.511-MeV line and the nuclear continuum from energetic heavy ions. Detailed spectroscopy revealing many gamma-ray lines will be possible for these flares, allowing the abundances of many elements to be determined. Every several months, a flare can be expected that is big enough to allow the source of emission of narrow prompt de-excitation lines from >10-MeV protons to be located. Thus, **tens of thousands of microflares, thousands of hard X-ray flares, and hundreds of gamma-ray line flares will be detected in the HESSI 3-year operating lifetime.**

Cosmic transient and steady sources can be detected by HESSI's open rear Ge segments between angles of ~60° and ~120° to the spin axis. The effective area is ~200 cm^2 up to ~200 keV. Earth-limb occultation and occultations of one Ge detector by another as the spacecraft rotates, can be used to produce sky maps with resolution of about 1° as demonstrated by BATSE (Zhang et al. 1993). Cosmic sources seen through the 1° × 30° field of view of the lower collimators will be modulated with the spacecraft rotation, giving localizations on the order of a degree or better.

Data Analysis: With such a wealth of data, we believe that the scientific potential of this mission can best be exploited by broadening the user base to include as large a segment of the solar community as possible. Therefore, we adopt a policy in which **all interested scientists will have equal, open, and prompt access to the data.** The PI team will not have any proprietary data rights.

To ensure the participation of US scientists, both data analysts and theorists, outside of the HESSI PI team, **we have set aside $1 million from the HESSI MO&DA funds for a Guest Investigator (GI) program.** GIs would be selected by the NASA solar physics discipline chief through the normal peer-review process.

To accommodate the large number of scientists expected to be interested in HESSI data, **the observational output and all software necessary for its analysis will be made easily**

and promptly accessible (see Section 3). In addition, analysts will have access to the complementary observations from other spacecraft and from ground-based observatories.

Context Observations: Important context observations from space are provided by NOAA's GOES and NASA's ACE missions. **NOAA's interest in HESSI is to improve the understanding and prediction of SEP events.** In both cases, we have added cognizant Co-Is and made arrangements for free data exchange on a no-exchange-of-funds basis.

Critical U.S. ground-based observations (Table 1-2) have been integrated into the mission to ensure the ability to interpret HESSI's high energy observations in physical terms. The HESSI team also includes key non-U.S. Co-Is to help provide 24-hour coverage. Additional worldwide ground coverage will be added later, on a no-exchange-of-funds basis.

Table 1-2. HESSI US Ground-based Program

Filter-based vector magnetograms	MSFC, Hawaii, BBSO
Stokes-polarimeter vector magnetograms	NSO/SP,Hawaii
Microwave imaging spectroscopy	OVRO
Optical imaging spectroscopy	Hawaii, NSO/SP
Millimeter-wave imaging	BIMA
Full-disk images, magnetograms	NSO/SP, NSO/KP, BBSO
High-resolution imaging	BBSO
Multiband imaging	NSO/SP
Microwave and optical patrols	SOON, RSTN

1.3 Minimum Science Mission

The minimum science mission would reduce the number of RMCs, germanium and Si(Li) detectors from twelve to seven and eliminate the finest grid (#1) and grids #5, 7, 9, and 11. Remaining grids #2 and #3 are made only 25 μm thick, and grids #4, 6, and 8 only 1 mm thick. Grids #10 and #12 remain 25 mm thick (see foldout).

The primary impacts on the development of HESSI are that the tolerances on grid twist maintenance and aspect determination are relaxed by a very significant factor, ~1.5, and that the weight, power, and cooling requirements are reduced by a similar factor. The fabrication costs are also reduced. The requirements on the spacecraft are relaxed because of the reduced weight and power.

The primary science impact is a significant, but acceptable, reduction in the overall imaging capabilities, with a small loss of sensitivity in gamma-ray line spectroscopy. The finest spatial resolution for imaging spectroscopy would then be 3 instead of 2 arcsec at energies $\lesssim$ 35 keV, 5 arcsec up to $\lesssim$ 200 keV, and 60 arcsec above 200 keV. The imaging quality is reduced since the number of uv points goes down by ~40%, and the effective area and number of RMCs for imaging at gamma-ray energies drops by a factor of ~2. The total effective area is reduced by ~40% at energies below ~35 keV, by ~30% between ~35 and 200 keV, but only ~20% at gamma-ray line energies.

The critical defining elements of HESSI, namely (1) hard and soft X-ray imaging spectroscopy with a few arcsec angular resolution and ~1 keV energy resolution, (2) the high resolution ~1 keV gamma-ray line spectroscopy, and (3) gamma-ray line and continuum imaging, would all be preserved.

We will examine this Minimum Science Mission during the definition phase in terms of the potential cost, schedule, and spacecraft implications, and possible decision points.

2.0 TECHNICAL APPROACH

2.1 Mission Operations Concepts and Requirements

The HESSI mission operations scenario is illustrated in Fig. 2-1 (left side) and the requirements are listed in Table 2-1. The low-altitude equatorial orbit requires only one ground station. **We propose to use a NASA-supplied Transportable Orbital Tracking Station (TOTS) at Guam.** This station will see HESSI every orbit for approximately 8 minutes and is capable of meeting all of the mission tracking, telemetry, and command requirements.

As a result of the store-and-dump method of data collection and the closed-loop attitude control system, no commands need be sent to the spacecraft for days or even weeks at a time, other than those required to activate the transmitter and dump data during each pass. The NASA-furnished MOC at GSFC described in Appendix C of the AO accomplishes these minimal day-to-day tasks, while an automated Science Operations Center will be located at UCB. This MOC/SOC arrangement is identical to that for the FAST SMEX. During the definition phase, alternate ground stations and communications lines (possibly provided by CNES, ESA, or Brazil), and an integrated MOC/SOC at UCB, will be studied as cost saving items.

2.2. Instrument

The instrument consists of the imager assembly, the spectrometer, and the electronics packaged in the IDPU. Fig. 2-2 (upper) shows the instrument block diagram.

2.2.1. Imaging System

Fig. 1-6 defines the parameters of a HESSI bi-grid rotating modulation collimator (RMC). For such collimators, we must consider the effects on imaging performance of possible misalignments of one grid relative to the other. Changing the separation (L) between grids has little effect. Neither does a displacement in the grid plane parallel to the slits. A relative displacement perpendicular to the slits affects the phase but not the amplitude of the modulation. Since any such displacement will be accurately monitored by the solar aspect system described below, such phase changes can be fully compensated for in the image reconstruction process. The critical alignment requirement is associated with the rotation or *twist* of one grid with respect to the other about the line of sight to the source. A relative twist of p/D reduces the modulated amplitude to zero. Thus, the grid pairs must be precisely aligned in twist, and this alignment must be maintained throughout the mission. For example, a one-arcmin alignment is needed for the finest grids, which provide an angular resolution - $p/(2L)$ - of 2 arcsec. **Thus, HESSI can achieve arcsec-quality images with an instrument having only arcmin alignment requirements.**

Matched grid pairs are mounted on stiff, planar grid trays that are attached to opposite ends of the metering structure. A high-resolution, high-bandwidth Solar Aspect System (SAS) monitors the imager pointing direction by continuous angular measurements of the sharply defined solar limbs. A side-looking Roll Angle System (RAS) provides the roll angle information by scanning the brightest stars. A three-point center mount to the spacecraft supports the imaging system, above, and completely separate from, the spectrometer, which is mounted behind the rear grids (see foldout). Detectors are independently mounted in the cryostat behind each rear grid to record the

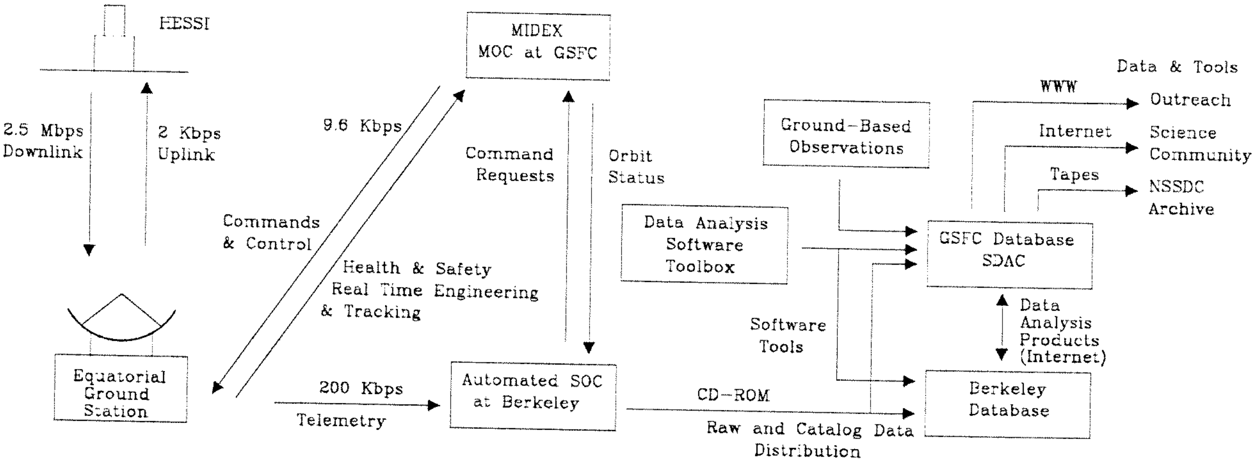


Figure 2-1. Mission operations and data analysis concept

Table 2-1. Mission Operations Requirements

Spacecraft pointing:	Spin axis within 0.2° of Sun center, spin rate ≥15 rpm
Attitude determination:	By FAST-type spinning Sun sensor following launch vehicle separation. By intermediate Sun sensor when spin axis >50 arcmin from Sun center. By instrument Solar Aspect System when <50 arcmin from Sun center.
Orbit determination:	Doppler ranging to <1 km in position and <10 km/s in velocity.
Communications (see Fig. 2-1):	Mean rate: 50 kbps Maximum rate: Dump 12 Gbits from instrument memory in 48 hours.
Mission lifetime:	Two years, three years preferred, during next solar maximum, 1999-2003.
Launch/operational window:	Launch in year 2000 to operate during next solar maximum.
Orbit:	Altitude: 600 ±10 km (MedLite capability) to ensure ≥3-year lifetime. Inclination: <1° to avoid the South Atlantic Anomaly

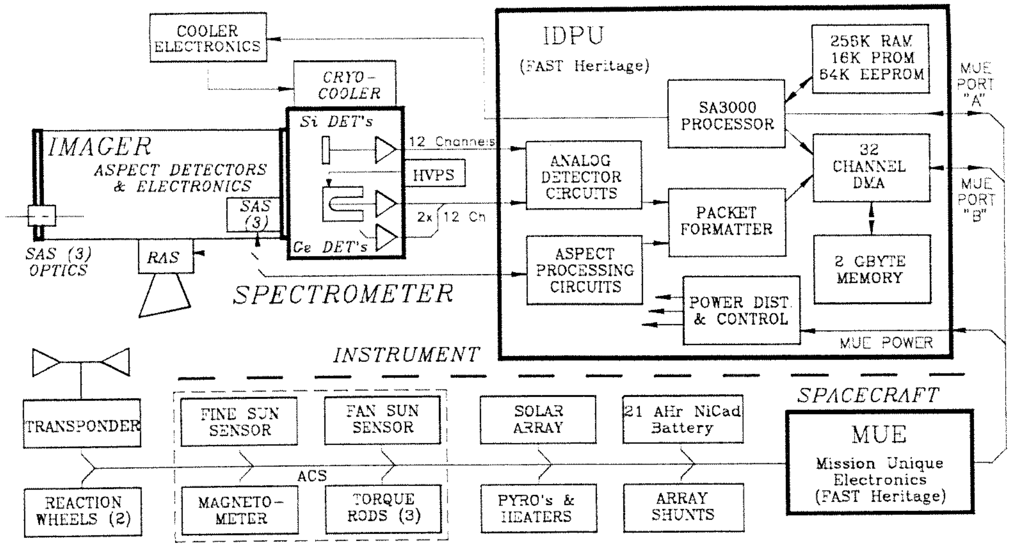


Figure 2-2. Instrument and electronics block diagram showing the different elements of the instrument and the connections to the IDPU, the MUE, and the spacecraft.

transmitted flux vs. time.

Grids. HESSI requires matched pairs of X-ray and gamma-ray absorbing grids with pitches ranging from 34 µm to 2 mm and corresponding thicknesses between 1.1 mm and 2.5 cm. Standard wire electric discharge machining (WEDM) was used successfully to produce monolithic tungsten grids (corresponding to HESSI grids #8 and #10) that flew on the GSFC High Energy Imaging Device (HEIDI) balloon payload. For the finest grids, the following requirements place tight constraints on the grid fabrication technique: the over 50:1 aspect ratio of grid thickness to slit width, the uniformity of the grid pattern across the full area, and the exact match needed with the second grid in a pair.

Recognizing the difficulties involved in making such fine grids, NASA has invested $2.7 million over the last five years to develop four different fabrication techniques. Two use different foil-stacking techniques, a third uses the LIGA process, and a fourth uses etching to produce thinner, high-resolution grids. **All four methods have produced test grids that meet HESSI requirements for slit width, uniformity, and ability to achieve the desired angular resolution.** Photographs of these grids are shown on the foldout.

The first method, developed by Co-I H. F. van Beek at Delft University in the Netherlands, involves stacking individual tungsten blades with stainless-steel spacers in a precisely machined reference frame. A full-sized grid with a pitch of 100 µm has been built and tested, including GEVS-level vibrations, and found to meet the needs for grid #4. A second test grid was also produced with 20-µm wide slits, sufficient to provide the 2-arcsec resolution of grid #1, but with a pitch of 70 µm. This coarser pitch would result in an acceptable factor-of-four loss in sensitivity.

A second stacking technique, developed by Artep Inc. in Columbia, MD, involves precision positioning of tungsten foils that are separated and bonded together with epoxy spacers. A full-sized pair of grids with 150-µm pitch (corresponding to grid #5) has been produced that satisfies the dimensional requirements according to on-going measurements and tests at GSFC.

The LIGA process is being developed at JPL and LBL by Associated Scientist M. Hecht. It is a multistep process that begins with a precise optical mask of the size and slit pattern needed for the final grid. A 25-µm thick gold mask with the identical pattern is produced by etching. It is placed in front of a PMMA acrylic sheet of the required thickness. After exposure to a synchrotron X-ray beam, the depolymerized acrylic material is dissolved away and the resulting mold is backfilled with gold by electroplating to produce a grid with the required thickness and the same pitch as the original optical mask. Small test grids with the finest 34-µm pitch have been produced to verify the process, and full-sized grids are now being fabricated with a summer completion date.

The intermediate etched 25-µm gold masks from the LIGA process are available now and could serve as the finest grids to provide 2-arcsec imaging for energies up to 35 keV. A matched pair of such grids has been fabricated, and measurements at GSFC show that, apart from the thickness, they fully satisfy the specifications for grid #1 and could be used for the Minimum Science Mission.

In summary, **we have four tested methods for making the finer HESSI grids, and the WEDM technique for the coarser grids.** For costing and scheduling purposes, we have obtained three independent estimates for each of the needed grid pairs (with spares) and used the highest value in each case. Final selections will be made in the definition phase.

The **Metering Structure** supports the front and rear collimating grids and the SAS and RAS. The single tightest science requirement is to maintain the one-arcmin twist alignment for the finest grids. The mechanical packaging strategy is to provide kinematic mountings using flexure elements to mount the telescope to the vehicle, the grid trays to the telescope, and the finest grids to the grid trays. Alignment of the finer grids will be adjusted and fixed by elastic deflection of the flexures. The thermal design uses blankets, coatings, and heaters to achieve a tray-to-tray difference of <3°C, and <0.3°C orbital variation using <9 watts for heaters. Less than 10 layers of multi-layer insulation (MLI) are used to satisfy the thermal requirements while retaining the ability to image down to 2 keV. This design has been evaluated by GSFC using TRASYS, SINDA, and NASTRAN models. Fabrication and test of the Telescope Demonstration Unit (TDU) at GSFC have demonstrated that traditional aluminum construction is adequate.

Aspect System. The aspect determination system consists of the Solar Aspect System (SAS) and the Roll Angle System (RAS). The SAS is conceptually identical to the system successfully flown on HEIDI. It gives the direction to the Sun center to an accuracy of 0.5 arcsec (RMS) every 10 ms, over a field of radius 12 arcmin. It also provides error signals to the spacecraft ACS, monitors twist between the grid trays, and produces white-light images of the Sun.

Three identical lens-filter assemblies mounted on the forward grid tray image the Sun onto three linear photodiode array assemblies mounted on the aft tray. Exposures of 2 to 8 ms are made every 10 ms by each of the 3 arrays, and are digitized and transferred to the IDPU. The IDPU selects four samples near each limb crossing on each sensor for inclusion in the raw T/M stream and these are used on the ground to generate the fine aspect solution.

The RAS is a star scanner which is based on the same sensor-family and electronics used for the SAS. The photodiode array is mounted behind a standard 50 mm f/1.0 lens with a ±15° field of view set orthogonal to the spin axis. The output of automatically selected pixels is recorded every 2 ms. The detection signal-to-noise ratio is 15:1 for +2 magnitude stars, at least one of which will pass through the field of view in each rotation. Multiple measurements of one star averaged over one minute will allow the roll angle to be determined with an rms accuracy of 0.9 arcmin. Typically, over 7 stars are detected per rotation providing a substantial performance margin.

Sunspot Imaging

The SAS is used to obtain white-light full-Sun images several times per orbit by reading out all the pixels in a given photodiode array for one half rotation. These images can be used to co-locate the X-ray images with respect to sunspots, thus allowing accurate coalignment with ground-based optical images.

We note that white-light imaging of solar active regions has scientific significance. The HESSI aspect system will be capable of continuous white-light imaging to support these basic and complementary kinds of observations.

Coalignment, Integration and Test

An optical Grid Characterization Facility (GCF) has been assembled at GSFC and used to characterize the HEIDI grids and all the test grids produced to date using the different fabrication techniques. Slit locations are routinely mapped at the micron level with respect to fiducials on the rims of the grids. Detailed maps of the grid slit edges are generated to evaluate compliance with the dimensional specifications and to enhance the quality of the reconstructed images. In addition to optical methods, X-ray characterization and accurate density measurements of the grids will be used to gauge uniformity of the X-ray absorption.

The TDU efforts at GSFC have identified a suitable assembly and alignment sequence to meet HESSI requirements. Imaging system alignment will follow three steps: (1) grid slit directions are characterized with the GCF with respect to fiducials mounted on the rims of the grids, (2) a Coordinate Measuring Machine is used to align grids and aspect system components to grid trays, and (3) the grid tray assemblies are aligned to the metering tube by an Electronic Coordinate Determination System. SAS and RAS evaluation and alignment will follow a similar path. The complete imager will be environmentally tested and qualified as a functioning system prior to integration. Observatory level testing will be focused on end-to-end alignment checks of the SAS and RAS, and functional testing.

The relative twist of front and rear grids is the most critical alignment requirement. Twist will be verified by independent electro-optical means based on the SMM/HXIS experience of Co-I F. van Beek, where ten grid planes were aligned to finer tolerances than required for HESSI. Optical laser calibrations, developed for the HEIDI program, will verify end-to-end performance, and will be used throughout the qualification sequence and during spacecraft I&T.

Critical alignment errors will also be monitored in flight by several methods. SAS performance is continuously monitored by redundant sub-arcsec determinations of the (constant) solar diameter. Tray-to-tray twist is directly monitored by the SAS. Relative grid displacements can be monitored by the relative phase of Fourier components, which should be consistent in alternate half rotations. Relative twist of each pair can be identified by noting the sensitivity of phase errors to off-axis sources. The centroid location of simple compact sources can be determined independently for each grid pair to identify errant pairs. Hard X-ray observation of the Crab pulsar provides absolute in-flight calibration of the alignment and a direct measurement of the point-response function.

Fourier-transform image-coalignment errors generally reduce sensitivity rather than distort images. If known, angular resolution and point-response corrections can be applied to improve images. This ability to compensate for moderate errors renders Fourier imaging a relatively "forgiving" process.

2.2.2. Spectrometer

The HESSI spectrometer is comprised of the germanium and silicon detector arrays, front-end electronics, cryostat, and cryocoolers.

Germanium (Ge) detectors have been flown in space previously on the HEAO-3, Mars Observer, and Wind spacecraft. Segmented Ge detectors of the type appropriate for HESSI were developed by UCB (Luke 1988) and have been flown successfully on HEXAGONE, HIREGS, and other balloon payloads since 1988.

The largest readily available n-type crystals, 7.1 cm diameter by 8.5 cm long, are utilized. Three inner electrodes in the central hole divide each Ge detector into two detector segments and a guard ring segment (see foldout). The top contact collects charge from the front ~1.5-cm-thick planar segment while the middle contact collects charge from the rear ~6.5-cm-long coaxial segment.

The bottom guard-ring contact drains off the surface leakage currents of the flat intrinsic Ge rear surface. We (UCB) have recently developed guard-ring coaxial detectors, using our proven segmentation technique to provide protection against surface contamination, which increases leakage current. Tests showed that surface leakage currents of well over one nanoamp (~ten times higher than usable for non-guard-ring detectors) resulted in no degradation in the detector's response. **This increased resistance to contamination allows the use of a single vacuum enclosure for all 12 detectors** instead of the more complex and expensive encapsulation of individual detectors.

The segmented detector acts as a 1.5-cm-thick planar detector in front of a 6.5-cm-thick coaxial detector, but without the intervening dead layer and spatial separation, which would significantly increase the background, and without the mechanical mounting complexities of two separate detectors.

The curved outer surface and top surfaces are implanted with a thin boron layer, allowing a transparent (~0.3-μm) surface for X-rays.

The mechanical design of the Ge detectors and their mounting is identical to the HEXAGONE and HIREGS detector systems, which have survived numerous balloon flights and recoveries. The use of teflon and gold foil to accommodate surface irregularities between detector and mounting hardware provides a rugged mounting system which has been vibration-tested and is fully capable of surviving a Med-Lite launch.

The **Silicon (Si(Li)) detectors** are a standard guard-ring configuration of ~1 cm^2 area and ~3 mm thick, cooled to 150-200 K. The sensitive surfaces are passivated, making them highly insensitive to the ambient environment. The grounded guard-ring is used not only for shunting large surface currents to ground but also for detector retention and cooling. The detector mount is fabricated from low-Z materials, with a beryllium foil entrance window.

Each Ge detector is biased at 3-5 kV by an independently-programmable high voltage converter, while the Si(Li) detectors are biased at <300V by independently programmable regulators.

Each detector channel (twelve Si(Li) and twenty-four Ge) has a low-noise Field-Effect Transistor (FET) integrated into its housing. The FET is placed as close to the detector as possible to provide a very high level of noise immunity, as seen on HEXAGONE and HIREGS. The FETs operate optimally between 120-200 K, about the same temperature at which the Si(Li) detectors operate. Each FET is thermally strapped to the cryostat thermal shield, and thermally isolated from its detector housing. The rest of the preamplifier circuitry is housed outside of the vacuum enclosure.

Calibration and test. The Si(Li) and Ge detectors in the spectrometer will be calibrated by utilizing a variety of radioactive sources to span the range of energies from ~2 keV to ~2.6 MeV. Higher energies, up to 15 MeV, will be obtained using neutron-gamma sources. Measurements will be made over a wide range of angles as well to calibrate a detailed computer model of the spectrometer, as was done for the HIREGS and HEXAGONE balloon spectrometers. This model includes all the materials around the detectors, and uses the GEANT code to provide a detailed instrument response to the data analysis.

After the imager and spectrometer have been independently integrated into the spacecraft, radioactive sources are again used to measure total transmission through the grid pairs, and confirm the detector calibrations. In flight, Ge background lines provide excellent calibrations, and an accurate on-board pulser will be used for periodic calibration checks.

The **Cryostat** provides the thermal and vacuum conditions required by the HESSI detectors. A Ge and Si(Li) detector is behind each RMC with a Be and Al window in front, chosen to obtain the required soft X-ray transmission down to 2 keV. The Ge detectors are mounted in the cryostat on an aluminum coldplate, in a configuration very similar to the HIREGS detectors (see foldout). The Si(Li) detectors are mounted on the cryostat thermal shield in front of the Ge detectors. In between, a shield over the front of the coldplate shields the Ge detectors from IR radiation, and isolates them from contamination in other parts of the cryostat. The thermal shield is blanketed with MLI, and provides a stage at which the power of all the detector FETs may be efficiently dissipated. Fiberglass struts support the thermal shield and coldplate inside the cryostat vacuum shell. The cryostat is evacuated on the ground, and is sealed for the duration of the mission.

Cryocooler. The coldplate and thermal shield are cooled on-orbit by a mechanical cryocooler and during ground operations by a simple liquid-nitrogen cooling loop. The coldplate, thermally isolated from the vacuum shell and with virtually no power dissipation, is maintained below 85 K, either by a small single-stage cryocooler, or by the second stage of a two-stage cryocooler. Either a second single-stage cryocooler or the first stage of a two-stage machine can cool the thermal shield, which is allowed to run at a temperature of 150-200 K. Detailed thermal modelling indicates that 0.7 watts cooling at 80 K and 1.5 watts at 150 K are conservatively required. Three different long-life cryocoolers, all with strong technical heritage, have been extensively evaluated for this application (foldout figure), including detailed thermal modeling and interface evaluation. A final cryocooler selection will be made early in the HESSI Phase-1 study.

The cryostat and detectors follow the highly successful design developed to minimize microphonic sensitivity on the HIREGS balloon experiment. **In two tests at UCB and one at JPL using a Ge detector in the standard UCB mount with different space flight cryocoolers, cryocooler vibration produced no measurable microphonic response in the detector signal.**

The cryocoolers are designed with moving components that are suspended on flexures and are precisely aligned to prevent any touching contact through the duration of the mission. Multi-year lifetime has been demonstrated in flight on the European ERS-1 and NASA's UARS missions, and in ground testing at ESA.

2.2.3 Instrument Electronics

As on FAST, to the extent possible, all digital and analog electronics is packaged in a single Instrument Data Processing Unit (IDPU) box. This approach minimizes the number of interfaces between subsystems, the weight in packaging and harness, the power in driver circuits, and the development costs.

To achieve the best energy resolution over the widest range of count rates, transistor-reset pre-amplifiers, developed at UCB under NASA SR&T funding and now used throughout the nuclear instrumentation industry, are used for both the germanium and silicon detectors (see Fig. 2-2). High level signals are passed from the cryostat to the IDPU, which contains the remainder of the detector analog electronics.

The Ge signals go to dual amplifiers: a spectroscopy amplifier with 4-µs peaking time trapezoidal shaping (required to correct for ballistic deficit in these very large detectors) driving an 8192-channel ADC for high resolution spectral measurements from ~10 keV to 2.7 MeV with ~0.33 keV/channel up to 50,000 c/s, and a triangular delay-line shaping amplifier with 0.5-µs duration driving a four-channel stacked discriminator to achieve count rates up to 500,000 c/s. An additional low gain amplifier in the rear segment channels extends the range of spectral analysis up to 20 MeV with ~2.5 keV/channel using the same ADC. The silicon channels use a similar circuit with an 8-bit flash ADC (~0.1 keV/channel) for the high resolution chain.

The digital design is based on FAST. The IDPU contains all the digital circuitry necessary to control the instrument and collect and format the science data and record it in a 16-Gbit solid-state recorder for later transmission to the ground. Since the interface to the spacecraft MUE is identical to that of FAST, the complete FAST I&T system, including both hardware and software, can be reused with substantial cost savings and reduced program risk.

2.3 Investigation Requirements on the Spacecraft

HESSI requires a very simple spin-stabilized spacecraft with the spin axis pointed at the Sun. Nutation, precession, or unbalance must be removed from the system to the extent required to keep the instrument axis parallel to the spin axis and within 0.2° of Sun-center. Analysis shows that the large rotational momentum of the spacecraft ensures that the motion will be sufficiently smooth to be fully characterized by pitch and yaw measurements from the instrument SAS every 10 ms and roll angle measurements made once or twice per rotation by the RAS. The requirements and how we plan to accommodate them are listed in Table 2-3.

The imager and the spectrometer are separately mounted to the spacecraft, one behind the other. The RAS and the IDPU complete the instrument elements.

Spacecraft resources beyond those described in Appendix B of the AO include an intermediate Sun sensor, a nutation damper, and modifications to the FAST MUE to accommodate the reaction wheels.

2.4 Spacecraft Description

The HESSI spacecraft concept is based extensively on the FAST and SWAS spacecraft described in Appendix B of the AO (see Table 2-4). HESSI weighs 324 kg, is passively spin-stabilized at 15 rpm, and points continuously at the Sun. A Med-Lite Launch Vehicle is used to place the spacecraft into a 600-km altitude, 0° inclination orbit, for at least 3 years lifetime at solar maximum before re-entry.

The electrical system concept is based on the FAST SMEX architecture, hardware, and software. The main component, the Mission Unique Electronics (MUE) box, contains the C&DH system, power and ACS electronics, and interfaces to the instrument-provided IDPU. Except for some minor modifications which have been costed against the instrument, the MUE can be used as is.

The Direct Energy Transfer power system consists of three 2-m^2 deployable silicon solar arrays which produce a total of 240 watts orbit average power, one 21-Ahr NiCd battery, power supply electronics located in the MUE, shunt boxes, and array-mounted shunt resistors. The array deployment mechanism design is a simple positive-locking system that rigidly positions the arrays perpendicular to the spacecraft-Sun line and is sufficiently robust to support the arrays in the deployed mode during ground-based dynamic balancing.

Temperatures of the spacecraft subsystems are maintained passively between -15° C and +50° C. The instrument is thermally isolated from the spacecraft.

The FAST-based ACS points the spacecraft to within 0.2° of the Sun center, spins it up to 15 rpm, and maintains that rate for the duration of the mission. The ACS includes a fan Sun sensor, a two-axis intermediate Sun sensor, a magnetometer, three 130 amp m^2 magnetic torquer rods, and a passive nutation damper. Detailed analysis shows that the magnetic torques are adequate, even in equatorial orbit. The instrument's SAS provides the pitch and yaw error signals necessary for maintaining the 0.2° Sun-pointing accuracy at all times during science operations. The FAST fan Sun sensor is substi-

Table 2-3. Investigation Requirements on the Spacecraft

Requirement	Accommodation
Spin rate of ≥15 rpm.	S/C spun up to ≥15 rpm with magnetic torquer bars.
Instrument axis must be within 0.2° of direction to Sun center for all solar observations.	Use pitch and yaw error signals from instrument Solar Aspect System (see Section 2.2.1.) in spacecraft ACS.
Spin axis must be within 0.2° of instrument axis for all solar observations.	Spacecraft is dynamically balanced before launch. Two reaction wheels are included for on-orbit balance.
Knowledge of roll angle to <1 arcmin at all times during solar observations.	Instrument Roll Angle System (Section 2.2.1.) senses star passage at least once per rotation.
Fore and aft grids of a pair must be aligned to <1 arcmin in twist about instrument axis for duration of mission.	Telescope is kinematically mounted to spacecraft. Grids are kinematically mounted to trays. Alignment verified prior to launch.
Front and rear grids must be at the same temperature to within 3° C.	Thermal blankets over telescope plus 9 watts of thermostatically-controlled heater power.
>1% transmission of solar X-rays through material above detectors at all energies above 2 keV.	Thermal blankets limited to total of 10 layers of MLI above and below grid trays.
Clear optical paths for Solar Aspect System.	Apertures in thermal blankets above three SAS lenses.
Minimum material around sides of detectors to provide largest possible clear FOV for cosmic source detection.	Mount spacecraft components on upper shelf above spectrometer level.

tuted for the SWAS digital Sun sensor offered in the AO since it is better suited to a spinning spacecraft. Since the costs are comparable, it is assumed that the instrument won't be charged for this change.

Both instrument and spacecraft have been configured to operate autonomously for weeks at a time. Following initial acquisition, even if the ACS should fail "off," the spacecraft spin axis will remain fixed in inertial space.

The primary structure is traditional aluminum construction based on the flight-proven design concept employed by the 6019 Delta launch vehicle payload attach fitting. The ratio of the 43 kg structure mass to the 324 kg total lift-off mass is 13%. We believe this is reasonable since the structure is simple and GSFC has designed and built Al structures in the 10-15% range. The open structural design permits ample thermal radiator area for heat rejection and enables easy access to subsystems. All spacecraft subsystems are attached to the middle deck allowing the spectrometer to have an open field of view radially. The spectrometer will be installed into the bottom of the spacecraft, and the imager assembly, which is structurally independent of the spectrometer, will be installed from above.

Spacecraft dynamic balance, which directly affects the 0.2° instrument pointing accuracy, is the single most critical spacecraft requirement. Recent experience with the Wind spacecraft shows that spinning spacecraft can be balanced on the ground to within 0.1° and that this precision can be maintained through launch and into orbit. The relative cost and assurance of this approach vs. incorporating an on-orbit dynamic balance system will be studied during the definition phase. For proposal costing, an on-orbit dynamic balance system using two of the reaction wheels described in the AO has been baselined.

RF communications with a TOTS ground station located near the equator (Guam for example) is accomplished with the 5-watt transponder and the two fixed S-band omnidirectional antennas described in the AO. The command link rate is 2 Kbps and the downlink rate is 2.5 Mbps. The downlink margin exceeds 3 db. While the costs of transporting and operating the TOTS at Guam are included in this proposal, less expensive CNES, ESA, or Brazilian alternatives are being explored.

The Pegasus XL launch vehicle has been studied as a low cost alternative to the Med-Lite launch vehicle. These studies show that, except for the solar array and battery and some minor modifications to secondary structure, this exact same spacecraft/instrument combination is compatible with the Pegasus XL launch vehicle.

3.0 DATA REDUCTION AND ANALYSIS PLAN

HESSI differs from many imagers in that, instead of transmitting a preselected subset of images, **the telemetry includes all of the information about each detected photon**. Thus, tradeoffs among time resolution, spectral range and resolution, spatial resolution, image quality, etc., can be made by the data analyst on the

Table 2-4. HESSI Subsystem Weight, Power, and Heritage Summary

Component	Weight-kg	Power-W	Heritage
Instrument	135.5	139.7	
Spacecraft Subsystems			
C&DH/Electrical: MUE, harness	38.5	14.8	SMEX FAST
Communications: Transponder, antennas	6.4	6.5	SMEX SWAS, TRACE, WIRE
Power: 21 Ahr NICd battery, Shunt boxes	77.3	0.0	SMEX SWAS
Direct Energy Transfer System			SMEX FAST (MUE)
Si solar arrays 6 sq m			Offered in the AO
Attitude Control: Torque rods (3)	10.7	3.2	SMEX SWAS
magnetometer, fan Sun sensor			SMEX FAST
intermediate Sun sensor, nutatuon damper			SMEX FAST
On orbit balance: Reaction Wheels (2)	8.6	16.0	SMEX SWAS
Mechanical: Structure, fasteners, balance weights	43.3	0.0	Conventional aluminum
Thermal Control: Blankets, heaters, radiators	6.2	10.0	SMEX
Spacecraft Total	188.0	50.5	
HESSI Total	323.5	190.2	
Med-Lite Capability	430.0	240.0	
Mass and Power Margins	106.5	49.8	

ground. These decisions can be made on a case-by-case basis to match the unique characteristics of the event under study and the relevant scientific objective. To preserve this flexibility and to extract the maximum scientific return from the observations, we have adopted the following principles for the preparation of our data reduction and analysis plan:

1) The complete data output of the HESSI mission, including the ground-based observations, will be made available promptly (typically within 24 hours of real time) to the scientific community, without restriction.

2) A fully-documented analysis package, supported by a range of platforms, will be available to the scientific community, with the same tool box of software used by the PI team.

3) A promptly-generated catalog of summary data products will be distributed with the HESSI data base, to serve as a multi-parameter index to the data base, to provide an overview of the data, and to meet the needs of users not requiring custom analyses.

3.1 Data Flow and Distribution

The data flow will follow the FAST model that was designed to minimize interfaces and the production of extensive secondary data bases. Data will flow from the spacecraft to the SOC (Sect. 2.1 and Fig. 2-1). The SOC will reformat the raw telemetry files into a "primary data base," with no value added except for the addition of "catalog" information. This will include pointers to make the primary data base appear as a sequence of time-ordered, non-duplicated, and quality-flagged data; a summary of spacecraft/instrument status; detector rates above representative energy thresholds; and orbital averages of full-resolution spectra. The rate data is used to identify transient events also listed in the catalog. For solar events, sets of representative images and spatially-integrated spectra will be generated by robust algorithms for inclusion in the catalog. The primary data base and catalog for each spacecraft day will be backed up on CD-ROM and made available by network access using a CD-ROM jukebox. Duplicate CD-ROMs will be sent daily to GSFC.

At GSFC, the HESSI solar data distribution and analysis task will be conducted under the auspices of the Solar Data Analysis Center (SDAC). Several levels of interaction with the HESSI data will be possible. Guest accounts will enable visiting or on-line scientists to use SDAC computers for HESSI analyses, limited by the capacity of the available resources. Remote scientists will use either on-line access or, as found with Yohkoh, will prefer to use their own computer resources. Additionally, copies of the data will be maintained on high-density magnetic tape for deep archive and for monthly transmission to the NSSDC. In addition to HESSI data, the SDAC will also maintain a data base of relevant spacecraft and ground-based observations. Using the World Wide Web (WWW), any interested person will be able to view and download the catalog (quick-look) products.

3.2 Software Development

The overall HESSI ground software development task can be divided into three areas:

1) Software for prelaunch system-level testing and post-launch operations. Its purpose is primarily command generation, status display, and generation of the primary data base (excluding the catalog). This software will be developed at UCB based on the FAST experience.
2) Prelaunch software associated with subsystem testing and calibration, developed by the group responsible for the corresponding subsystem.
3) Post-launch analysis software will be coordinated at GSFC, where careful attention will be paid to optimizing user and data interfaces across different elements of the toolbox.

The primary data base contains the following principal elements: engineering/housekeeping; time-tagged photons; solar and roll aspect system data; and white-light imaging data from the solar aspect system. To generate the observational output of maps and spectra needed for scientific analyses, the analysis software toolbox will include the following capabilities:

- Utilities for the manipulation and editing of primary data base files;
- Utilities for the generation of light curves and flare lists for the catalog;
- Analysis software to convert SAS and RAS data to an aspect solution;
- Photon calibration software to associate each photon with its corresponding aspect solution and correction factors reflecting grid calibration, dead time, etc.
- Imaging algorithms to convert calibrated photon data to images.
- Spectral analysis algorithms to obtain calibrated photon energy spectra for selected time intervals throughout a flare, either spatially integrated or for selected pixels in the images.
- Conversion of the rotating one-dimensional scans from the solar aspect system into two-dimensional optical images.
- Software for the analysis of both steady and transient cosmic sources.
- Utilities to facilitate the display and comparison of HESSI data with complementary data sets, based on ground- and other space-based observations.

For the most "interesting" computational task, namely image formation from the list of photons, there are several options, all of which have been developed or demonstrated. Each technique has its advantages, with the optimum choice in any situation depending on such issues as photon statistics, computing time restrictions, and map parameters. These techniques include direct Fourier inversion, back projection, maximum entropy, pixon methods, and model fitting.

The analysis system will be structured so that the tools can be individually wielded or driven by a suite of standard scripts controlled by an intuitive graphic-user-interface which will allow concentration on the science issues rather than the instrumental details. In almost all cases, similar software has been developed for other missions and ground-based observatories, and the team can build upon extensive experience in developing such code.

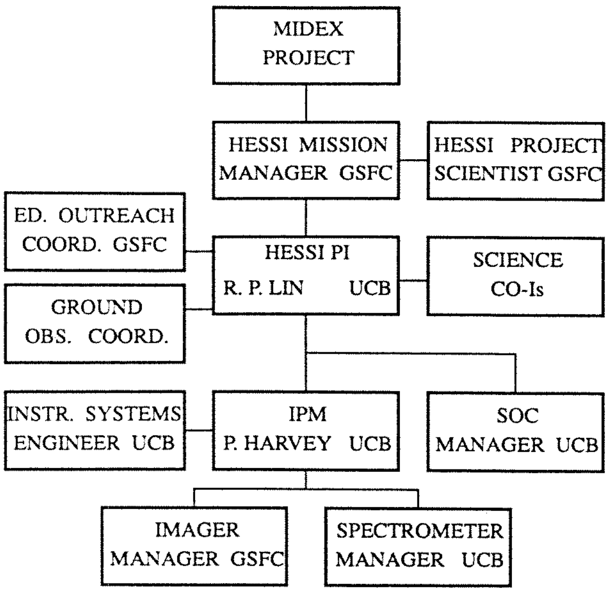
Substantial resources are allocated to the software development effort to ensure that the HESSI ground software will be fully debugged, documented, and tested prior to launch. Our language of choice is IDL. It is easily maintained, well-suited to rapid development, can operate seamlessly on many different systems, and is widely used throughout the solar and astrophysical communities (e.g., Yohkoh and CGRO), allowing us to take advantage of the significant investment in a large body of preexisting software.

4.0 MANAGEMENT PLAN

The **Management Organization** is shown in Fig. 4-1. The PI will be the point of contact between the instrument team and the MIDEX project. He will be supported by the Science Co-Investigators (listed in Table 4-1), by the Education Outreach Coordinator, and by the Ground Operations Coordinator. The Project Manager (designated as the Instrument Project Manager, IPM) will be at UCB and will report to the PI. He will be responsible for managing instrument development activities for both the spectrometer and imager sections. Managers for the imager effort (at GSFC) and the spectrometer and electronics efforts (at UCB) will report to the IPM.

Mr. Peter Harvey of UCB will be the IPM. He holds B.A. and M.A. degrees from UC and has over 20 years' experience on space projects, including being Project Manager and designer of the Electric Field Instruments on the Polar and Cluster missions, both to be launched this year; Project Manager for the UCB part of the CRRES Langmuir Probe; and software manager for FAST. In all of these projects he has been heavily involved in working with GSFC.

Figure 4-1 Organization Chart



Decision-making process. The PI will delegate to his IPM the responsibility and decision-making authority for the day-to-day operation of the project, with particular emphasis on cost and schedule control. The IPM will be responsible for monitoring all aspects of the project, including GSFC's instrument development work. The PI will also direct a Science Operations Manager at UCB who will prepare for and conduct the science operations effort.

The development team will use in-place electronic communications (used for preparation of this proposal) for daily coordination and data exchange. In addition, the PI will hold monthly project reviews with his key managers and co-investigators to ensure effective communication with regard to all aspects of the project. The IPM will review overall schedule status and technical issues in a weekly teleconference with the PI and the other managers. A common scheduling tool and a common WBS will be used for schedule and cost control. Product Assurance and Configuration Management (CM) will be based on those used with success on FAST, SOHO XDL, Wind 3D Plasma, Polar EFI, etc. An overall CM Plan will be developed for use at both institutions. The IPM will develop an integrated (UCB and GSFC) cost and performance report, and provide monthly submissions to the PI and the HESSI Mission Manager.

Teaming arrangements. The HESSI hardware development team consists of the UCB Space Sciences Laboratory and GSFC. This small, well-integrated team has been working on this mission concept for over three years,

Table 4-1. HESSI Roles and Expertise

Role	Institution/Responsible People	Relevant Expertise
Principal Investigator	UCB/Lin	PI: HIREGS, Wind 3DP, etc.
Instrument Project Manager	UCB/Harvey	IPM: Polar EFI, Cluster EFW, CRRES, etc.
Instrument Systems Engineer	UCB/Heetderks	IPM: FAST, Systems Eng.: EUVE, etc.
Project Scientist	GSFC/Dennis	PI: SMM/HXRBS, SAC-B/GXRE
Educational Outreach Coord.	GSFC/Crannell	NSF/REU Site Director
Ground-based Coordinator	UHi/Canfield	Chairman Max '91 Program, Yohkoh Co-I
Spectrometer		
Ge and Si Detectors	UCB/Madden, Cork, Luke; GSFC/Tueller, Desai	HIREGS Ge, GRIS Ge, SAC-B Si
Electronics, IDPU	UCB/Curtis, Heetderks, Primbsch	HIREGS & FAST IDPU
Cryostat, Coolers	GSFC/Boyle	COBE, SHOOT, Cryocoolers
Calibration & Modelling	UCB/Slassi; UMd/ Smith	HEXAGONE, HIREGS
Imager		
SAS Electronics & RAS	UCB/Curtis, Heetderks	
Grids, trays, telescope, SAS, T&E	GSFC/Bundas, Crannell, Davila, Hurford, Orwig; Delft/van Beek; JPL/Hecht; UMd/Schmahl	HEIDI, SERTS Rocket Program , SMM Radio
Operations & Data Analysis		
SOC Operations, Data Analysis	UCB/Curtis, Fisher, McTiernan	FAST SOC, Yohkoh & HIREGS data
Solar Data Analysis	GSFC/Holman, Hurford, Ramaty	Flare Modelling & Data Interpretation
	GSFC/Schwartz, Zarro	Solar Data Analysis Center
	UMd/Aschwanden, Schmahl	SMM, Yohkoh, Radio Observations
	U. Glasgow/Brown; UAH/Emslie;	Flare Modelling & Data Interpretation
	UHi/Hudson; NAOJ/Kosugi	Yohkoh
Astrophysics Data Analysis	JPL/Ling, Wheaton, UCB/Hurley, Slassi; UMd/Smith; UCSD/Pelling	HEAO-3 & BATSE, Ulysses, HEXAGONE
Complementary Observations	Zurich/Benz, Nobeyama/Enome, Meudon/Vilmer	Radio Observations
	SEL/Bornmann; GSFC/von Rosenvinge	Soft X-Rays, Energetic Particles

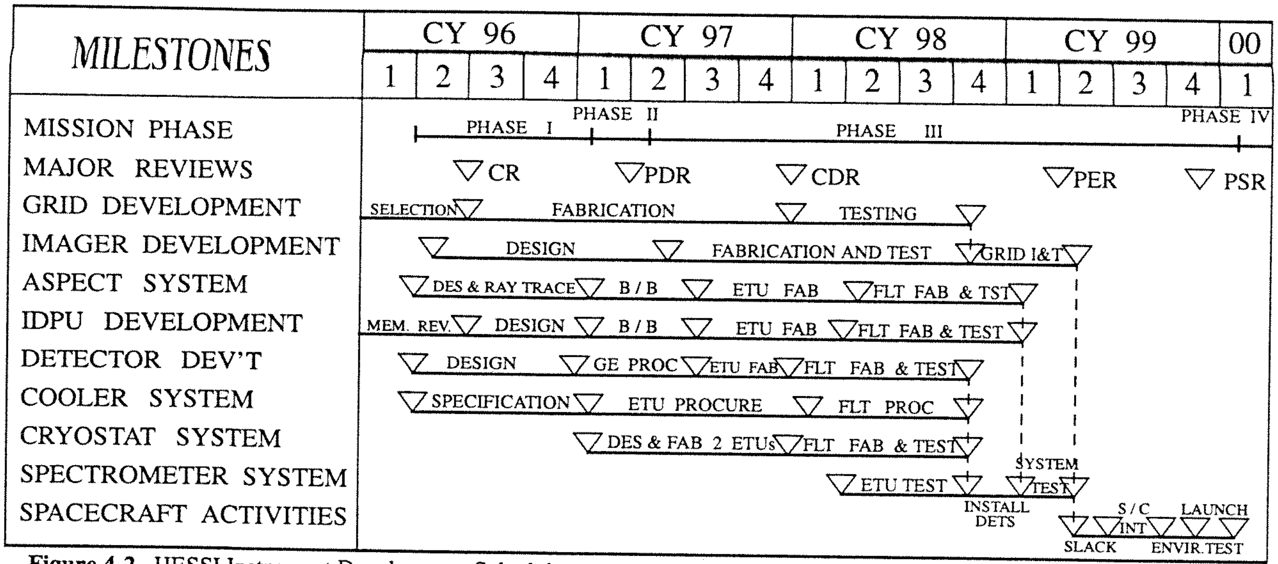


Figure 4-2. HESSI Instrument Development Schedule

and builds on a long history of UCB and GSFC successfully working together, the most recent example being the FAST Small Explorer program. UCB was designated as the PI institution, team leader, and developer of the spectrometer and electronics systems, based on the solar high-energy and space-flight experiment expertise of Professor Robert Lin, who led NASA's HESP and HESI (precursors to HESSI) Science Study Team, and was PI of the HIREGS long-duration balloon program, the Wind 3-D Plasma, and other space-flight experiments. The capabilities of the UCB Space Sciences Laboratory have been amply demonstrated on FAST, SOHO XDL, Polar EFI, Wind, EUVE, etc. GSFC was designated to develop the imager assembly and the cryostat, based on their HEIDI balloon program, their grid fabrication and characterization expertise, their cryogenics experience on numerous programs, and their recent work in developing prototype imaging systems to reduce risk.

The interface between the spectrometer and imager sections is entirely mechanical with easily-attainable mm tolerances on relative position. This permits a straightforward, manageable interface between the principal team partners.

The rest of the HESSI team was chosen for their relevant expertise. The roles and expertise of the individual Co-Is, Associated Scientists, and key engineers are shown in Table 4-1.

Schedule. Fig. 4-2 is the top-level schedule for the definition and development phases. There are two key interdependencies associated with the development of HESSI. GSFC will provide the thermal control system to UCB for integration into the spectrometer, while UCB will provide the SAS electronics and the RAS to GSFC for integration into the imager. Critical paths include the cooler procurement driving the spectrometer development and the grid procurement driving the imager. Since the imager and the spectrometer are mechanically independent of each other, there is virtually no interaction between these activities in the schedule. The long-lead-time cooler procurement will be fit into the program by overlapping the purchase of the ETU and flight coolers. Timely procurement of the grids will be accomplished by including funds in the cost plan for parallel development of two approaches for fabrication of the finest few grids, and by having available now a backup which meets the minimum requirements of the mission (see Section 2.2.1).

Delivery of the instrument to GSFC for I&T will occur 9 months prior to launch. The HESSI mission has only a single science instrument. The spacecraft-to-instrument (MUE-to-IDPU) interface is identical to that of FAST, which has already undergone integration and extensive testing. Thus, we believe that this allows ample schedule slack.

5.0 COST PLAN

Our team has studied this mission concept for over three years, and we thoroughly understand the requirements and design/cost implications. This effort has produced a simple design, with few, and well-understood, interfaces among the major elements. To further reduce mission risk, NASA has invested $2.7M to develop prototype grids. A full-scale, high-fidelity Telescope Demonstration Unit has been fabricated and successfully vibration-tested, and a Grid Characterization Facility has been set up at GSFC. In addition, UCB and GSFC have successfully developed HESSI-like instruments on the HIREGS and HEIDI balloon programs, respectively. GSFC has in-depth cryogenics expertise, and extensive experience with operating the Solar Data Analysis Center to analyze and archive SMM, Yohkoh, BATSE, and ground-based solar observations. UCB has developed a Science Operations Center for FAST, which is nearly identical to that required for HESSI.

Table 5-1 Mission Cost Breakdown with Reserves ($M-FY94)

Category	WBS	Phase I	Phase II	Phase III	Total	Phase IV
Instrument	1-5.0	4.8	5.5	21.5	31.8	
Spacecraft	8.1	0	0.1	0.7	0.8	
MSI&T	6.0	0	0	0.9	0.9	
Operations Prep.	7& 8.2	0	0.1	5.8	5.9	
MO&DA	9.0					15.0
Total		4.8	5.7	28.9	39.4	15.0

Added cost for 22-month Phase I	$320K	**Alternate Investigation Funding**	$200K/year

A grass-roots estimate was made, using the WBS contained in the AO. Table 5-1 shows costs by mission phase and major cost category, including reserves. The GSFC Resource Analysis Office (RAO) developed an independent estimate (Table 5-2), which substantially agrees with the grass roots estimate.

Table 5-2 Total Mission Cost Summary

Item	Grass Roots	RAO
Total Cost (No Reserve)	30.0	30.6
Spacecraft Add Ons	0.8	Not Costed
Development Reserve	6.2	6.1
Civil Servant Reserve	2.4	None
Total ($M-FY94)	39.4	36.7

Instrument. This category includes costs for management, science support, systems engineering, instrument systems, and instrument integration (WBS elements 1.0 - 5.0). These costs are grass-roots estimates based on (1) actual costs for flight subsystems (e.g., IDPU) taken from the FAST program; (2) the costs for subsystems (e.g., detectors, grids) from the HIREGS and HEIDI balloon programs with additions for upgrading to space-flight level; and (3) the most conservative estimates from component suppliers (e.g., fine grids, coolers).

The large increase in spending rate in Phase II is due to the procurement of long-lead items: the cooler, grids, and solid-state recorder memory components.

Spacecraft. Costs under WBS 8.1 are for spacecraft capabilities beyond those offered in the AO. They include changes to the FAST MUE to accommodate the two reaction wheels, and the addition of the nutation damper and intermediate Sun sensor. The cost estimates are based on SMEX program experience. Approximately $3M to support functions normally provided by the spacecraft, however, is included in the instrument cost. This is a result of the use of the FAST IDPU and MUE, which were designed to move many functions to the instrument side of the interface to reduce overall mission cost, and the use of the SAS to provide fine error signals to the ACS.

The **MSI&T** costs are based on the FAST program experience, and actual costs for the operation and use of GSFC facilities.

The **Operations Preparations** costs include preparations for science operations, data distribution, and ground-based observations. It is assumed that ground-system costs which would normally be paid by NASA for tracking from US tracking stations will not be charged against the instrument. Transportation, site preparation, installation, and per diem and travel costs for the first 30 days of operations of the TOTS at Guam are included in instrument costs.

The **MO&DA** costs are based on a grass-roots estimate, assuming a 35-month operations lifetime plus a fourth year of data analysis. They include the costs for science operations, data analysis and distribution, and $1.0M to fund a Guest Investigator program. We have included per diem and travel costs of operating TOTS and of disassembly and shipping back to Wallops.

Rationale for Budget Reserves. The development reserve was generated by allocating 10% for items which have been previously built for space flight; 20% for items with balloon program heritage; and 30% for newly developed items, e.g., the cooler and fine grids.

Costing of the GSFC portion assumes that 80 man-years of Civil Service manpower will be available to the program during Phases I through III. Additional reserves cover the cost of replacing 30% of the civil servants with contractors were included to protect against the possibility of a reduction in available civil service manpower. The total net reserve is ~28% of the instrument cost.

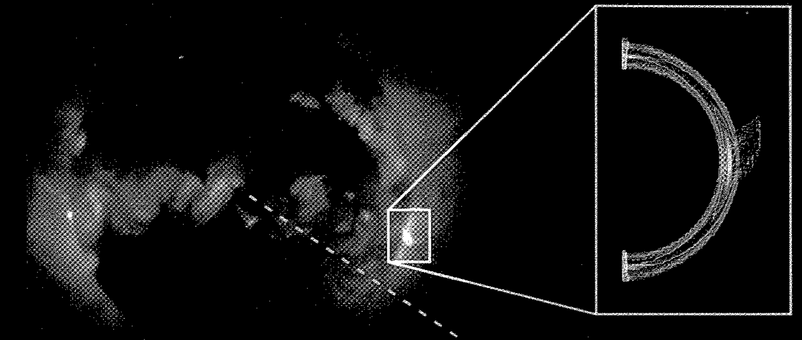
REFERENCES

Band, D.L. et al. 1994 *ApJ* **434**, 560.
Benka, S.G. and Holman, G.D. 1994 *ApJ*, **435**, 469.
Canfield, R.C. et al. 1993 *ApJ* **411**, 362.
Chupp, E.L. 1990 *Physica Scripta* **T18**, 15.
Crannell, C.J. 1976 et al. *ApJ* **210**, 52.
Crosby, N.B. et al. 1993 *Solar Phys.* **143**, 275.
Fenimore et al. 1982 *AIP Conf. Proc.*, **77**, 201.
Henoux, J.C. et al. 1990 *ApJ Suppl.* **73**, 303.
Holman, G. 1995 *ApJ,* in press.
Hua, X.M. and Lingenfelter, R.E. 1987 *Solar Phys.* **113**, 229.
Hua, X.M. et al. 1989 *ApJ* **341**, 516.
Johns, C.M. and Lin, R.P. 1992 *Solar Phys.* **137**, 121
Kanbach, G. et al. 1993 *A&A Suppl.* **97**, 349.
Kane, S.R. et al. 1992 *ApJ* **390**, 687.
Kundu, M.R. et al. 1995 *ApJ* 444, 922.
Kiplinger A.L. 1995 *ApJ,* in press.
Lin, R.P. et al. 1981 *ApJ Letters* **251**, L109.
Lin, R.P. et al. 1984 *ApJ* **283**, 421.
Lin, R.P. and Johns, C. 1993 *ApJ Letters* **417**, L53.
Lin, R.P. and Schwartz, R.E. 1987 *ApJ* **312**, 462.
Lingenfelter, R.E. and Hua, X.M. 1991 *ApJ* **381**, 426.
Luke, P.N. 1988 *Nucl. I&M in Phys. Res.* **A271**, 567
Masuda, S. et al. 1994 *Nature* **371**, 495.
Matsushita et al. 1992 *PASJ* **44**, L89-L93.
Metcalf, T. R. et al. 1993 *AIP Conf. Proc.* **294**, 59.
Misra, R. and Melia, F. 1993 *ApJ* **419**, L25.
Murphy, R.J., et al. 1991 *ApJ* **371**, 793.
Pelling, R.M. et al. 1987 *ApJ* **319**, 416.
Prince, T.A. et al. 1982 *ApJ* **255**, L81.
Prince, T.A. et al. 1988 *Solar Phys.* **118**, 269.
Ramaty, R. and Mandzhavidze, N. 1994 *Kofu Symp.*, NRO Report **360**, 275.
Ramaty, R. and Murphy, R.J. 1987 *Sp. Sci. Rev.* **45**, 213.
Ramaty, R. et al. 1987 *Adv. Space. Res.* **13**, 275.
Reames, D.V. 1994 *ApJ Suppl.* **73**, 235.
Reames, D.V. et al. 1985 *ApJ* **292**, 716.
Reames, D.V. et al. 1994 *ApJ Suppl.* **90**, 649.
Sakao, T. et al. 1994 *Kofu Symp.*, NRO Report No. **360**, 169.
Schoenfelder, V. 1994 *17th Texas Symposium*, Munich.
Share, G.H. and Murphy, R. J. 1995 *ApJ*, in press.
Shibata, K. et al. 1992 *PASJ* 44, L173.
Skibo, J.G. et al. 1994 *ApJ* **431**, L39.
Vestrand, W.T. & Forrest, D.J. 1993 *ApJ* **409,** L69.
Zhang, S.N., et al. 1994 *IEEE Trans. Nucl. Sci.* **41**, 1313.

ACRONYMS AND ABBREVIATIONS

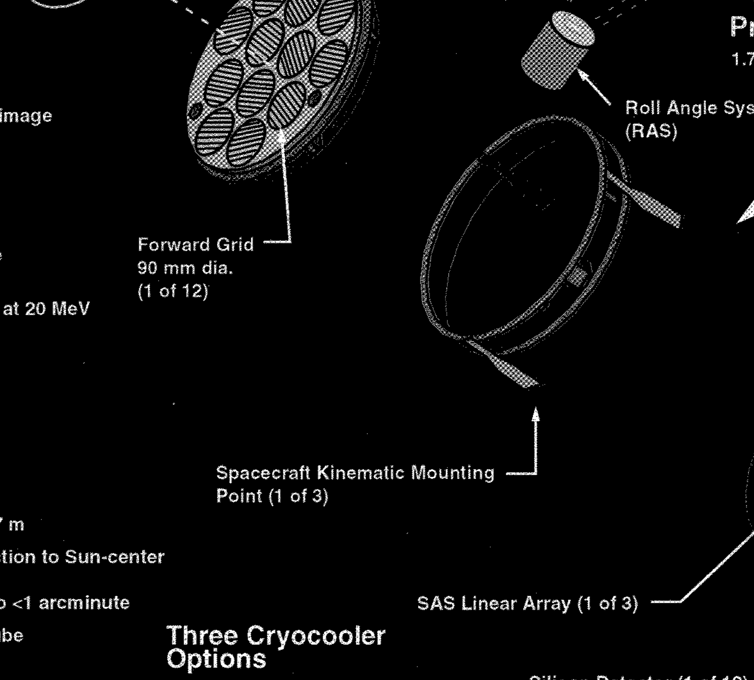
ATSR	Along Track Scanning Radiometer on ERS-1
BATSE	Burst and Transient Source Experiment on CGRO
BBSO	Big Bear Solar Observatory
BIMA	Berkeley-Illinois-Maryland Array, radio interferometer
CGRO	Compton Gamma Ray Observatory
CNES	Centre National d'Etudes Spatiales
EGRET	Energetic Gamma Ray Experiment on CGRO
ERS-1	European Remote Sensing Satellites 1
ESA	European Space Agency
FAST	Fast Auroral Snapshot Explorer, a SMEX mission
GCF	Grid Characterization Facility at GSFC
GEVS	General Environmental Verification Specification
GOES	Geostationary Operational Environmental Satellite
GRS	Gamma Ray Spectrometer on SMM
HEAO-3	High Energy Astrophysics Observatory-3
HEIDI	High Energy Imaging Device-GSFC
HEXAGONE	High Energy X-ray And Gamma-ray Observatory for Nuclear Emissions-UCB
HIREGS	High Resolution Gamma Ray Spectrometer-UCB
HIREX	High Resolution X-ray Spectrometer-UCB
HXIS	Hard X-ray Imaging Spectrometer on SMM
HXRBS	Hard X-ray Burst Spectrometer on SMM-GSFC
HXT	Hard X-ray Telescope on Yohkoh
IDL	Interactive Data Language -Research Systems, Inc.
IDPU	Instrument Data Processing Unit
INTEGRAL	International Gamma Ray Astrophysics Laboratory
ISAMS	Improved Stratospheric and Mesospheric Sounder on UARS
ISTP	International Solar Terrestrial Physics
KP	NSO's Kitt Peak
LBL	Lawrence Berkeley Laboratory
LIGA	German name for deep-etch X-ray lithography of acrylic resists, electroforming, and replication
MSFC	Marshall Space Flight Center
MUE	Mission Unique Electronics
NASTRAN	NASA Structural Analysis program
NOAA	National Oceanic and Atmospheric Administration
NRO	National Radio Observatory
NSO	National Solar Observatory
OSSE	Oriented Scintillation Spectrometer Experiment on CGRO
OVRO	Owens Valley Radio Observatory
PMMA	Polymethyl Methacrylate, an acrylic used for LIGA
POLAR	Polar Plasma Laboratory, ISTP spacecraft
RAS	Roll Angle System
ROSAT	Roentgen Satellite
RSTN	Radio Solar Telescope Network-USAF
SAS	Solar Aspect System
SDAC	Solar Data Analysis Center at GSFC
SEP	Solar Energetic Particle
SERTS	Solar EUV Rocket Telescope and Spectrograph-GSFC
SIGMA	A Russian satellite
SINDA	Systems Improved Differencing Analyzer
SMEX	Small Explorer
SMM	Solar Maximum Mission (1980-1989)
SOHO	ISTP Solar and Heliospheric Observatory
SOON	USAF's Solar Optical Observing Network
SP	NSO's Sacramento Peak Observatory
SUMER	Solar Ultraviolet Measurement of Emitted Radiation on SOHO
SWAS	Submillimeter Wave Astronomy Satellite, SMEX
SXI	Soft X-ray Imager on GOES
SXT	Soft X-ray Telescope on Yohkoh
TDU	Telescope Demonstration Unit-GSFC
TOTS	Transportable Orbital Tracking Station
TRASYS	Thermal Radiation Analyzer System
UARS	Upper Atmosphere Research Satellite
uv	Coordinates in Fourier space
VLA	Very Large Array, radio interferometer
WEDM	Wire Electric Discharge Machine
Wind	An interplanetary spacecraft of ISTP
XDL	Cross Delay Line detector on SOHO

Model Flare



Spin axis
(to Sun Center within 0.2°)

≥ 15 RPM



Solar Aspect System
(SAS) Lens (1 of 3)

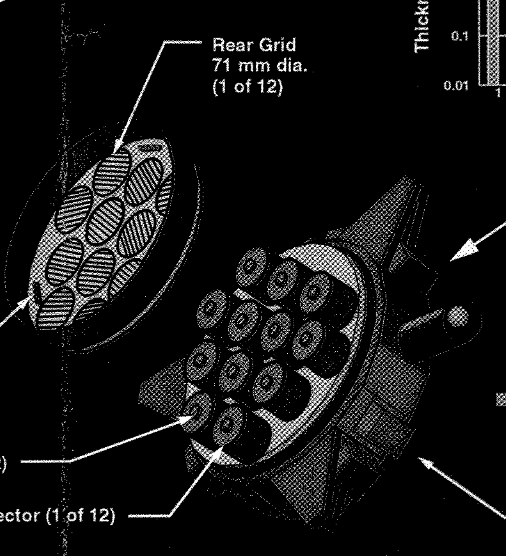
Roll Angle System
(RAS)

Forward Grid
90 mm dia.
(1 of 12)

Spacecraft Kinematic Mounting
Point (1 of 3)

SAS Linear Array (1 of 3)

Modulation Collimators



Rear Grid
71 mm dia.
(1 of 12)

Silicon Detector (1 of 12)

Germanium Detector (1 of 12)

Spectrometer

Cryostat and Cooler

Time-Tagged
Detector Counts

X-ray and Gamma-ray Imaging Spectroscopy

Imaging

• Angular Resolution	2 arcseconds to 300 keV increasing to 20 arcseconds above 1 MeV
• Angular Coverage	2 arcseconds - 2 arcminutes
• Field of View	Full Sun
• Temporal Resolution	Tens of ms for basic image, 2 s for detailed image
• Technique	Fourier-transform imaging with 12 rotating modulation collimators (RMC's)

Spectroscopy

Hard X-rays and Gamma-rays

• Detectors	Two-segment hyperpure germanium - HPGe
• Energy Range	10 keV to 20 MeV
• Energy Resolution	<1 keV FWHM to 1 MeV, increasing to 5 keV at 20 MeV

Soft X-rays

• Detectors	Lithium-drifted silicon - Si(Li)
• Energy Range	2 keV to 20 keV
• Energy Resolution	<1 keV FWHM

Imaging Components

• Grids	12 pairs of tungsten or gold grids Thickness 1 mm to 30 mm, separated by 1.7 m
• Aspect System	Solar Aspect System to determine the direction to Sun-center to sub-arcseconds Roll Angle System to determine roll angle to <1 arcminute
• Metering Structure	1.7 m long x 45 cm dia. riveted aluminum tube

Spectroscopy Components

• Detectors	12 germanium detectors each 7.1 cm dia. x 8 cm long, cooled to 80 K 12 silicon detectors Si(Li) each 1 cm dia. x 2 mm thick, cooled to 150 K
• Cryostat	Aluminum, 30 cm long x 55 cm dia. Sealed vacuum space with contamination barrier around germanium detectors
• Cooler	Stirling-cycle or pulse-tube options Cooling power: 0.7 watts at 80 K, 1.5 watts at 150 K Input power: 70 watts

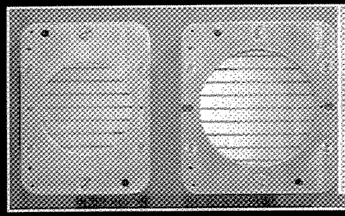
Instrument Characteristics

• Weight	136 kg
• Power	140 watts
• Telemetry	12 Gbits in 2 days

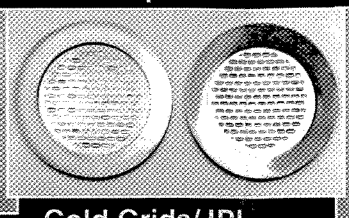
Special Requirements

• Orbit	Equatorial, ~ 600 km altitude, >3-year lifetime
• Launch Date	Dec. 1999 preferred, Dec. 2000 acceptable
• Operational Lifetime	2 years, 3rd year highly desirable

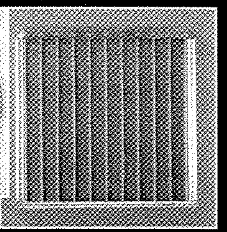
Fine Grid Options



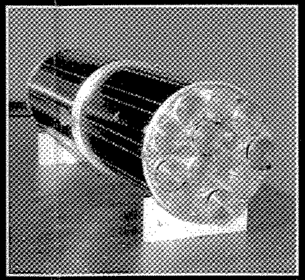
Tungsten Grids/Artep
150 micron pitch, 5 mm thick, 70 mm and 90 mm diameter



Gold Grids/JPL
34 micron pitch, 25 micron thick, 60 mm diameter

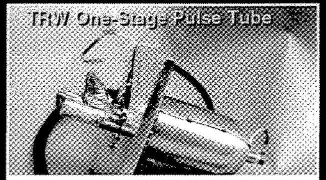


Tungsten Grid/Delft
98 micron pitch, 3 mm thick, 130 mm square

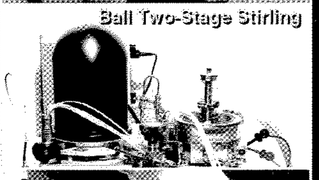


Prototype Telescope/GSFC
1.7 m long, 45 cm diameter

Three Cryocooler Options



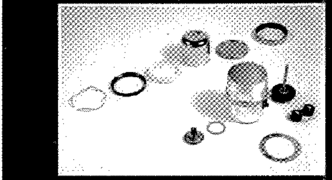
TRW One-Stage Pulse Tube



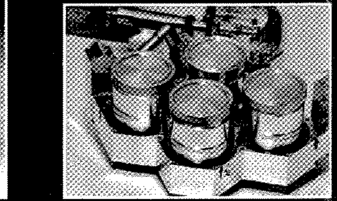
Ball Two-Stage Stirling

MMS One-Stage Stirling

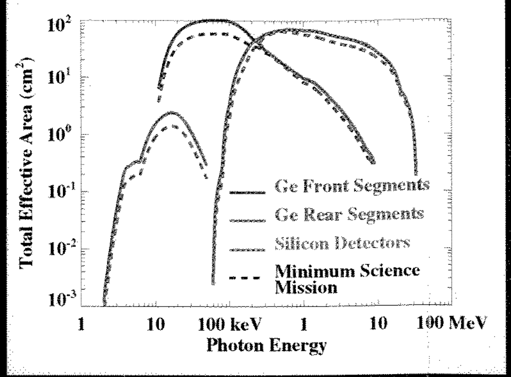
HIREGS Germanium Detector Components

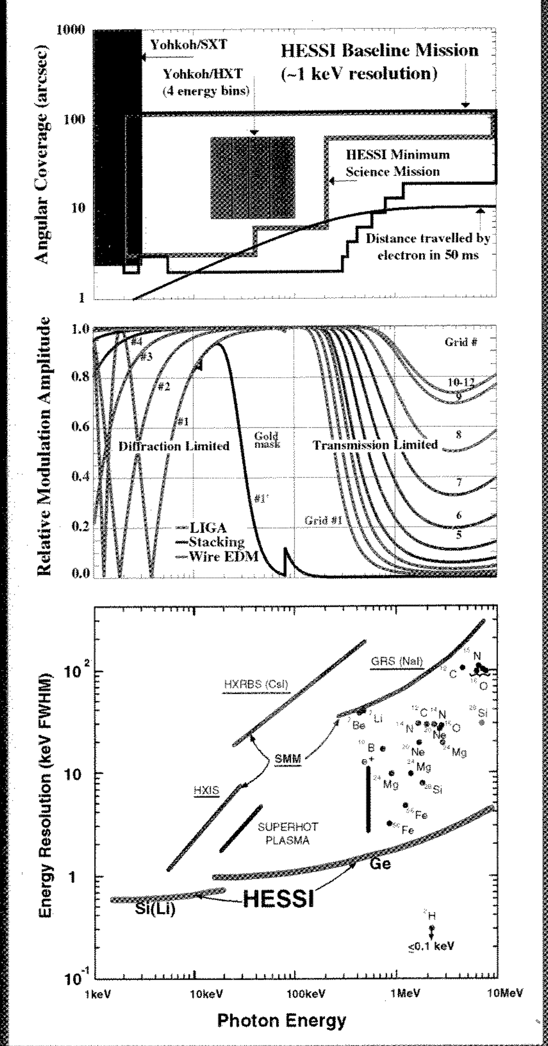


Four HIREGS Germanium Detectors

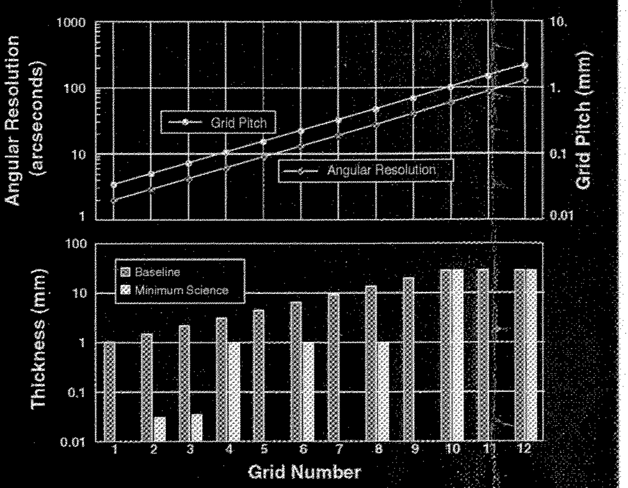


Instrument Characteristics





Grid Characteristics



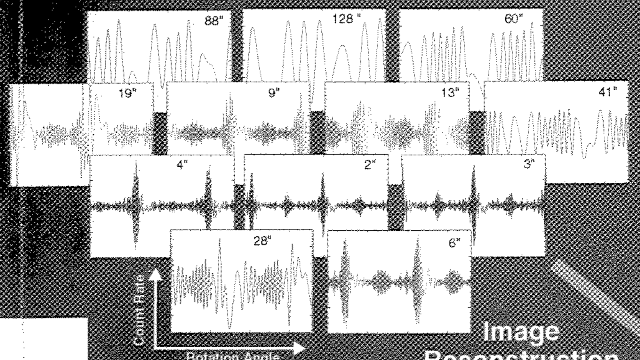
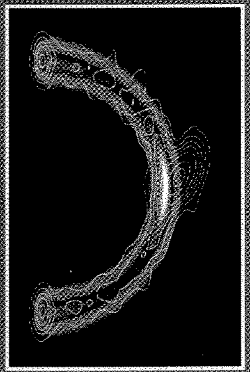


Image Reconstruction



Germanium and Silicon Detectors

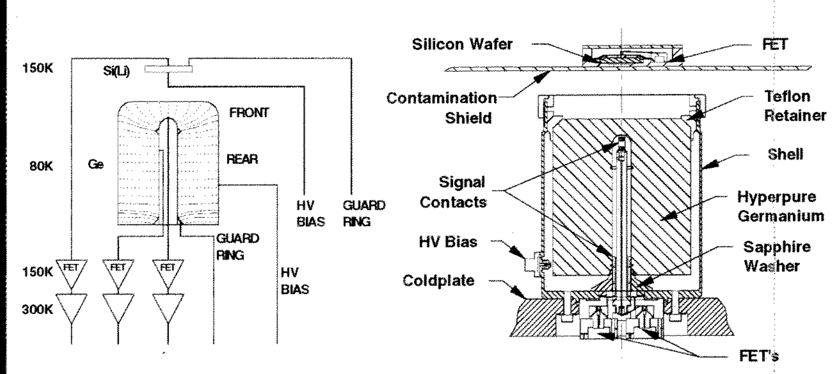


Figure 1-5

University of Hawai'i at Mānoa

Institute for Astronomy

Richard C. Canfield
2680 Woodlawn Drive • Honolulu, Hawaii 96822
Telex: 723-8459 • UHAST HR
FAX: (808) 956-9402
Phone: (808) 956-6898

June 20, 1995

Prof. Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Prof. Lin:

This is to express our acceptance of your invitation for the participation of Dr. Richard C. Canfield (Astronomer, Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, 808-956-6898) and Dr. Hugh S. Hudson (Astronomer, Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, 808-956-6898) as Co-Investigators in the High Energy Solar Spectroscopic Imager (HESSI) Investigation being proposed under NASA Announcment of Opportunity AO-95-OSS-02 for Medium-Class Explorer (MIDEX) missions. Final approval of the budget and committtment of University resouces will occur during Step Two.

We look forward to participating in this exciting mission.

Sincerely,

Richard C. Canfield
Astronomer

Endorsements:

Peter V. Garrod
Interim Director of Research
Office of Research Administration
Spalding 253
2540 Maile Way
Honolulu, HI 96822
(808) 956-8612

D. Hall

Donald N. B. Hall
Director
Institute for Astronomy
2680 Woodlawn Drive
Honolulu, HI 96822
(808) 956-8566

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-4321

JPL

June 5, 1995

Refer to: 700-CE:kp

Professor Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Professor Lin:

Subject: Joint Participation on the High Energy Solar Spectroscopic Imager (HESSI) Mission Team

Reference: Announcement of Opportunity, "Medium-class Explorer Missions (MIDEX)," dated March 27, 1995 (AO No. 95-OSS-02)

The Jet Propulsion Laboratory is pleased to support the subject proposal with Dr. James C. Ling as a co-investigator. JPL will be responsible for, but not limited to, developing data analysis packages with other member of the HESSI team and to participate, as an active member, in the HESSI team in the planning, design and implementation of the following subsystems: (1) GeD cryostat and cooler, (2) telescope, (3) data analysis, (4) calibration, and (5) mission operation.

Contingent upon proposal award, direct receipt of funds from NASA Headquarters should be administered to JPL under the Prime Contract NAS7-1260.

If you have any questions regarding this proposal, please contact Dr. William McLaughlin of my staff at (818) 354-1234.

Sincerely,

Charles Elachi
Director
Space and Earth Science Programs Directorate

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-4321

JPL

June 2nd, 1995

Professor Robert Lin
Space Science Laboratory
University of California, Berkeley
Berkeley, CA 94720

Fax: (510)643-8302

Subject: JPL Co-Investigator Role of the High Energy Solar Spectroscopic Imager (HESSI) Mission

Dear Professor Lin:

It is a great pleasure for me to accept your invitation (your letter dated 17 May 1995) to participate as a Co-investigator of the High Energy Solar Spectroscopic Imager (HESSI) Mission team for the NASA MidEX program of which you will be Principal Investigator.

As we discussed in our telephone conversation several weeks ago, following the letter I wrote you dated 16 April 1995, my specific role, as a Co-Investigator, during the Phases B, C, D and MO&DA of the HESSI program will be the followings:

Phases B, C & D

1. to lead the JPL effort in the joint development of the following data analysis packages with other members of the HESSI team :

   a. the Earth Occultation Analysis package for monitoring cosmic sources

   b. pulsar analysis package for known pulsars

   c. gamma-ray burst analysis package

   d. adapt the LINKWINDS tool of Bub Jacobson for HESSI application

   e. development of the solar and Crab imaging technique

2. to participate as an active member in the HESSI team in the planning, design and implementation of the following subsystems: (1) GeD cryostat and cooler, (2) telescope, (3) data analysis, (4) calibration, and (5) mission operation

MO&DA Phases

1. maintain and upgrade those data analysis packages developed by JPL

2. deliver secondary data products to SOC .

3. conduct science analysis

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 685

June 7, 1995

Prof. Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Bob,

We are pleased to accept your invitation to participate as Co-I's in the proposal for the High Energy Solar Spectroscopic Imager in response to the NASA MIDEX Announcement of Opportunity (AO-95-OSS-02). We have the full backing of the Goddard Space Flight Center as indicated in the accompanying letter of endorsement from the Acting Director, Dr. Rothenberg.

We look forward to working with you on this exciting mission.

Yours sincerely,

Carol Jo Crannell

Carol Jo Crannell
Code 682
(301) 286-5007
STARS::CRANNELL

Brian R. Dennis

Brian R. Dennis
Code 682
(301) 286-7983
STARS::DENNIS

Gordon D. Holman

Gordon Holman
Code 682
(301) 286-4636
STARS::HOLMAN

R. Ramaty

Reuven R. Ramaty
Code 665
(301) 286-8715
LHEAVX::RAMATY

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: Code 661

June 13, 1995

Professor Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Bob,

I hereby agree to becoming an unfunded Co-Investigator on the HESSI proposal. As a current Co-Investigator on the Advanced Composition Explorer (ACE), I agree to take an active role in fostering collaborations between the ACE and HESSI investigator teams. The Solar Isotope System (SIS) on ACE is designed to observe the isotopic composition of energetic particles from the sun, even in the largest events. It will be of special interest to compare the composition observed by SIS with that inferred from solar gamma rays observed by HESSI. The Electron Proton and Alpha Monitor (EPAM) instrument on ACE will also provide essential information for understanding the production of solar gamma rays.

I wish you success with your proposal and thank you for your interest in the ACE mission.

Sincerely,

Tycho von Rosenvinge

Tycho von Rosenvinge
Laboratory for High Energy Astrophysics

cc: R. A. Mewaldt/ Caltech
B. Dennis/ Code 680

We tentatively agreed that the total cost for the JPL effort is estimated to be $450k - $530k for Phase I through III (4/96 - 1/00) period, and $780k - $850k for the MODA Phase. A more detailed budget will be determined during Phase I of the mission,.

I look forward to working with you toward the success of this mission after it is selected.

Sincerely,

James C. Ling

James C. Ling

cc: **W. Mahoney**
W. Wheaton
M. Janssen
S. Gulkis

UAH

The University of Alabama in Huntsville

Research Administration

Huntsville, AL 35899
Phone: (205) 895-6000
Fax: (205) 895-6677

May 30, 1995

Dr. Robert P. Lin
Space Physics Research Group
Space Science Laboratory
Berkeley, CA 94720

Dear Dr. Lin:

The University of Alabama in Huntsville hereby approves and is committed to, the participation of Dr. A. Gordon Emslie, Professor of Physics, in the High Energy Solar Spectroscopic Imager (HESSI) Investigation being proposed under NASA Announcement of Opportunity #95-OSS-02. We look forward to our involvement in the exciting science return that this mission promises.

Sincerely,

Sue B. Weir

Sue B. Weir
Research Administrator

Concurrence:

A. Gordon Emslie
Professor, Department of Physics
(205) 895-6167

A Space Grant College
An Affirmative Action / Equal Opportunity Institution

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
325 Broadway
Boulder, Colorado 80303-3328

June 20, 1995

Prof. Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Prof. Lin:

I confirm to you that NOAA's Space Environment Laboratory approves and is committed to the participation of Dr. Patricia L. Bornmann in the High Energy Solar Spectroscopic Imager mission. This Investigation was proposed by you in response to the Announcement of Opportunity AO-95-OSS-02 for Medium-class Explorer (MIDEX) missions. Dr. Bornmann will be the CO-I in this investigation and no funding for her salary is required from you or NASA for her collaboration.

Sincerely yours,

Ernest Hildner

Ernest Hildner, Director
Space Environment Laboratory

Co-I

Dr. Patricia L. Bornmann
Physicist
NOAA
Space Environment Laboratory
325 Broadway
Boulder CO 80303
pbornmann@sel.noaa.gov
303-497-3532

Authorizing Official
Ernest Hildner, Director
NOAA
Space Environment Laboratory
325 Broadway
Boulder, CO 80303
ehildner@sel.noaa.gov

Lawrence Berkeley Laboratory
1 Cyclotron Road, Mail Stop 90/1070 Berkeley, California 94720
Contracts and Licensing Office (510) 486-4000

June 6, 1995

University of California, Berkeley
Space Sciences Laboratory, Room 201
Phone: (510) 642-1374
Fax: (510) 643-7629
Attn: Dave Weldon

RE.: HESSI
LBL Concurrence

Dear Mr. Weldon:

I am writing this letter to confirm that Lawrence Berkeley Laboratory (LBL) has a strong interest in participating in the activity described in your proposal *HESSI,* should it be awarded by the Sponsor. Norm Madden is designated as the technical point of contact working on flight detectors, which are components of the flight instrument. LBL hereby agrees to perform as proposed in the proposal, if approved by The U.S. Department of Energy, making facilities and personnel available from April 1, 1996 through January 31, 2000.

Should any other business entity require these services, the Laboratory is mandated under fairness of opportunity doctrines to also be available. Lawrence Berkeley Laboratory is operated by The Regents of the University of California for the Department of Energy (DOE) under prime contract DE-AC03-76SF00098 and all work is conducted under the terms of that contract and subject to the approval of DOE. Under this contract LBL effort is mandated to be fully cost reimbursable.

Lawrence Berkeley Laboratory, as a Federally-funded laboratory, may not provide services in competition with the private sector (see Article IV of the proposed agreement). Therefore, as soon as possible after making a decision to favor this proposal with an award, please forward to my attention, at the address above, **an explanation supporting the conclusion that the services required under the award are unique to LBL and cannot be obtained from private facilities on an independent, convenient and timely basis and at a reasonable charge.** Should Lawrence Berkeley Laboratory and Space Science Laboratory reach a written agreement, a letter containing the above explanation must be submitted.

I am looking forward to contributing to this exciting and important research effort.

Sincerely,

Nancy Saxer
Contracts.Officer

cc: J. Jaklevic D. Rondeau
N. Madden M. St. Hill

CALIFORNIA INSTITUTE OF TECHNOLOGY

SOLAR ASTRONOMY 264-33

June 9, 1995

Dr. R. P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720

Dear Bob:

This letter is to formally accept your invitation to join the HESSI team as a Coinvestigator for the mission proposed in response to NASA MIDEX AO-95-OSS-02.

Since, following our discussions, it would appear that my contributions to the mission would require full-time presence over several years at Goddard Space Flight Center, it is my intention that following our final selection, I would take a leave of absense from Caltech and apply for an appropriate position with a university/contractor in the GSFC area who was funded to provide appropriate services to the project.

I look forward to working with you and the team towards a successful mission.

Yours truly

Gordon Hurford

Gordon Hurford
Senior Scientist

PASADENA, CALIFORNIA 91125 TELEPHONE (818) 395-4011 TELEX 3730923 CALTECH PSD FAX (818) 395-3814

ETH **Eidgenössische Technische Hochschule Zürich**

Ecole polytechnique fédérale de Zurich
Politecnico federale di Zurigo
Swiss Federal Institute of Technology Zurich

Institut für Astronomie

Prof. Dr. Jan O. Stenflo

Häldeliweg 15
Telefon direkt: +41 1 632 38 04
Sekretariat: +41 1 632 38 13
Telefonzentrale: +41 1 632 11 11
Telefax: +41 1 632 12 05
E-mail: stenflo@astro.phys.ethz.ch
jstenflo@solar.stanford.edu

Postadresse:
Institut für Astronomie
ETH-Zentrum
CH-8092 Zürich

2504

To whom it may concern

May 31st, 1995

We have taken notice of the invitation to Professor Arnold O. Benz of our Institute to join as a Co-Investigator the HESSI Investigation proposed by Professor R.P. Lin in response to NASA AO 95-OSS-02.

We are glad to support and sponsor this collaboration on a no-exchange-of-funds basis.

Sincerely yours

Prof. Dr. Jan O. Stenflo

Professor John C. Brown DSc, FRSE
Chair of Astrophysics
Astronomer Royal for Scotland

UNIVERSITY
of
GLASGOW

JCB/DD

Professor Robert P. Lin,
Space Sciences Laboratory,
University of California,
Berkeley, CA 94720-7450,
U.S.A.

1 June, 1995.

FAX No: 001 510 643 8302

Dear Bob,

NASA MIDEX Proposal - HESSI

I am delighted to accept your invitation of May 17 to join the HESSI proposal as a foreign Co-I. I believe this mission to be the most important study ever of high energy plasma processes on the sun. In particular I am excited to see the advent of Ge detectors finally making it possible for the first time ever to acquire data of adequate quality to enable inversion of photon spectra to yield source electron spectra (as I first discussed in Solar Phys.**18**, 489, 1971) which are crucial in our understanding of flares. Acquisition of such unique data in the spectral/spatial domain, and in coordination with gamma-ray and other data, should answer many of the key questions on the fundamental problems of cosmic particle acceleration.

I understand that your invitation is on a '*no exchange of funds*' basis and anticipate applying to our PPARC for any necessary support in due course.

Yours sincerely,

John

Ian Carter 9/5/95

Dr Ian M Carter
University Research Officer,
The University of Glasgow,
Glasgow G12 8QQ
Telephone 041 339 8855

Original sent 1/6/95.

DEPARTMENT OF PHYSICS AND ASTRONOMY
UNIVERSITY OF GLASGOW,
GLASGOW, G12 8QQ
Tel.: 0(44)141-330-5182 (Secy 4152) *Fax:* 0(44)141-334-9029 *Telex:* 777070 UNIGLA *E-Mail: John@*Astro.gla.ac.uk

NRO
Nobeyama Radio Observatory
NATIONAL ASTRONOMICAL OBSERVATORY

NOBEYAMA
MINAMISAKU
NAGANO
384-13 JAPAN

PHONE 0267-63-4300
0267- -
FAX 0267-98-2884
0267- -
TELEX: 3329005 (NAONRO J)

May 31, 1995

Prof. R. P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450
USA

Dear Dr. Lin:

This is to certify that I will be pleased to join your collaboration, as a Co-Investigator, for the development of a High Energy Spectroscopic Imager (HESSI) in response to NASA's AO-95-OSS-02. The conditions you have described in your letter of May 17, 1995, are acceptable to me and I look forward to supporting this investigation. Approval for my participation is not required at a government agency level, and at the institutional level it has already been approved as confirmed by the attached statement of the Director of the National Astronomical Observatory.

Sincerely Yours,

Shinzo Enome

Shinzo Enome, Professor
Nobeyama Radio Observatory
of National Astronomical Observatory

Dear Dr. Lin:

With this note I confirm that Prof. Enome is free to participate in the HESSI program as a Co-Investigator under your leadership. He has a regular position in the National Astronomical Observatory and his continuous involvement in this program will be supported by our institution during the development of the instrumentation and through its observation and data-analysis phases.

Sincerely Yours,

Keiichi Kodaira

Keiichi Kodaira, Director
National Astronomical Observatory

NATIONAL ASTRONOMICAL OBSERVATORY
MITAKA TOKYO 181 JAPAN

May 31, 1995

Prof. R. P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450
USA

Dear Dr. Lin:

This is to certify that I will be pleased to join your collaboration, as a Co-Investigator, for the development of a High Energy Spectroscopic Imager (HESSI) in response to NASA's AO-95-OSS-02. The conditions you have described in your letter of May 17, 1995, are acceptable to me and I look forward to supporting this investigation. Approval for my participation is not required at a government agency level, and at the institutional level it has already been approved as confirmed by the attached statement of the Director of the National Astronomical Observatory.

Sincerely Yours,

Takeo Kosugi

Takeo Kosugi, Professor
National Astronomical Observatory

Dear Dr. Lin:

With this note I confirm that Prof. Kosugi is free to participate in the HESSI program as a Co-Investigator under your leadership. He has a regular position in the National Astronomical Observatory and his continuous involvement in this program will be supported by our institution during the development of the instrumentation and through its observation and data-analysis phases.

Sincerely Yours,

Keiichi Kodaira

Keiichi Kodaira, Director
National Astronomical Observatory

TU Delft

Faculty of Mechanical Engineering and Marine Technology

Delft University of Technology

to: Prof. Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450
U.S.A.

31 May 1995

Dear Prof. Lin,

With pleasure I accept your invitation to be a Co-I on the NASA High Energy Solar Spectroscopy Imager (HESSI) mission, the mission that is proposed in response to the Announcement of Opportunity AO-95-OSS-02 for Medium-class Explorer (MIDEX) missions.

I understand that our (non-U.S.) participation is on a 'no-exchange of funds' basis. For that reason I further understand that endorsement is needed by my institution, the Faculty of Mechanical Engineering and Marine Technology of the Delft University of Technology, for support and sponsoring my Co-Investigatorship.
For reason of endorsement, ir. W. van Horssen, managing director of our Faculty, undersigns this letter as well.

Sincerely yours,

H F van Beek

prof. dr. H.F. van Beek
Delft University of Technology, WbMT
2628 CE Delft
the Netherlands

for endorsement:

ir. W. van Horssen

MINISTERE DE L'EDUCATION NATIONALE

OBSERVATOIRE DE PARIS

SECTION D'ASTROPHYSIQUE
5, Place Jules Janssen
92195 - MEUDON PRINCIPAL CEDEX

Tél. (1) 45.07.75.30
Télex 634103 OBSASTR - 631987 LAM
Télécopie : 45.07.74.69

URA 1756
DASOP

MEUDON, May 29 1995

Prof. Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

To whom it may concern

This letter confirms the interest of the URA-CNRS 1756 (DASOP Observatoire de PARIS) in participating in the High Energy Solar Spectroscopic Imager (HESSI) Investigation which is proposed by Prof. R.P. Lin in response to NASA AO 95-OSS-02. The Nançay Multifrequency Radioheliograph observations will provide support to the ground-based network of solar data which will be coordinated with the HESSI observations. Furthermore, we propose to bring our expertise in the treatment of images at radio wavelengths and in the development of software to analyze X-ray/γ ray data in order to participate to the development of post-launch software, in particular the imaging software. Finally, we shall bring our expertise in the analysis, the interpretation and modelisation of X-ray/γ-ray and radio emissions. Therefore, we will propose to our funding agency, the CNES, to support our participation to this project.

As usual, our actual participation in this project will ultimately depend upon the decision of CNES.

Yours Truly.

Dr. Alain KERDRAON
Director of the Laboratory CNRS-URA1756

MINISTERE DE L'EDUCATION NATIONALE

OBSERVATOIRE DE PARIS

SECTION D'ASTROPHYSIQUE
5, Place Jules Janssen
92195 - MEUDON PRINCIPAL CEDEX

Tél. (1) 45.07.75.30
Télex 634103 OBSASTR - 631987 LAM
Télécopie : 45.07.74.69

URA 1756
DASOP

MEUDON, May 29 1995

Prof. Robert P. Lin
Space Sciences Laboratory
University of California
Berkeley, CA 94720-7450

Dear Pr Lin:

You will find enclosed the letter of endorsment that you asked for in your letter of May, 17 1995. I hope that this is this type of letter that you expected from us.

Yours Sincerely

Nicole Vilmer

High Energy Solar Spectroscopic Imager HESSI

Science Objective

To explore the basic physics of particle acceleration and explosive energy release in solar flares.

Observational Approach

Observations of X-ray and gamma-ray flares from 2 keV to 20 MeV with an unprecedented combination of high resolution spectroscopy and imaging.

The first hard X-ray imaging spectroscopy.

The first high resolution solar gamma-ray line spectroscopy from space.

The first imaging observations above 100 keV.

The first imaging in narrow gamma-ray lines.

High resolution X-ray and gamma-ray spectra of cosmic sources.

Hard X-ray images of the Crab Nebula with 2 arcsecond resolution.

Primary Observations

Hard X-ray images with an angular resolution as fine as 2 arcseconds, temporal resolution as fine as 10 ms, and energy resolution of <1 keV from 2 keV to >200 keV.

High resolution X-ray and gamma-ray spectra with ~1 keV resolution to energies as high as 20 MeV.

Complementary Observations

Images from the Soft X-ray Imager on GOES.

Energetic particle spectra and abundances from the Advanced Composition Explorer (ACE).

Groundbased radio and optical images, spectra, and magnetograms.

Expected Numbers of Flares

Tens of thousands of microflares.

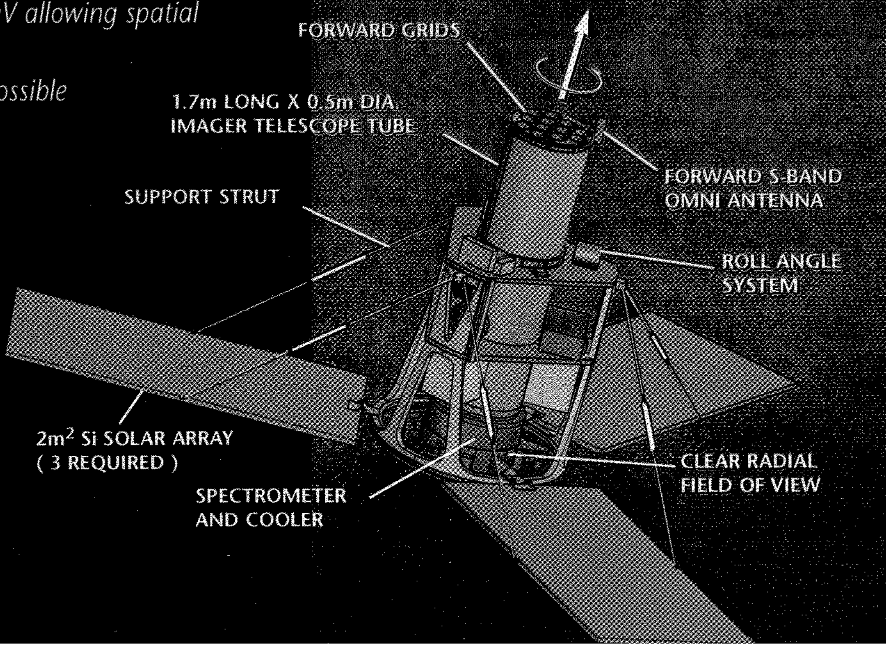
Thousands of hard X-ray flares with crude imaging and spectra to >100 keV.

Hundreds of flares with >10^3 counts s^{-1} above 20 keV allowing spatial changes to be followed on timescales of 0.1 s.

Tens of flares sufficiently intense to allow the finest possible imaging spectroscopy.

Hundreds of flares with the detection of the narrow gamma-ray lines.

Tens of flares with detailed gamma-ray line spectroscopy and the location and extent of the source to 20 arcseconds.



Special Requirements

Pointing to within 0.2° of Sun center.

Spinning at ≥15 rpm.

Equatorial orbit at 600km altititude.

Operations for 2-3 years during next period of high solar activity expected between 1999 and 2003.