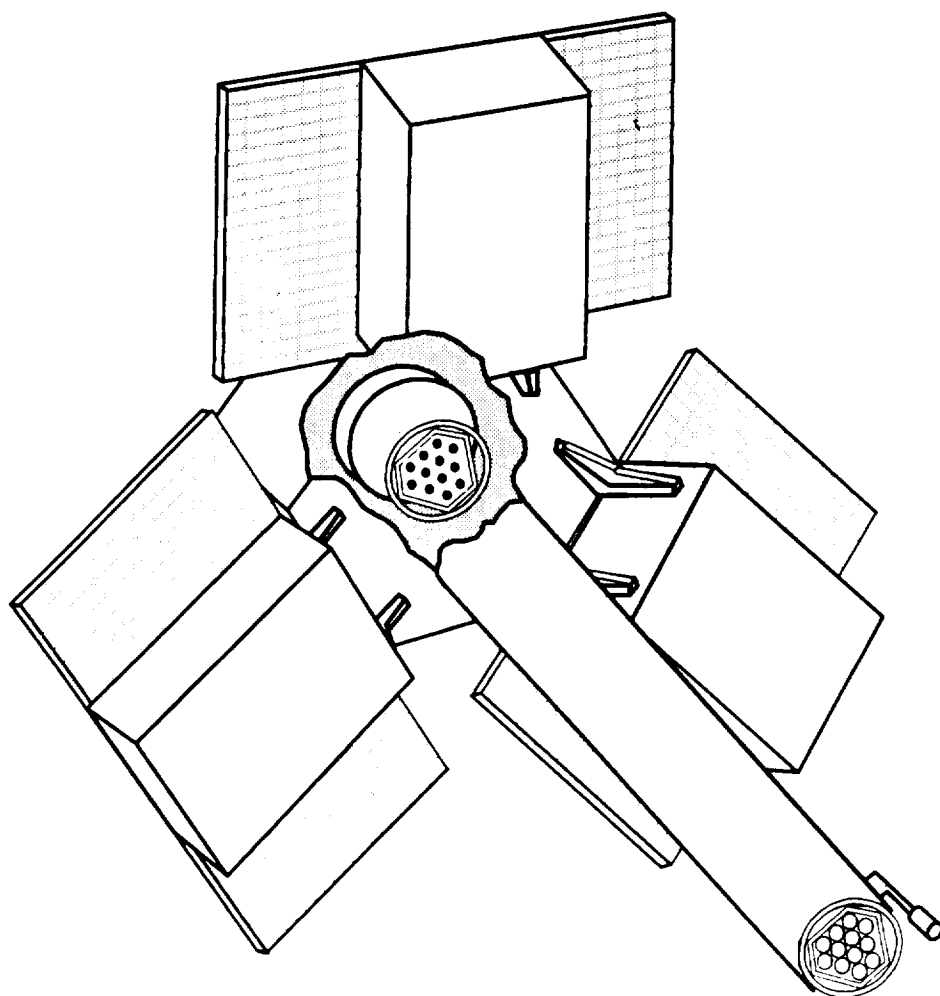# The HIGH ENERGY SOLAR PHYSICS Mission (HESP)

Scientific Objectives and Technical Description

Prepared by the HESP Science Study Group

July 1991

Front cover solar image.

A composite picture, for display purposes only, showing the solar image in soft X-rays and a spectacular coronal mass ejection observed about a year later with the SMM Coronograph/Polarimeter (outer corona), the MLSO Mark-III K-Coronameter (inner corona), and the MLSO Prominence Monitor. The coronal pictures (courtesy of A. Hundhausen and D. Sime, High Altitude Observatory) were taken on 13 October, 1988, and the X-ray image (courtesy of A. Walker, Stanford University) was taken in October, 1987. **HESP** would image the accompanying flare within a circle one tenth the size of the solar disc or about the size of the prominance.

PREFACE

This document is the report of the HESP Science Study Group that was selected by the Solar Physics Branch at NASA Headquarters in January, 1991. It should be read in conjunction with the following three other reports on various aspects of the HESP program:

"Preliminary Mission Study for NASA Space Physics Division (Code SS) High Energy Solar Physics Addendum 1" prepared by Ball Aerospace Systems Group, February, 1991.

"Pre-Phase-A Study Report for the High Energy Imaging Spectrometer (HEISPEC) on the High Energy Solar Physics Mission (HESP)" prepared by the Instrument Concept Design Office, Goddard Space Flight Center, July, 1991.

"Pre-Phase-A Study Report on the High Energy Solar Physics Mission (HESP) - Spacecraft Concept" prepared by the Advanced Missions Analysis Office, Goddard Space Flight Center, July, 1991.

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EXECUTIVE SUMMARY

The **High Energy Solar Physics** mission offers the opportunity for major breakthroughs in our understanding of the fundamental energy release and particle acceleration processes at the core of the solar flare problem. **HESP** will address the following scientific questions:

- What are the processes that release the stored magnetic energy to produce a flare and where in the solar atmosphere does this energy release take place?

- How are electrons and ions efficiently and rapidly accelerated to sub-relativistic and relativistic energies?

- What mechanisms transport the flare energy and the accelerated particles from the energy release site?

- What is the composition of the accelerated particles and of the solar atmosphere with which they interact?

- What are the characteristics of microflares and what is their contribution to coronal heating?

HESP will build on the pioneering observations made during the previous solar cycle and on new observations expected during the current active phase with instruments on **GRO** and **Solar-A**, and with the balloon-borne **HIREGS** and **HEIDI** instruments. In particular, **HESP** will have the following unique capabilities for solar flare observations:

- High resolution (1 - 5 keV FWHM) spectroscopy from 2 keV to 20 MeV. This resolution is sufficient to resolve the gamma-ray lines and to measure their shapes, thus allowing the full potential of gamma-ray line spectroscopy to be realized for the first time. In addition, measurement of the detailed structure of the X-ray and gamma-ray continuum will provide information on the spectrum of the accelerated electrons.

- Gamma-ray imaging of solar flares with 4-to-8 arcsecond angular resolution, with the possibility of imaging in specific lines or continuum regions, e. g., in proton or alpha-particle induced lines, or in the continuum from energetic heavy nuclei. Comparisons with images in hard X-rays produced by electrons affords the exciting possibility of demonstrating the existence of large-scale electric fields in flare loops.

- Hard X-ray imaging with an angular resolution of 2 arcseconds and a temporal resolution of tens of milliseconds, commensurate with the known size scales of the flaring magnetic structures and with the stopping distances and times for the accelerated electrons. Furthermore, the images will be obtained with sufficiently high sensitivity to detect the initial impulsive flare energy release and to study microflares.

- Imaging of energetic (20 MeV to $\sim$1 GeV) neutrons in large solar flares, providing information on particle acceleration to the highest energies.

- High resolution X-ray and gamma-ray imaging spectroscopy, i.e., high resolution spectroscopy at each spatial point of the image, thus allowing the spectral evolution during a flare to be traced in both space and time. This is a new capability not available in any other instrument.

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The **HESP** payload consists of a single instrument, the **High Energy Imaging Spectrometer** (**HEISPEC**), that responds to photons over the entire energy region from ~2 keV to ≳ 200 MeV and also neutrons from 20 MeV to ≳ 1 GeV.

The imaging is based on a Fourier-transform technique using 12 rotating modulation collimators (RMC's). Each RMC consists of two widely-separated, fine-scale grids that temporally modulate the photon or neutron signal from sources in the field of view as the spacecraft rotates. The modulation can be measured with a detector having no spatial resolution located behind the RMC. The modulation pattern over half a spin period for a single RMC contains information on the amplitude and phase of many spatial Fourier components of the image covering the full range of angular orientations for a given source size. Multiple RMCs, each with different slit widths, provide sensitivity to a wide range of source sizes. An image is constructed from the set of measured Fourier components in exact mathematical analogy to multi-baseline radio interferometry.

HEISPEC will have tungsten grids with the thicknesses (from 2.8 mm to 4 cm) chosen to give full-Sun field of view so that all flares will be observed no matter what their location. With the 5-m separation between grids and slit widths from 50 microns to 3 mm, **HEISPEC** will provide spatial resolutions of ~2 arcseconds at X-ray energies below ~400 keV, 4 to 8 arcseconds for ≳ 0.5 MeV gamma-ray lines and continuum, and ~40 arcseconds for neutrons.

A 7.5-cm diameter x 8-cm long hyperpure germanium coaxial detector placed behind each RMC provides the high spectral resolution from ~10 keV to ~20 MeV. These detectors will be cooled to their 80 K operating temperature using dual Stirling-cycle mechanical refrigerators. A bismuth germanate (BGO) active anticoincidence shield and collimator enclose the germanium detectors to reduce the background, provide Compton rejection, and extend the energy range to ≳ 200 MeV for moderate spectral and spatial resolution gamma-ray imaging. In addition, the BGO and Germanium detectors provide coarse spectral and spatial resolution imaging of energetic neutrons up to ~1 GeV. Silicon semiconductor detectors, located in front of the germanium detectors, extend the imaging spectroscopy down to ~2 keV to cover the transition from non-thermal to thermal emission and to relate the high energy measurements to the thermal soft X-ray flare.

HESP will be placed in a Sun-sychronous, dawn-dusk, polar orbit with an altitude of ~600 km by a Delta launch vehicle. The spacecraft will be spin-stabilized at ~15 rpm with the spin axis pointed within a few arcminutes of Sun-center. This orientation and rotation rate provides for a stable thermal environment and close to 100% solar coverage. Data from solar flares will be stored on board in an ~2 Gbyte memory and read out each day during passages over the Wallops ground station.

With a planned 3-year lifetime during the next solar maximum, **HESP** will detect ~ 10^4 flares and ~ 10^5 microflares. Of these, ~ 10^3 will be suitable for imaging and detailed spectroscopy in hard X-rays to ≳ 400 keV. Several tens of flares should be sufficiently intense for imaging in gamma rays and neutrons and for gamma-ray line spectroscopy. Such a database of high resolution X-ray and gamma-ray imaging spectroscopy results would revolutionize our understanding of solar flares.

HESP will also provide the first high resolution imaging spectroscopy of cosmic hard X-ray and gamma-ray sources within ±25° of the ecliptic plane.

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1. INTRODUCTION

The ability to release energy impulsively and accelerate particles to high energies is a common characteristic of cosmic plasmas at many sites throughout the universe, ranging from magnetospheres to active galaxies. These high-energy processes play a central role in the overall physics of the system at each site where they are observed. The detailed understanding of these processes is one of the major goals of astrophysics, but in essentially all cases, we are only just beginning to perceive the relevant basic physics.

Nowhere can one pursue the study of this basic physics better than in the active Sun, where solar flares are the direct result of impulsive energy release and particle acceleration. Here, the acceleration of electrons is revealed by hard X-ray and gamma-ray bremsstrahlung; the acceleration of protons and nuclei is revealed by nuclear gamma-rays, pion decay radiation, and neutrons. The accelerated particles, notably the electrons with energies of tens of keV, probably contain a major fraction of the total flare energy, thus indicating the fundamental role of the high-energy processes in solar flares.

The scientific potential of solar high-energy observations has been demonstrated by the results from the instruments flown during the active phase of the previous solar cycle (1978 to 1984) on the NASA **Solar Maximum Mission** (SMM) and the **International Sun-Earth Explorer 3** (ISEE-3), the Japanese **Hinotori** satellite, the DoD **P78-1** spacecraft, and on high altitude balloons. These pioneering observations showed that high-energy processes were at the core of the solar flare phenomenon, and they provided a glimpse of the potential major breakthroughs in the understanding of flares that could result from observations with powerful new X-ray, gamma-ray, and neutron instrumentation. These indications, and the promise of new discoveries anticipated from future observations, are the main drivers of the proposed High Energy Solar Physics (**HESP**) mission.

The major areas that will be addressed by observations with **HESP** are energy release, particle acceleration, and energy redistribution in solar flares. We would like to know what processes liberate the energy stored in unstable magnetic configurations, how this energy is converted into kinetic energy of fast particles and thermal energy of hot plasma, how the particles are accelerated rapidly to high energies, what mechanisms transport particles and energy away from the energy release site, and what observational consequences result from the operative radiation mechanisms. The physics of these processes is highly involved, drawing on plasma physics, magnetohydrodynamics, kinetic theory, particle and radiation transport, and atomic and nuclear physics.

In addition to the purely scientific motivation for studying high-energy processes in solar flares, their detailed understanding must be of primary importance for any reliable flare prediction scheme. This is particularly true for the prediction of the intense solar flare energetic particle events that are the most dangerous for extended space travel. **HESP** will contribute to a more accurate prediction capability for these events by providing a greater understanding of the processes that drive solar flares and accelerate high energy particles.

This report describes the scientific objectives and instrumentation of **HESP**, an intermediate-class mission optimized for the study of solar high-energy phenomena in the next cycle of solar activity, which is expected to begin in 1998 and extend through 2005. The

payload consists of a single instrument capable of simultaneous high-resolution imaging and spectroscopy of X-rays, gamma-rays, and neutrons from solar flares.

HESP will have arcsecond spatial resolution and sub-second temporal resolution and will be capable of producing images at photon energies between 2 keV and $\geq$200 MeV. These images, the first at photon energies above 100 keV, will be sufficiently sharp to match known size scales of flare structures and sufficiently fast to match the characteristic time scales of the acceleration, transport, and loss mechanisms. With its unusually high sensitivity, **HESP** will be able to locate the regions where the initial energy release and particle acceleration occur, and follow the subsequent redistribution of the released energy. In addition, **HESP** will be able to detect and study microflares.

HESP will also provide high-resolution spectroscopy from $\sim$2 keV to GeV energies, with $\sim$keV resolution up to 20 MeV. Thus, the many nuclear gamma-ray lines observed with **SMM** can be resolved for the first time, providing information on the angular distributions of accelerated particles and on solar abundances. High energy resolution is also essential for resolving structure in the continuum, such as very steeply falling thermal spectra and sharp breaks in the non-thermal spectrum. At energies above $\sim$20 MeV, **HESP** will be capable of obtaining images and spectra of neutrons and gamma-rays independently. The spectra of these two components will be obtained with modest energy resolution sufficient to separate pion-decay gamma-rays from relativistic electron bremsstrahlung and to investigate the highest-energy processes occurring in flares.

Soft X-ray images and spectra with keV energy resolution will also be obtained with **HESP** at energies down to $\sim$2 keV. Such observations will define the structures in which the explosive high-energy phenomena take place and will reveal other direct manifestations of the impulsive energy release. Simultaneous interplanetary energetic-particle observations and vigorous ground-based and theoretical support programs are also required to achieve the **HESP** scientific objectives.

It should be emphasized that **HESP** provides *spatially resolved* spectroscopy, so the full diagnostic power of high-resolution spectroscopy can be applied on a spatial point by point basis. This is an important new capability not available from instruments that provide imaging and high resolution spectroscopy separately.

The **HESP** observations will be highly complementary to the solar observations from the **International Solar-Terrestrial Physics (ISTP) Solar and Heliospheric Observatory (SOHO)** and from the **Orbiting Solar Laboratory (OSL)**. They will also be complementary to the interplanetary particle observations of the **ISTP/Wind** spacecraft and the **Advanced Composition Explorer (ACE)**.

HESP will also make major advances in non-solar hard X-ray and gamma-ray astrophysics with its unique combination of unmatched spatial resolution and high spectral resolution. It will provide high resolution spectra for the many cosmic sources within $\pm25°$ of the ecliptic plane, as well as fine imaging of extended sources such as the Crab Nebula and the quasar 3C273. In addition, many cosmic gamma-ray bursts will be detected by **HESP** with high temporal and spectral resolution.

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2. THE SCIENTIFIC OBJECTIVES OF HESP

The principal scientific objective of **HESP** is the study of the high-energy processes at the core of the solar flare problem. These involve the rapid release of energy stored in unstable magnetic configurations, the equally rapid conversion of this energy into kinetic energy of accelerated particles and hot plasma, the transport of these particles, and the subsequent heating of the ambient solar atmosphere. Observations of hard X-rays, gamma rays, and neutrons serve as the best diagnostic of these processes by providing direct evidence for the interaction of accelerated particles in solar flares. The strong scientific need for the observations of these high-energy emissions with high spatial, temporal, and spectral resolutions is widely recognized. The necessary spatial and temporal resolving powers must match the spatial and temporal scales that characterize the processes of energy release, acceleration, and transport. The sensitivity should be high enough to detect the initial energy release and particle acceleration, and also to provide observations over a wide range of intensities from microflares to large flares. Equally important, the spectral resolving power must be high enough to allow the deciphering of the rich information encoded in both the gamma-ray lines and the highly structured photon continuum. The observations should provide imaging *with* spectroscopy and should cover the entire photon energy range from soft thermal X-rays to high-energy gamma rays, as well as energetic neutrons. It is the primary goal of **HESP** to provide, for the first time, such comprehensive observations. Additional objectives of **HESP** include the study of the composition of the solar atmosphere, using gamma-ray spectroscopy, and the investigation of microflares and their contribution to the heating of the corona.

In describing these scientific objectives in more detail, we first review the main characteristics and implications of solar flare X-ray, gamma-ray, and neutron observations. We then discuss some key aspects of energy release and particle acceleration, and show how **HESP** observations will lead to a much deeper understanding of the underlying physics of solar flares.

2.1 X-Rays — Diagnostics of Subrelativistic Electrons

One of the most outstanding signatures of solar flares is the hard X-ray emission. This emission is the defining characteristic of the impulsive phase, but it can also be observed several minutes before the onset of this phase, as well as many tens of minutes afterwards. Hard X-rays are generally attributed to bremsstrahlung produced in collisions between suprathermal electrons and the constituents of the ambient solar atmosphere. This interpretation of the hard X-rays, supported by the observed energy spectra that appear to be nonthermal, has fundamental consequences. These follow from the fact that the ratio between the bremsstrahlung energy loss rate of the electrons to the energy loss rate to Coulomb collisions, which heat the gas without producing hard X-rays, is extremely small ($\sim 10^{-5}$ in the deka keV range) when the electron energy E_e is much larger than the kT of the ambient gas. In this situation, the fast electrons must contain many orders of magnitude more energy than the X-rays that they produce. Since observed hard X-ray spectra are typically steep power-laws produced by steep electron spectra, the total energy content of the electrons is critically dependent on the low-energy cutoff of the accelerated electron

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spectrum. Even for assumed cutoffs in the 20 to 30 keV range, the inferred electron energy can amount to a substantial fraction, ~10 to 50%, of the total energy released in the flare. Thus, particle acceleration must be a significant part of the flare energy release process.

The bulk of the radiative output of flares appears at lower energies, in the visible, UV and soft X-ray bands, with a substantial fraction of the total output radiated in soft X-rays (e.g., Canfield *et al.* 1980). These soft X-rays are thermal bremsstrahlung produced by plasma heated to a temperature of the order of 10 to 20 million K, although a "superhot" component at ~35 million K has been observed (Lin *et al.* 1981). The high energy part of this thermal spectrum often overlaps the non-thermal hard X-ray spectrum at energies of 20 to 30 keV. Because so much energy is contained in the hard X-ray producing electrons, it is reasonable to assume that it is the energy deposited by these electrons into the ambient solar atmosphere which produces the observed lower energy emissions. The thick-target model (Brown 1971) assumes that the primary result of the energy release process is the impulsive acceleration of electrons, probably in the coronal part of a loop or arcade of loops. These electrons propagate along the magnetic field lines and deposit their energy predominantly in the lower corona and the chromospheric portions of the loops, heating the ambient gas. This model has been shown to be consistent with much of the observational data (e.g., Emslie 1986).

The fact that the impulsive energy release and particle acceleration is assumed as a starting point in these models illustrates how little is known about these fundamental processes. A clue to the their nature may be contained in high spectral resolution (~1 keV FWHM) observations of hard X-rays, presently available from only a single medium-sized flare observed with a balloon-borne instrument (Lin and Schwartz, 1987). These measurements show that the hard X-ray spectrum has a characteristic double power-law shape with a sharp downward break at an energy that varied during the flare from ~30 keV to greater than 100 keV. This sharp break may result from the electrons being accelerated by quasi-static electric fields parallel to the magnetic field; the break energy would then be a measure of the maximum potential drop. This type of acceleration occurs in the Earth's aurora, but with potential drops of ~10 kV compared to the ~100 kV required in flares. Furthermore, the very large number of accelerated electrons required for flares and the substantial currents they carry pose difficult challenges to models.

Largely as a result of the recognition of the formidable constraints that the non-thermal models place on the primary energy release process, alternative thermal models with $E_e \simeq kT$ have been put forward with the general feature of requiring less energy in sub-relativistic electrons for a given hard X-ray bremsstrahlung yield. In these models (Brown *et al.*, 1979, Smith and Harmony, 1982, and references therein), the bremsstrahlung is produced in a quasi-thermal plasma with a temperature in excess of 100 million K located in the coronal part of the loop at or close to the initial energy release site. Since $E_e \simeq kT$, the energy lost by one electron to Coulomb collisions just goes to increase the energy of other electrons of about the same energy. Thus, primary energy losses for this plasma take the form of thermal conductive and convective losses, together with free-streaming of the very high energy component of the distribution function. These losses can be considerably less than the collisional losses in models where $E_e \gg kT$. Consequently, less flare energy is required for a given observed hard X-ray fluence.

It is quite clear from the foregoing that fundamental questions relating to energy release and particle acceleration in solar flares remain unanswered. While very substantial amounts of energy must be contained in the hard X-ray producing electrons, this energy still can not be reliably calculated because it is not known whether the X-ray source is predominantly thermal or nonthermal. A suitable hybrid model, involving both particle acceleration and direct heating, may be required to account adequately for all of the observed complexities and subtleties of flare emission.

The discovery of hard X-ray microflares (Lin *et al.* 1984), impulsive bursts up to $\sim$100 times less intense than normal flares, suggests that the flare process may be a fundamental way by which stored magnetic energy is released in the Sun's corona. During $\lesssim 2$ hours of balloon observations, one microflare was detected every $\sim$5 minutes. These microflares last $\sim$10 s and have power-law spectral shapes, similar to normal flares. If the spectrum extends down to $\sim$5 keV, as appears to be the case, the rate of energy release in accelerated electrons in the observed microflares averages $\sim 3 \times 10^{26}$ ergs/sec, which is a significant fraction of the total power required to heat the active corona. The occurrence frequency for normal flare hard X-ray bursts (Dennis 1985) is observed to vary as $\frac{dN}{dI_x} \propto I_x^{-1.8}$, where I_x is the peak hard X-ray intensity, and a similar dependence is seen for microflares (Figure 2.1). Thus, significant additional energy could be released by even smaller events below the observational threshold.

2.2 Gamma Rays and Neutrons – Diagnostics of Ions and Relativistic Electrons

Gamma-ray and neutron emissions from solar flares are signatures of ion and relativistic electron interactions (e.g., Ramaty and Murphy 1987). Gamma-ray bremsstrahlung continuum from primary relativistic electrons has been observed up to at least 100 MeV (Forrest *et al.* 1985). Gamma-ray lines are produced in nuclear reactions of accelerated protons and heavier nuclei interacting with the ambient solar atmosphere. A rich spectrum of lines, resulting from de-excitations of all the abundant constituents of the solar atmosphere up to Fe, has been observed from many flares (Chupp 1984; Murphy *et al.* 1990b). Such a spectrum is shown in Figure 2.2a taken from Murphy *et al.* (1991), with the predicted spectrum shown in Figure 2.2b. The nuclear reactions also lead to the production of neutrons and positrons. Capture of neutrons in the photosphere produces the 2.223-MeV line. This very narrow line is the strongest observed line from solar flares, except when the flare is close to the solar limb (Wang and Ramaty 1974; Chupp 1982). Annihilation of positrons produces the 0.511-MeV line, whose shape and accompanying positronium annihilation continuum are sensitive probes of the temperature, density, and state of ionization of the ambient solar atmosphere (Crannell *et al.* 1976). Neutrons from flares have been detected directly (Chupp *et al.* 1987), as have the protons resulting from the decay of the neutrons in interplanetary space (Evenson *et al.* 1983). The nuclear reactions also produce pions (Murphy, Dermer, and Ramaty 1987; Mandzhavidze 1987) and these have been detected through their decay products. The neutral pions decay into gamma rays directly. The charged pions produce secondary positrons and electrons, which produce bremsstrahlung gamma rays. In addition, the positrons also produce high-energy photons by annihilating in flight. The resultant high-energy gamma-ray emission (> 10 MeV) has been observed from several flares (Rieger 1989).
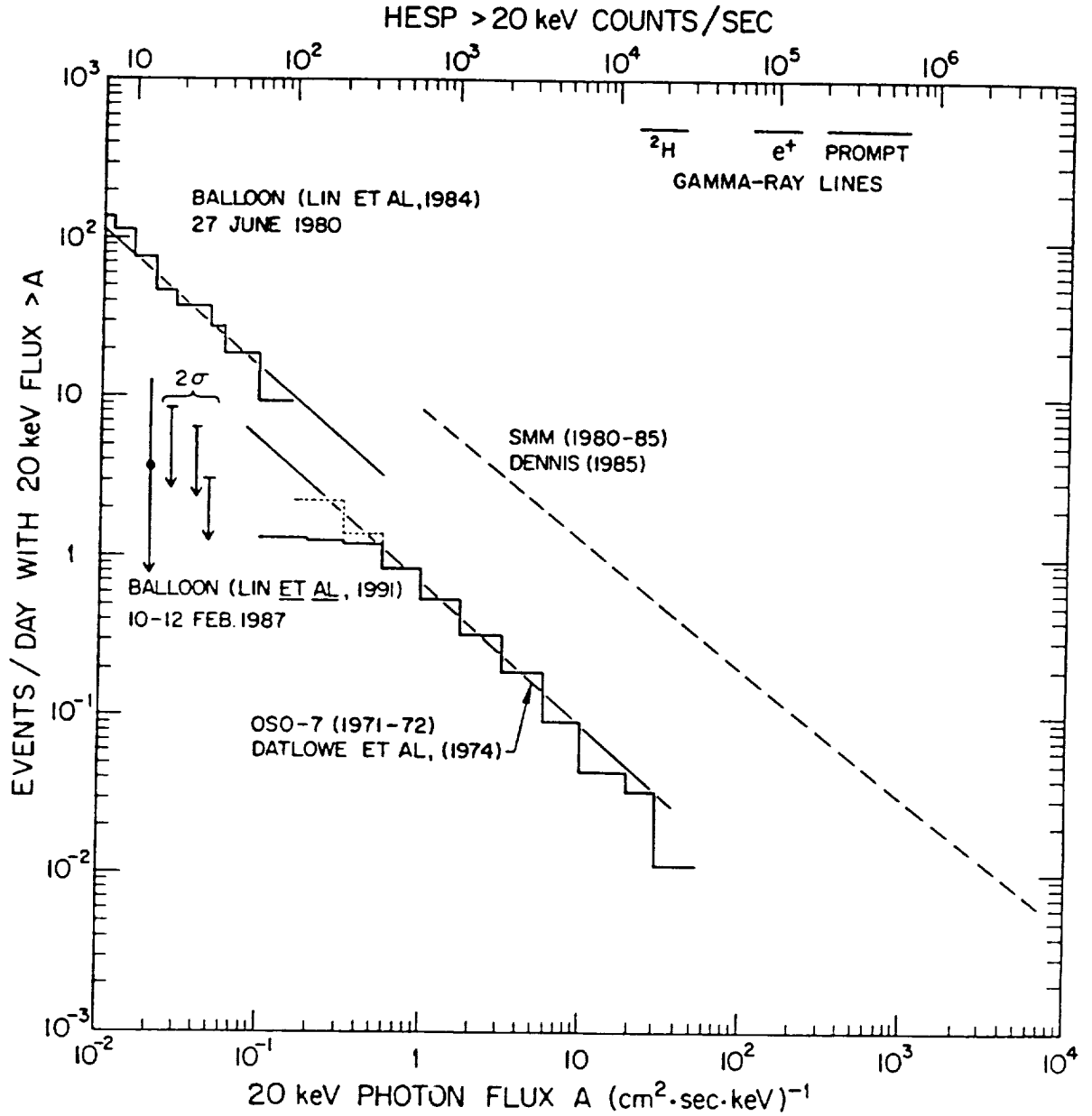
Figure 2.1 The distribution of the integral rate of occurrence of events vs. peak 20 keV photon flux for flares and microflares. The scale on top gives the >20 keV counting rate for **HESP**. In the upper right corner, the 3σ detection threshold for the 2.223 MeV deuterium line, the 0.511 MeV positron annihilation line, the prompt de-excitation lines of Ne, Mg, Si, C, N, O, Fe, etc., are indicated.
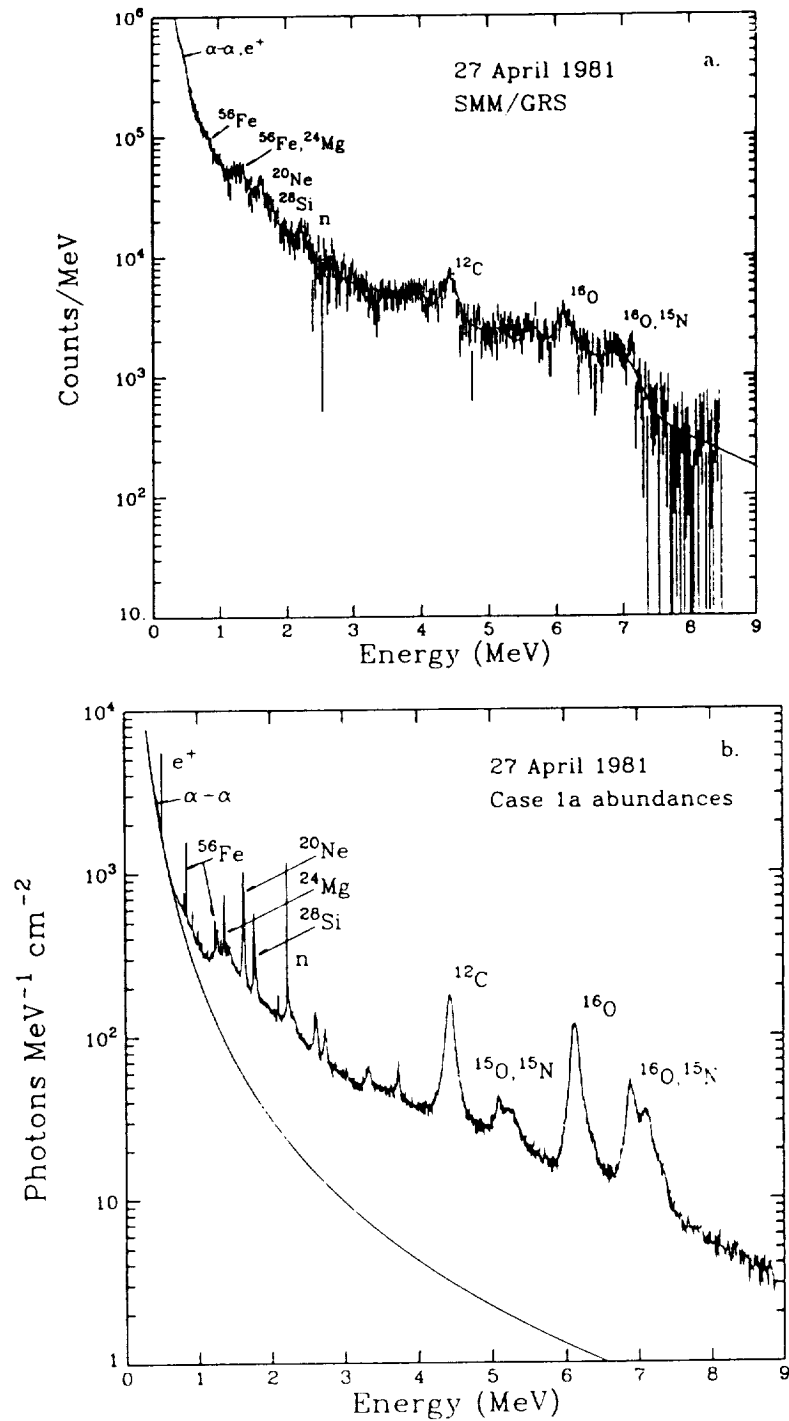
Figure 2.2a. Count spectrum of the 27 April 1981 flare measured with the NaI(Tl) gamma-ray spectrometer on **SMM**, together with a best-fit calculated spectrum.

Figure 2.2b. The corresponding calculated incident photon spectrum showing the ions responsible for many of the lines. The smooth curve represents the bremsstrahlung fluence. Clearly, much more information will be obtained with high resolution Ge detectors since they will be able to identify and resolve the individual lines seen in the calculated spectrum.

Before observations with the gamma-ray spectrometer on SMM, it was thought that only subrelativistic electrons are accelerated impulsively in flares. While the acceleration of ions in flares was established much earlier by direct particle observations in interplanetary space, it was thought that this acceleration is merely a secondary phenomenon that occasionally accompanies the much more frequent impulsive acceleration of electrons. This now appears not to be the case. Ion and relativistic electron acceleration, as evidenced by impulsive gamma-ray emission observed from many flares, must also be closely linked to the primary energy-release mechanisms. Relativistic neutrons and prompt gamma rays from pion decay have also been observed. Produced in GeV ion interactions, these emissions show that the acceleration of these highest energy particles is also quite impulsive, with the lag, if any, between the acceleration of MeV and GeV protons being less than about 10 seconds. The energy contained in ions above 10 MeV, reliably determined from the gamma-ray observations, amounts to at least several percent of the flare energy. Even more energy could be contained in lower energy ions. The ions in gamma-ray flares are most probably accelerated in closed magnetic loops and forced to interact in the loops. This follows from the comparison of the number of interacting particles (as derived from the gamma-ray data) and escaping particles (as deduced from interplanetary particle observations), which shows that many more particles interact than escape (Cliver et al. 1989). In some large solar energetic particle events, however, more particles escape than interact to produce gamma rays.

A variety of other interesting results have already been obtained from analysis of gamma-ray data. It has been shown that elemental abundances can be derived for both the ambient gas and the accelerated particle population (Murphy et al. 1991). The derived accelerated particle abundances resemble more closely the particle abundances measured in interplanetary space from impulsive solar flares rather than from large proton flares. The composition of the particles accelerated in impulsive flares exhibits strong enhancements of heavy elements. On the other hand, the composition of the particles seen in large proton events resembles that of the corona (e.g., Reames 1990). The fact that the accelerated particle composition deduced from the gamma-ray data agrees with that for particles observed escaping to interplanetary space from impulsive flares supports the result obtained from the timing observations, namely that the gamma-ray production is a direct consequence of the primary energy release.

The shapes of the gamma-ray lines are sensitive functions of the angular distribution of the interacting ions, which, in turn, depends on the acceleration and transport processes (Murphy et al. 1990a). Magnetic mirroring has been shown to play an important role in ion and relativistic electron transport (MacKinnon and Brown 1989; Miller and Ramaty 1989; Hulot et al. 1989; Gueglenko et al. 1990). This is because the stopping ranges of the high-energy particles are sufficiently long to allow the particles to sample the chromospheric magnetic field gradient. Thus, the distribution on the solar disk of the locations of flares observed at energies greater than 10 MeV (Rieger 1989) turns out to be a sensitive probe of the topology of the magnetic field in the chromospheric portions of magnetic loops.

2.3 Energy Release, Acceleration, and Transport

From the foregoing discussion, we can identify the following critical questions:

1. How can a large fraction of the available magnetic field energy be released on a short time scale?

2. What process converts much of the released energy into accelerated particles?

3. How can ions be accelerated up to GeV energies and electrons up to $\gtrsim 100$ MeV, essentially simultaneously, on time scales of less than a few seconds?

4. What is the nature of the magnetic field structures in which the acceleration and transport occur?

5. What is the origin of the many compositional anomalies (enhancements of e.g., Fe/C and ^{3}He/^{4}He) that seem to characterize the acceleration process?

6. Are these same energy release and particle acceleration processes responsible for the heating of the active corona?

Magnetic structures or "loops" in the chromosphere and corona appear to play a pivotal role in the triggering and development of the flare process, either by interacting with each other or by relaxing from a pre-stressed state. However, order-of-magnitude calculations, using classical plasma parameters (such as resistivity), suggest that the timescale for energy release over observable dimensions ought to be much longer than typical flare timescales. This implies that these plasma parameters have highly nonclassical values, for which large electric fields with modest current densities could be established. Clearly, these electric fields are directly or indirectly involved in the energization of the hard X-ray producing electrons. We do not understand the details of the process, but believe that the observation of hard X-rays from the original energy release site, or from sites as close as possible to it, will ultimately lead to the solution of the problem.

In addition to energization by electric fields, other acceleration mechanisms have also been considered, especially for ions and relativistic electrons (see Forman *et al.* 1986). One candidate process is the mechanism proposed by Fermi to explain the origin of the cosmic rays. In the modern version of this mechanism the particles are accelerated stochastically due to resonant interactions with magnetohydrodynamic turbulence. Alfvén turbulence is particularly promising, since ion acceleration can be one of the dominant damping modes of such turbulence. Resonant interactions with Alfvén turbulence, however, require that the energies of the particles exceed an injection threshold which, for solar flare conditions, is several tens of keV for ions and about 10 MeV for electrons. The existence of a threshold energy seems essential for providing an explanation for the compositional anomalies, provided that suitable preacceleration processes can be found, which would preferentially energize some of the particles. An example is the ^{3}He preheating mechanism by ion cyclotron waves proposed by Fisk (1978). Furthermore, as recently proposed (Miller 1991), protons and heavier ions could be preheated by the nonlinear damping of the same Alfvén waves which subsequently accelerate them. Likewise, electrons could be accelerated to MeV energies by resonant interactions with whistler waves (Melrose 1974; Miller and Ramaty 1987). However, since there appears to be a high degree of correlation between the various observed particle populations (impulsive flares always produce heavy element

and ^{3}He enrichments), if the preheating and acceleration are due to wave turbulence, an essential condition that must be satisfied is that all of the required turbulence develop practically simultaneously and on a very short time scale.

Particles could also be accelerated by shocks, in particular if there is upstream and downstream turbulence, so that the particles crossing the shock can scatter back and forth, remain trapped around the shock, and gain energy each time they cross the front. This mechanism has been successfully applied to interplanetary shocks and planetary bow shock, where both the shocks and the accelerated particles are observed *in situ* (see Jones and Ellison, 1991, for a recent review). Shock acceleration could be responsible for the acceleration of particles in large proton events, the composition of which, as pointed out above, is similar to that of the corona.

While it is generally expected that the energy release and particle acceleration would occur in the coronal portions of the loops, the location of the site or sites of particle energization remains to be settled observationally.

2.4 Non-Solar Scientific Objectives

With its combination of high spectral and unmatched spatial resolution, **HESP** can make significant advances in non-solar hard X-ray and gamma-ray astrophysics. Below we describe some of the scientific issues that will be addressed with **HESP**.

1. In the course of normal solar-pointed operations, **HESP** will also make unique observations of cosmic hard X-ray and gamma-ray sources located within about ±25° degrees of the ecliptic plane. This band includes the galactic-center region with numerous X-ray pulsar and burst sources, as well as the Crab Nebula and 3C273. Sources within this band will be viewed for tens of days each year, so temporal variations can be studied in detail. The source positions will be determined to better than 1°, and high resolution hard X-ray and gamma-ray spectra will be obtained for each individual source. These spectra can be used to search for features such as cyclotron line emission or absorption from magnetized neutron star sources.

2. **HESP** can determine the large scale structure of the diffuse galactic emissions in the positron annihilation line and the ^{26}Al line, both of which have been attributed to nucleosynthesis in supernovae and novae. **HESP** will be able to follow the evolution of the variable 511 keV line emission for about a month every year from what is believed to be a few solar mass black hole source near the galactic center.

3. **HESP** will provide high resolution spectra for the tens of cosmic gamma-ray bursts which occur in its 50° FWHM field of view each year. These spectra and their temporal evolution can be used for the detailed study of cyclotron lines, gravitationally red-shifted positron annihilation lines, and any other spectral features.

4. With 5-10° offset pointing from the Sun, extended sources such as the Crab Nebula and 3C273 can be imaged with unprecedented (a few arcsecond) resolution in the hard X-ray and gamma-ray range. These images will give detailed information on the distribution of energetic electrons in these sources. In addition, fine imaging of the galactic center region can provide individual source spectra and arcsecond positions for the multiple sources in that region.

3. WHAT WE CAN EXPECT FROM THE HESP OBSERVATIONS

3.1 Subrelativistic Electrons

The high spatial, spectral, and temporal resolving power of **HESP**, together with **HESP**'s unprecedented sensitivity and coverage over the entire energy range from thermal to relativistic energies, are needed to unravel the solar flare problem. In the flare environment in the lower corona and upper chromosphere, where densities are typically 10^{10} to 10^{12} cm^{-3}, electrons with deka-keV energies will suffer significant energy loss on spatial and temporal scales of several arcseconds and a few tens of milliseconds, respectively. All previous observations of solar hard X-ray spectra have integrated over both spatial and temporal scales that are significantly larger than these values. On the other hand, **HESP** has the capability to provide high-quality spectra in 2-arcsecond "pixels" and on timescales of $\sim$15 ms. Since no significant energy loss occurs over the spatial extent of the "pixel" or over the duration of the observation, **HESP** will be able to unambiguously determine the variation of the electron phase-space distribution function of the electrons (or, more precisely, their line of sight and velocity-direction integrated moment) from point to point, and time to time. The results will provide answers to the following questions:

(1) How much energy is contained in the accelerated electrons and in hot plasma?

   HESP's fine spatial, spectral, and temporal resolution will be able to separate the hot thermal plasma from the accelerated electrons in most cases. The high spectral resolution and complete energy coverage will accurately define the spectrum of the accelerated electrons including the low-energy cutoff, and will clearly show the evolution of the spectral form across the thermal, superhot and nonthermal energy ranges.

(2) Where is the flare energy released?

   With its high sensitivity and temporal resolution, **HESP** should be able to detect and locate the X-ray emission of energetic electrons accelerated in the initial flare energy release in the corona, before the electrons propagate to other parts of the flare.

(3) What is the spectrum of the accelerated electrons and how does it vary spatially and temporally?

   Because the bremsstrahlung cross-sections are well known (Koch and Motz 1959), the high spectral resolution measurements of **HESP** can be deconvolved to obtain the parent X-ray producing electron spectrum (Johns and Lin 1991). This electron spectrum represents a balance between sources (acceleration) and losses such as Coulomb collisions. With the high spectral sensitivity of **HESP** and its temporal and spatial resolution, it will be possible to accurately assess losses and therefore derive the accelerated electron source spectrum.

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(4) What are the conditions in the energy release/particle acceleration regions?

The plasma conditions and the magnetic structure of the energy release and particle acceleration regions can be obtained from **HESP** soft X-ray observations. Plasma at temperatures between 10^6 and 10^8 K can be imaged, and these images trace out (with 2-arcsecond resolution) the magnetic configuration before, during, and after the flare. The slow preflare heating that is seen as a gradual rise in the broadband soft X-ray flux will be studied in detail with **HESP**. In addition synoptic soft X-ray images at lower energies will be provided by the **GOES** spacecraft (expected to begin in 1995 to 1996).

It is generally recognized that high current densities (i.e., high magnetic "shear") are a prerequisite for flare activity. The regions of strong magnetic shear can be seen in vector magnetograms obtained from ground-based observations. By combining these observations with spatially resolved hard X-ray observations (to indicate the location of the electron precipitation) and with spatially-resolved soft X-ray observations (showing regions of enhanced coronal pressure resulting from evaporation of heated chromospheric material), much will be learned about the processes of energy release, particle acceleration, and transport. Ground-based microwave imaging spectroscopy can provide magnetic fields, densities, and temperatures at coronal altitudes; and Hα observations can map magnetic field structure and energy deposition sites at chromospheric levels for comparison with the hard X-ray and gamma-ray images.

(5) How is energy transported and lost in flares?

HESP will be able to trace the propagation and energy loss of the accelerated electrons, and the evolution of hot thermal plasma in the flare. By following the spectral evolution in both space and time, we will differentiate between the energy loss rate expected for a beam of electrons that is losing energy solely by Coulomb collisions and a beam losing energy by wave-particle interactions, for example. Such information will provide unique signatures for the different energy transport and energy-loss processes occurring in flares. Combined with ground-based optical, radio, and magnetograph observations, it will allow the flow of energy to be determined throughout the flare.

(6) What is the nature of coronal particle acceleration and storage in flares?

The very high sensitivity of **HESP** will provide electron spectra and spatial size and location for type III–V bursts, shocks/radio type-II events, and coronal mass ejection/radio moving type-IV sources, and for coronal storage regions of energetic particles.

(7) What is the nature of microflares and how are they related to the heating of the active corona?

HESP will be able to obtain the location and size of hard X-ray microflares and will determine how much energy is released by measuring the low energy extent of the electron spectrum. **HESP** will also measure the soft X-ray emission of the active regions to obtain the rate of energy dissipated for comparison.

3.2 Ions and Relativistic Electrons

As already mentioned, gamma-ray emission from solar flares has not yet been observed with high resolution germanium detectors on spacecraft (except for a very limited observation with **HEAO-3** in 1979), and neither the gamma-ray nor the neutron emissions have been imaged. Figures 2a and 2b show the improvements over gamma-ray spectra obtained with scintillators that are possible with germanium detectors. We can expect the following results from the high resolution gamma-ray imaging spectroscopy of **HESP**:

(1) The angular distribution of the interacting ions.

This will be achieved by making precise measurements of the shapes of the various prompt de-excitation gamma-ray lines. It has been shown (Murphy *et al.* 1989) that the shapes of such lines, in particular those of the 0.429- and 0.478-MeV lines of ^{7}Be and ^{7}Li produced in interactions of accelerated alpha particles with ambient He, are very sensitive to the angular distribution of the alpha particles. These distributions, in turn, depend on the acceleration mechanism and on the transport model, with effects such as magnetic mirroring and pitch-angle scattering playing a decisive role. For example, it should be possible to gain information on the level of Alfvén turbulence in the corona by observing in detail the shapes of these lines.

(2) Abundances in both the ambient gas and the accelerated particles.

The high spectral capabilities of **HESP** will lead to much more accurate results than those achieved with the gamma-ray spectrometer on SMM. Individual lines from many more elements will be resolved. In particular, in the energy region between 1 and 2 MeV, there are many lines from Ne, Mg, Si, and Fe, and these were only poorly resolved by SMM observations. **HESP** observations, with the much higher spectral resolving power of the Ge detectors, will allow the determination of the abundances of these elements for many flares. The SMM observations have already shown that the abundances of these elements relative to C and O differ from photospheric abundances, with the variation possibly correlated with the first ionization potential of the elements. Such a correlation could be caused by charge-dependent mass transport from the photosphere to the corona. The differences between the coronal and photospheric K/Ar and Ca/Ar ratios inferred from X-ray observations (Doschek *et al.* 1985) are consistent with this correlation. Gamma-ray observations made with **HESP** will also provide information on the photospheric abundance of ^{3}He from the time profile of the 2.223-MeV line (Wang and Ramaty 1974, Hua and Lingenfelter 1987). The ^{3}He abundance is of importance to cosmology as well as to our understanding of the burning and mixing processes in the solar interior.

Abundances of the accelerated protons and alpha particles can be obtained by comparing the proton induced gamma-ray lines with the alpha-induced lines. The broad continuum between $\sim$2 and 8 MeV is produced by the inverse process of fast heavy nuclei colliding with ambient hydrogen and helium in the solar atmosphere. This continuum can be modeled to provide abundances of the accelerated heavy ions (Murphy et al. 1990). For large gamma-ray flares separate images in accelerated

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protons, alphas and heavy nuclei could detect spatial variations in the composition of the accelerated particles.

(3) Densities and Temperatures of the Ambient Gas.

Observations with **HESP** of the time dependence and spectrum of positron annihilation radiation will provide information on densities and temperatures at the sites where these particles annihilate. This site is probably also the interaction site of the accelerated protons. The time profile of the 0.511 MeV line observed with poor time resolution on SMM (Share *et al.* 1983) suggests that the positrons slow down and annihilate in less than several seconds, implying an ambient density of $>10^{12}$ cm^{-3}. The **HESP** energy resolution at 0.511 MeV ($\sim$1 keV) is sufficiently good to measure the temperature of the annihilation site down to 10^4 K. Furthermore, the 0.511-MeV line should be accompanied by a characteristic continuum resulting from positronium annihilation if the density of the ambient medium is less than about 10^{15} cm^{-3} (Crannell *et al.* 1976). This continuum will also be detectable with **HESP**.

(4) The frequency of flares accelerating ions.

A very important question is whether protons are accelerated in all flares or only in the more energetic ones. A definitive indicator of the presence of high-energy protons is the 2.223-MeV line, which, as already mentioned, is the strongest gamma-ray line (except for flares near the limb) and intrinsically very narrow. Because of its high energy resolution and low background, **HESP** is a factor of at least 20 more sensitive in this line than the gamma-ray spectrometer on SMM. Consequently, if ions are accelerated in all flares, and the gamma ray emission scales as the microwave emission, **HESP** will detect $\sim$10 flares per month in the 2.223-MeV line near solar maximum.

(5) Spectroscopy of individual loop foot points.

We expect the gamma rays to be produced at loop foot points. If large-scale, field-aligned electric fields exist in the loops, the positively charged ions would interact preferentially at one foot point while the electrons would interact at the other. Such effects, observable with **HESP**, would lead to different gamma-ray line-to-continuum ratios at the two foot points, as the lines are produced by the ions, while the continuum results from the electrons. Electric fields could also preferentially drive the positrons into one foot point, producing a much stronger 0.511-MeV line at this foot point than at the other. Imaging spectroscopy with **HESP**, therefore, could lead to unambiguous evidence for electric fields in the loops. Such a result would be of fundamental importance in establishing the acceleration mechanism responsible for these high-energy particles.

(6) Separation of the gamma-ray emission produced in the coronal portions of the loops from that produced at the foot points.

The fraction of the gamma-ray emission produced in the coronal portion of the loop depends on the amount of mirroring and pitch-angle scattering suffered by the particles in the loop. If a significant fraction of the emission comes from the coronal portions, the ions and relativistic electrons will have to remain trapped in the corona,

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most likely due to mirroring in convergent magnetic flux tubes. Pitch-angle scattering, however, will tend to remove the particles by scattering them into the loss cone. The rate of such scattering should depend on the energy of the particle. Thus, much information will come from imaging the loops at various gamma-ray energies. Imaging in nuclear lines provides information on ions of tens of MeV, while imaging of the pion-decay emission provides information on GeV ions.

(7) Search for large gamma-ray sources or many individual localized sources.

A possible model for the production of pion-decay radiation observed over long time scales ($\sim$ 1000 s) involves the acceleration of ions by a large-scale shock moving outward in the solar atmosphere with some of the accelerated particles "raining" back onto the denser layers of the atmosphere. In this model, we expect gamma-ray emission to come from a large part of the solar disk, as either diffuse emission or localized emission from a number of point sources, depending on the structure of the magnetic fields. **HESP** imaging of the pion-decay radiation will distinguish between these possibilities.

(8) Images of 2.223-MeV line emission.

This line is known to be produced in the photosphere by neutrons traveling from the ion interaction site downwards toward the photosphere. Depending on the height of the production site and the initial angular distribution of the neutrons, the 2.223-MeV source on the photosphere could be quite large scale size, possibly tens of arcseconds, and hence could be spatially resolved with **HESP**. Of particular interest will be to determine the relative positions of the centroids of the 2.223-MeV source and the nuclear de-excitation line source, which is also the source of the neutrons. For flares located midway between the limb and disk center, the displacement between these centroids will determine the altitude of the ion interaction site.

(9) Imaging of the gamma-ray and neutron emissions for flares behind the limb of the Sun.

It is possible that the accelerated particles are transported over large distances to interact at sites substantially removed from the site of the primary energy release. Such transport will allow the observation of gamma rays and neutrons from flares behind the limb. The imaging of these gamma rays and neutrons will be particularly interesting.

3.3 Expected Performance of HESP

It is important to realize that **HESP** will provide hard X-ray imaging spectroscopy, not just for a few flares, but for many thousands of flares in its 3-year lifetime. Figure 2.1 shows the integral distribution of solar flare bursts versus peak 20-keV hard X-ray flux as measured at different times in the solar cycle and with different detectors. The SMM distribution from the Hard X-Ray Burst Spectrometer (**HXRBS**) is indicative of the period near the maximum and on the declining phase. The balloon measurements on the

left show that the microflare distribution has essentially the same power-law slope. The expected $\geq$ 20 keV count rate for the **HESP** instrument is shown at the top of the plot.

The **HESP** background rate at energies between $\sim$20 and 100 keV will be dominated by the diffuse sky emission. The total rate from this component, summed over all 12 Ge detectors, is expected to be $\sim$5 counts s^{-1} between 20 and 50 keV. Thus, microflares, which last $\sim$10 s, would be detectable at the 3σ level down to a few **HESP** counts s^{-1} per detector or down to a 20-keV photon flux of $\sim$3 x 10^{-3} (cm^2 s keV)$^{-1}$. Since a minimum of about a hundred counts are needed to form a simple image, the location and spatial size of mircroflares could be determined with **HESP** for events as small as $\sim$2 x 10^{-2} photons (cm^2 keV)$^{-1}$.

The smallest bursts detectable by the **SMM HXRBS** instrument would give $\sim$10^3 counts s^{-1} above 20 keV in **HESP**. In those events, rapid spatial changes in the X-ray sources could be followed on time scales of 0.1 s. Imaging spectroscopy, i.e., obtaining the spectrum as a function of spatial location, could be done with simple images in each of ten energy intervals with $\sim$1-s resolution. For the once-per-day flare (i.e., 10^4 **HESP** counts s^{-1} above 20 keV), imaging information could be obtained every 10 ms and imaging spectroscopy every $\sim$100 ms. For a once-per-ten-day flare, these time scales can be reduced by about a factor of ten, with the limit for obtaining spatial information being $\sim$1 ms at the finest spatial resolution of 2 arcseconds.

HESP will provide, for the first time, images and high resolution spectroscopy of gamma-ray lines and continuum for solar flares. Assuming that every flare accelerates ions with fluxes proportional to the hard X-ray flux, the 3-σ detection thresholds for the 2.223-MeV neutron-capture deuterium line, the 0.511-MeV positron annihilation line, and prompt nuclear deexcitation lines of Ne, Mg, Si, C, O, N, Fe are indicated on Figure 2.1.

Thus, the 2.223-MeV line should be detected, on average, once every $\sim$2 to 3 days, the positron annihilation line every $\sim$10 days, and prompt nuclear lines every 20 days. Table 3.1 lists the narrow gamma-ray lines and their widths and fluxes expected for a large gamma-ray flare, such as the 27 April 1981 flare (Murphy et al, 1990). (Measured and predicted spectra for this flare are shown in Figure 2.2) Also listed in Table 3.1 are the expected total photopeak counts in **HESP**. These narrow lines are produced by protons or alpha particles colliding with the hydrogen or helium of the solar atmosphere. The primary background is the continuum emission from the flare itself. This consists of two components – bremsstrahlung emission produced by relativistic electrons, and broad lines produced by the inverse process of accelerated heavy ions colliding with hydrogen and helium in the solar atmosphere. The line-to-continuum ratio is $\sim$3 to 10 for the narrow, prompt, inelastic-scatter lines in this flare, but these ratios appear to vary from flare to flare. The line widths are typically 5 to 10 times narrower than the energy resolution of scintillation detectors (see Figure 4.3). The high spectral resolution of Ge detectors is, thus, essential in order to obtain unambiguous images of the accelerated ions.

For a large flare such as that on 27 April 1981, it will be possible to obtain separate images of the energetic protons (from the sum of the narrow lines produced by proton excitation) and the energetic alphas (from the alpha-excited lines such as the 0.454-MeV Li-Be lines). At the same time, the analysis of the line shapes will provide information on the angular distribution of the energetic protons and alpha particles. In addition, a separate image

can be obtained from the ~4-8 MeV continuum, which, for flares like 27 April 1981, is dominated by the broad lines produced by energetic heavy nuclei.

Images in the delayed 2.223-MeV line would delineate the neutron capture region, which should be in the photosphere since high densities are required to slow the neutrons down. The size of the neutron capture region should be indicative of the height and size of the neutron production region. Images in the 511-keV lines will show where positrons are annihilating. Since positrons are charged, they will be guided by the magnetic structure where they are produced. Furthermore, the 0.511-MeV line width and shape will give information on the density and temperature of the annihilation region. Finally, imaging in π^0-decay photons and energetic neutrons will show where the highest energy ions (several hundred MeV to GeV) are interacting.

3.4 HESP Performance for Cosmic Sources

The HESP detectors have a field of view of ~50° FWHM, set by the anticoincidence shield and collimator, so in the course of normal operation HESP will scan the sky within about ±25° of the ecliptic plane. The lower grid further limits the field of view to ~1° FWHM in one dimension so that, as the spacecraft spins, the 1° by 50° FOV rotates across the sky, enabling cosmic hard X-ray and gamma-ray sources to be located to $\lesssim 1°$.

A given source in the ±25° band around the ecliptic plane will be viewed for tens of days each year with a typical on-source accumulation of a few 10^5 seconds each year. Based on estimates of the detector background, we expect that hard X-ray sources with an intensity of one thousandth the Crab could be detected at greater than 3σ significance. Thus, HESP will map such sources within ±25° of the ecliptic plane, obtain high resolution spectra for each source, and monitor sources for temporal variability over tens of days each year.

With its 50° FWHM field of view, HESP should also detect tens of cosmic gamma-ray bursts every year. For each CGRB detected, high resolution spectra will be obtained as well as the temporal profile of the burst and position information to about 1°.

The slow movement of the Sun across the sky will permit mapping of the galactic diffuse positron annihilation (511 keV) line emission and of the ^{26}Al line emission.

Finally, with offset pointing of up to 10° from the Sun, extended sources such as the Crab Nebula and 3C273 could be imaged with a few arcseconds resolution. Such imaging could also provide accurate positions and individual high resolution spectra of the multiple sources in the crowded galactic-center region.

Table 3.1. Solar Flare Gamma-Ray Lines*

Line Energy (MeV)	Excited Nucleus	Fluence (ph/cm^2)	HESP Counts	Line Width ** (keV)
$0.454 \begin{bmatrix} 0.429 \\ 0.478 \end{bmatrix}$ •••	^{7}Be ^{7}Li	22	1.5×10^3	$84 \begin{bmatrix} 5 \\ 10 \end{bmatrix}$ •••
0.847	^{56}Fe	5	280	5
1.02	— †	9	460	30
1.238	^{56}Fe	11	520	7
1.369	^{24}Mg	23	1070	15
1.634	^{20}Ne	22	980	22
1.778	^{28}Si	8	300	20
4.439	^{12}C	17	260	97
~5.3	^{15}O, ^{15}N	9	100	—
6.129	^{16}O	20	180	114
~7	^{16}O, ^{15}N	15	110	—
DELAYED LINES				
0.511	e^+	20	1.3×10^3	3 – 10
2.223	^{2}H	13 (60) ‡	460 (2.1×10^3) ‡	≤ 0.1

*   Based on 27 April 1981 flare (Murphy *et al.*, 1990).

**   Theoretical line widths.

***   84 keV is the width for isotropic incoming α-particles. For beam distribution the Be and Li lines separate with widths of 5 and 10 keV respectively.

†   Believed to be due to α-particle excitation of Fe.

‡   The 2.223 MeV line for 27 April 1981 flare is highly attenuated because the flare is near the limb; the fluence of 60 is expected for a comparable flare within 70° of disk center.

4. THE HIGH ENERGY IMAGING SPECTROMETER (HEISPEC)

The **HESP** payload consists of a single instrument, **HEISPEC** (Figure 4.1), that is designed to image the entire range of flare energetic photons from soft X-rays ($\sim$2 keV), to π^0 decay gamma-rays ($\gtrsim$ 200 MeV), as well as energetic neutrons. Furthermore, **HEISPEC** has the capability to perform spatially resolved spectroscopy with high spectral resolution, to allow the full diagnostic power of hard X-rays and gamma-rays to be applied on a point-by-point basis within solar flares. Table 4.1 summarizes the characteristics of **HEISPEC**.

The imaging is based on a Fourier transform technique using a set of rotating modulation collimators (RMC's), each of which is similar to those used on previous missions such as the US **SAS–C** and the Japanese **Hinotori** spacecraft. The technique is illustrated schematically in Figure 4.2. Each RMC consists of two widely-spaced, fine-scale linear grids, which temporally modulate the photon signal from sources in the field of view as the RMC rotates about its long axis. The modulation can be measured with a detector having no spatial resolution placed behind the RMC. The modulation pattern over half a spin for a single RMC provides the amplitude and phase of many spatial Fourier components over a full range of angular orientations but for a single spatial size. Multiple RMC's, each with a different slit width, can provide coverage over a full spectrum of flare source sizes. An image is constructed from the set of measured Fourier components in exact mathematical analogy to multi-baseline radio interferometry.

The grid diameters and thicknesses are chosen to give full-Sun fields of view. Thus, upper and lower grids have diameters of 12.5 cm and 7.5 cm, respectively, and grid thicknesses range from $\sim$2.8 mm for the finest (100-micron pitch) grids up to a maximum chosen thickness of 4 cm. With $\sim$5-m separation between the grids, **HESP** will provide spatial resolution of $\sim$2 arcseconds at hard X-ray energies (below $\sim$400 keV), 4-8 arcseconds for gamma-ray lines and continuum above $\sim$0.5 MeV, and $\sim$40 arc seconds for neutrons.

The chosen rotation rate of $\sim$15 rpm provides a complete image with the maximum number of Fourier components ($\sim$5 x 10^3) in 2 s, but some spatial information is available on timescales down to $\sim$1 ms, provided the count rates are sufficiently high.

Behind the RMC's, dual-segment coaxial germanium detectors cooled to $\sim$85 K provide high spectral resolution from $\sim$10 keV to $\gtrsim$ 20 MeV. The segmentation allows undistorted high resolution gamma-ray line measurements in the presence of very intense hard X-ray fluxes in large flares. The spectral resolution of Ge detectors is sufficient to resolve all of the solar gamma-ray lines with the exception of the neutron-capture deuterium line, which has an expected FWHM of about 0.1 keV. This capability is illustrated in Figure 4.3, where the spectral resolution of the two-segment Ge detectors is compared with the typical line widths expected for gamma-rays in solar flares. It should be noted that high spectral resolution is also required to resolve sharp breaks in the non-thermal continuum and the steep super-hot thermal component of solar flares. Shown for comparison are the resolutions of the hard X-ray and gamma-ray spectrometers on **SMM**.

The bismuth germanate (BGO) scintillator acts as an active anti-coincidence shield and collimator to reduce the background, provide excellent Compton rejection, and extend the energy range to $\gtrsim$ 100 MeV for moderate spectral and spatial resolution gamma-ray
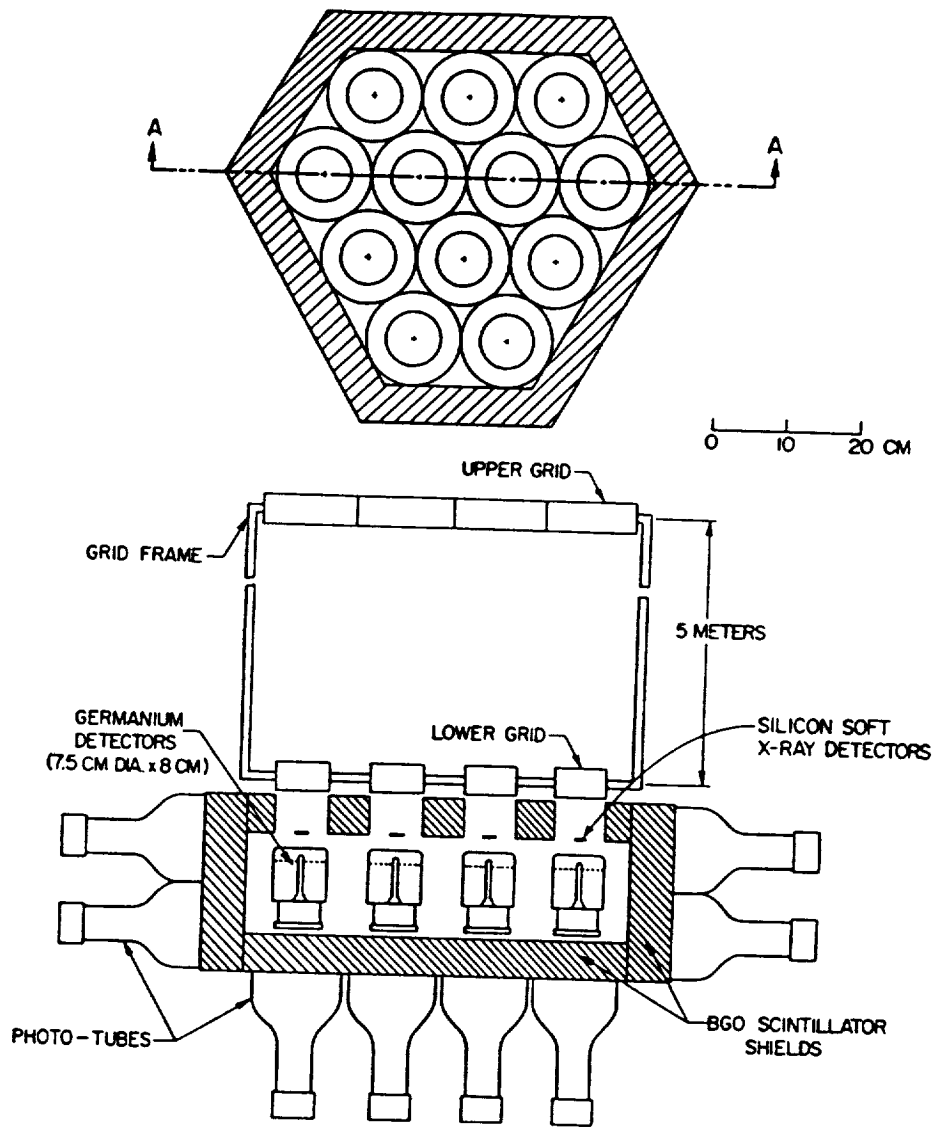
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Figure 4.1. Schematic cross-sections of the High Energy Imaging Spectrometer (**HEI-SPEC**). The upper and lower tungsten grids separated by 5 m, form the rotating modulation collimators (RMC's). The two-segment germanium detectors provide high spectral resolution measurements from ∼10 keV to 20 MeV. The combination of the Ge detectors and the bismuth germanate (BGO) shield extends the gamma-ray range to >200 MeV and provides neutron coverage from ∼20 MeV to ∼1 GeV. The silicon detectors cover the energy range from ∼2 keV to $\gtrsim$ 20 keV. The BGO shield and collimator form an active anti-coincidence shield to reduce the background.

Table 4.1. Characteristics of HEISPEC

Imaging

Technique: Fourier-transform imaging with rotating modulation collimators (RMC)

Angular resolution:
~2 arcsecond — 2 to 400 keV X-rays
~4–8 arcseconds — 0.4 to $\geq$200 MeV γ-rays
~40 arcseconds — ~20 MeV to 1 GeV neutrons

Field of view: Full Sun (0.6 degrees)

Temporal resolution: ~ tens of milliseconds for basic image, 1 sec for detailed image

Spectroscopy	Energy Range	Energy Resolution	Detector Type
Hard X-rays and Gamma-rays:	10 keV to 20 MeV	0.6-5 keV FWHM	Germanium (Ge)
	20 MeV to $\geq$200 MeV	$\Delta E/E \leq 5\%$	Ge & Bismuth Germanate (BGO)
Soft X-rays:	2-20 keV	~1 keV FWHM	Silicon
Neutrons:	20 MeV to ~1 GeV	$\Delta E/E \approx 5\%$	Ge & BGO

Instrument Characteristics

Weight: ~800 kg

Power: ~300 watts (includes ~100 watts for coolers)

Data Rate: ~25 kbps average

Rotating Modulation Collimators

Number of RMCs: 12

Length: 5 meters

Grid slit spacing: ~50 microns to 3 mm (2 arcsecond to 2 arcminutes)

Grid thickness: ~0.3 to 4 cm (depending on slit spacing)

Material: Tungsten (35 kg upper grids, 11 kg lower grids)

Germanium Detectors

Area and volume: 530 cm^2, 4240 cm^3 (12 Ge, each 7.5 cm dia × 8 cm)

Cooling: to 85° K by mechanical and thermoelectric coolers

Active anti-coincidence shield: 5-cm thick BGO well and collimator
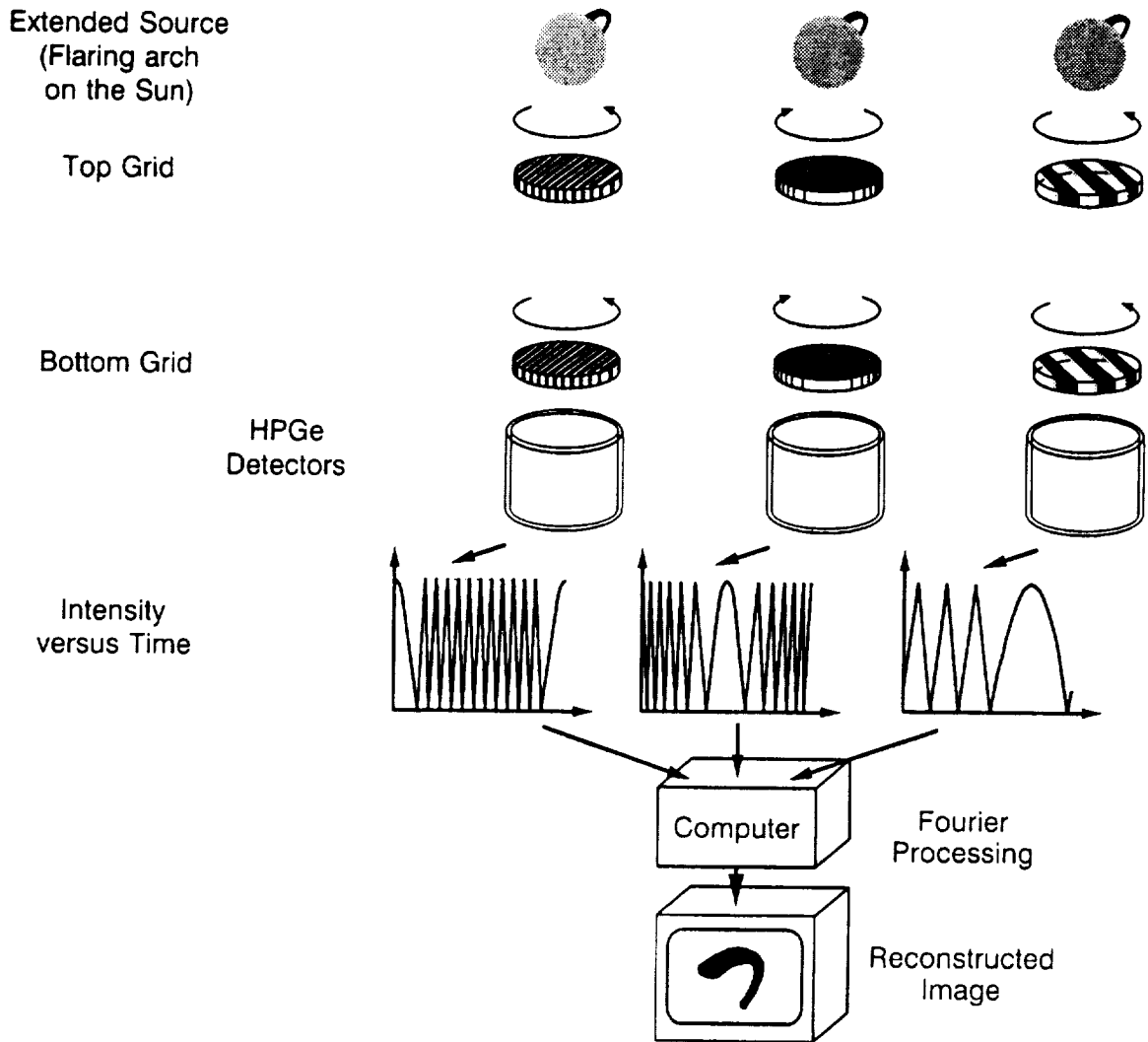
ROTATING MODULATION COLLIMATORS

Figure 4.2. Schematic representation of the Fourier-transform technique used to obtain images of solar flares with multiple rotating modulation collimators (RMC's).
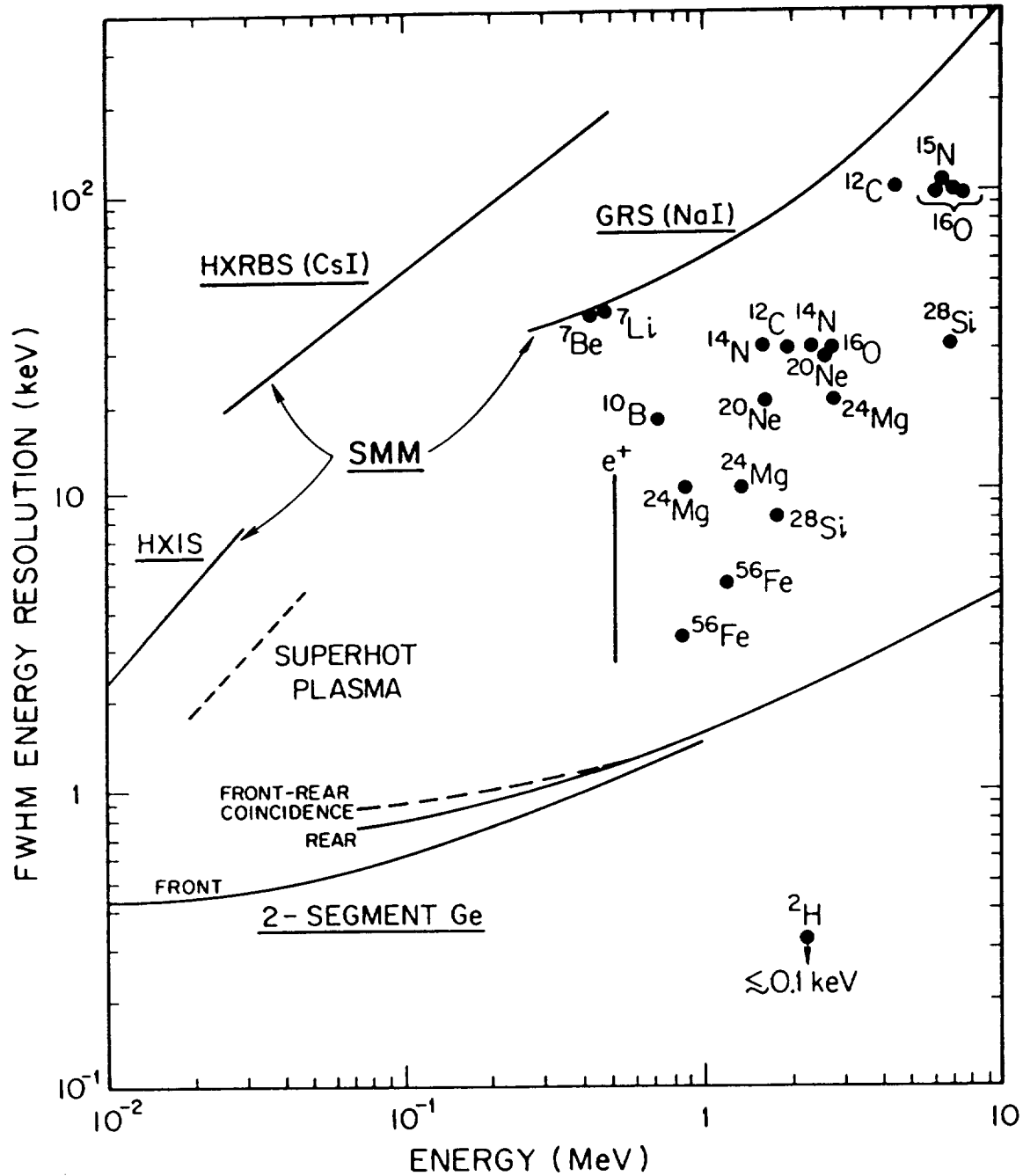
Figure 4.3. The spectral resolution as a function of photon energy for a two-segment HPGe detector is compared to the resolutions of the hard X-ray and gamma-ray spectrometers on **SMM**. The typical widths expected for gamma-ray lines in solar flares are also shown. Note that none of these lines were resolved with the Gamma-Ray Spectrometer (GRS) on **SMM** but all, except the neutron-capture deuterium line at 2.223 MeV with a predicted width of <0.1 keV, can be resolved with a cooled HPGe detector. Similarly, the broken line indicating the energy resolution required to resolve the X-ray spectrum from a superhot plasma at a temperature of $\geq 30 \times 10^6$ K shows that this component was not resolved with the **SMM** instruments but can be clearly resolved with a cooled HPGe detector.

imaging. In addition, the combination of BGO and Ge detectors provides coarse spectral and spatial resolution imaging of energetic neutrons up to ~1 GeV.

Silicon semiconductor detectors (or alternatively, proportional counters) placed in front of the germanium detectors serve to extend the imaging spectroscopy down to ~2 keV to cover the transition from non-thermal to thermal emission and to relate the high energy measurements to the thermal soft X-ray flare.

4.1 Imaging System

4.1.1 *RMC Imaging Concept*

HESP imaging is based on a set of 12 rotating modulation collimators. Each collimator consists of a pair of identical grids whose rotation temporally modulates the X-ray transmission of the grid pair (Figure 4.2). The transmitted X-rays for each collimator are measured by a detector which need not have any spatial resolution. Collimators such as these have been successfully flown for over 20 years (Schnopper *et al.* 1968) for the detection and location of cosmic X-ray sources.

For the analysis of imaging properties of an array of such collimators, it is useful to exploit their equivalence to imaging with radio interferometers. Referring to the set of triangular waveforms during a small fraction of a rotation (Figure 4.2), if we consider only the fundamental Fourier component of this waveform, then it can be shown (Prince *et al.* 1990) that the observed amplitude and phase of the waveform is a direct measurement of a single Fourier component of the source distribution on the sky. This is in precise analogy to a measurement using the amplitude and phase of the correlated signal from a single baseline of a radio interferometer. For an interferometer, the spatial frequency (u-v point) that is measured is determined by the length and orientation of the baseline. For the X-ray collimator, the magnitude of the spatial frequency is determined by the ratio of the slit spacing on the grid to the grid-pair separation; the position angle is determined by the instantaneous orientation of the collimator grid.

During the course of a single half-rotation of the spacecraft (2 s), the position angle of the sampled spatial frequency changes so that a single subcollimator fully samples a complete half-circle in the u-v plane. (Only a half-circle need be measured.) Since each subcollimator has grids of a different pitch, a total of 12 such half-circles are measured. Grid spacings are chosen logarithmically so that a range of source size scales from less than 2 arcseconds to over 2 arcminutes can be effectively sampled and distinguished. In summary, the imaging performance of HEISPEC is identical to that of a 12-baseline "VLA" located at the North Pole with a source near the zenith. For HEISPEC the equivalent of Earth rotation synthesis is the rotation of the spacecraft.

One notable difference between radio and X-ray analogs is that for the array of X-ray subcollimators, the optical performance of the X-ray imager (the "u-v coverage") is similar at all energies, thereby greatly simplifying spectral studies.

Although full u-v coverage can be obtained every two seconds, in analogy to VLA "snapshot" imaging, a significant imaging capability is retained for imaging on significantly

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shorter timescales. A lower limit to the timescale for such measurements is set by the need to measure the amplitude and phase of an individual "sawtooth" in the modulation pattern (Figure 4.2). (A single sawtooth corresponds to a single "natural fringe" in the radio analog.) Depending on the location of the flare relative to the rotation axis and the spatial frequency under consideration, this can often be accomplished in less than ~ 10 ms. On such timescales, background is negligible and the amplitude and phase can be established with the detection of as few as ~ 10 photons. Thus, high time resolution "snapshot" imaging with reduced dynamic range but full angular resolution can be achieved with rates as low as ~ 1000 counts per second in each subcollimator. Although the u-v coverage of the briefest snapshots is limited, it is fully adequate to monitor source motions or to test the spatial consistency of successive spikes in the X-ray emission.

A complementary facet of the rapid time variations in solar flares is the issue of whether such variations could introduce spatial artifacts into images. To evaluate this matter, it is useful to note that at any instant, the temporal modulation of an individual subcollimator occurs over a restricted and known range of frequencies which is distinct for each subcollimator. A first implication of this is that by properly combining the light curves from all subcollimators, a true spatially integrated light curve can be obtained which is independent of any spatially-based modulation effects. Modulated waveforms from individual subcollimators can be normalized to this integrated waveform.

A second implication is that the measurement of an amplitude or phase will only be affected if the incident X-ray flux has statistically significant power in the temporal frequency range that is instantaneously relevant to the modulation pattern for a given subcollimator. The radio analogy here is the potential for compromising the microwave images by significant power at the precise temporal frequency corresponding to the natural fringe frequency. In a decade of microwave burst observations, no such effects have been reported. The implication for the X-ray observations is that the integrity of individual measurements of amplitudes and phases and of the spatially integrated light curves will not be affected by time-varying sources.

Combining the visibility measurements into images is a distinct task which can then be done in the context of the known flare time variations as suggested by the flare light curve. Given the fundamental integrity of the data base, the analyst can knowledgeably trade off image quality and time resolution to test for and, if necessary, follow the spatial development on timescales short compared to 2 s.

4.1.2 Grids and Metering Structure

As described in the previous section, the pitch of a subcollimator grid, together with the length of the canister or metering structure, defines the spatial Fourier component that is measured. The **HESP** optical design employs slit widths in the range from 50 microns to 3 mm to resolve sources with angular dimensions ranging from 2 arcseconds to 2 arcminutes.

Two fabrication techniques will be used to produce the required set of grids. These are illustrated in Figure 4.4.

The Electric Discharge Machine (EDM) or ELOX technique is the method of choice for the grids with slit widths of 150 microns or greater. This technique has been verified at GSFC (Crannell *et al.*1986), where it is now being used to fabricate grids with slit widths of 620 and 280 microns for the High Energy Imaging Device (HEIDI) balloon payload. A tungsten/nickel/iron alloy with a specific gravity of 17.6 is used to facilitate cutting while maintaining the high-density advantage of tungsten. A photograph of the 620-micron grid, as it was being machined, is shown in Figure 4.5.

For slit widths less than 150 microns, a technique involving horizontal stacking of thin slats, or blades, will be used. Several variations on this approach have been investigated at GSFC and at the Technical University of Delft (UT Delft) in The Netherlands using tungsten and tantalum blades. A sample grid segment fabricated at UT Delft with tantalum blades and stainless steel spacers yielding a slit width of 50 microns is shown in Figure 4.6. Segments of this grid, comprised of alternating layers of tantalum and spacer, maintain the required pitch and regularity over lengths as great as the full grid diameter and for widths up to 20 mm. At Goddard, a test grid with 100-micron slit spacing and a diameter of 97-mm has been constructed using tungsten blades with registration of every blade. This test grid is shown in Figure 4.7. The pitch registration of this grid is adequate for **HESP** but the distribution of slit widths about the nominal value has a 40-micron (RMS) deviation or about a factor of four worse than the desired requirement for **HESP**. More detailed descriptions of these efforts are presented in the GSFC Instrument Study Report.

The metering structure being studied for **HESP** is an aluminum honeycomb canister in a cylindrical configuration. The structure supports the forward and aft grid trays, insulation, and Sun shade. During assembly, the fine sub-collimator grids will be shimmed to correct for tilt in the pitch and yaw axes. Once their respective Z axes are normal to the tray planes, each of the fine grids will be co-aligned with its sub-collimator counterpart. In flight, the lower grid tray will be actively aligned in roll rotation relative to the upper tray in order to assure that subcollimator co-alignment is maintained. A more detailed description of the canister and its analysis is presented in the GSFC Instrument Study Report.

4.1.3 *Aspect, Alignment, and Pointing*

The solar aspect system baselined for **HESP** is substantially identical to that used by **HEIDI**. Its purpose is to provide high-bandwidth arcsecond aspect information relative to Sun center. A lens mounted in the front grid plane focuses a 6-cm diameter solar image onto the rear grid plane where a set of crossed linear diode arrays sense the position of the limb every 4 ms. This system provides both relative and absolute aspect data in a coordinate system which rotates with the spacecraft. Two identical but well-separated lens/array systems are used. The difference in their outputs provides a direct measurement of any residual twist in the alignment of the upper and lower grid planes.

A side-looking star tracker provides a relative roll fiducial at least once per rotation. Knowledge of relative roll (required to 2 arcminutes rms) at intermediate times is obtained by
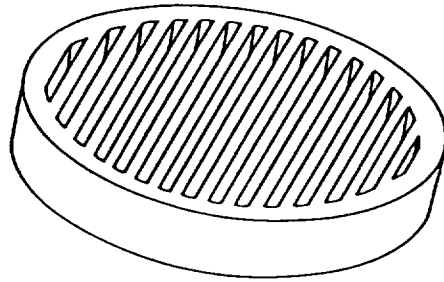
A. COARSE GRID MANUFACTURED
BY ELOX PROCESS.
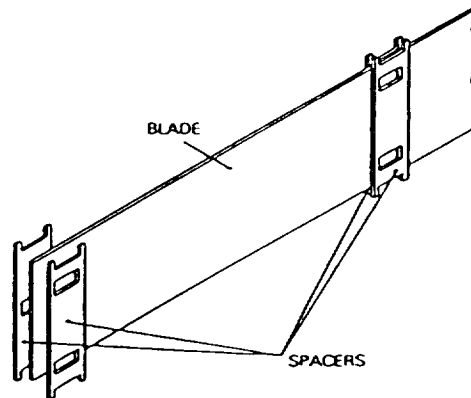
B. SECTION OF ACTUAL SINGLE BLADE
AND SPACERS FOR FINE GRID.
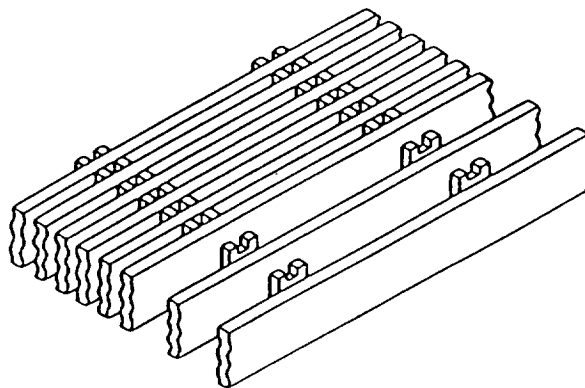
C. DESIGN CONCEPT FOR PACKET OF BLADES
AND SPACERS FOR FINE GRID.

Figure 4.4. Illustration of two different grid fabrication techniques.

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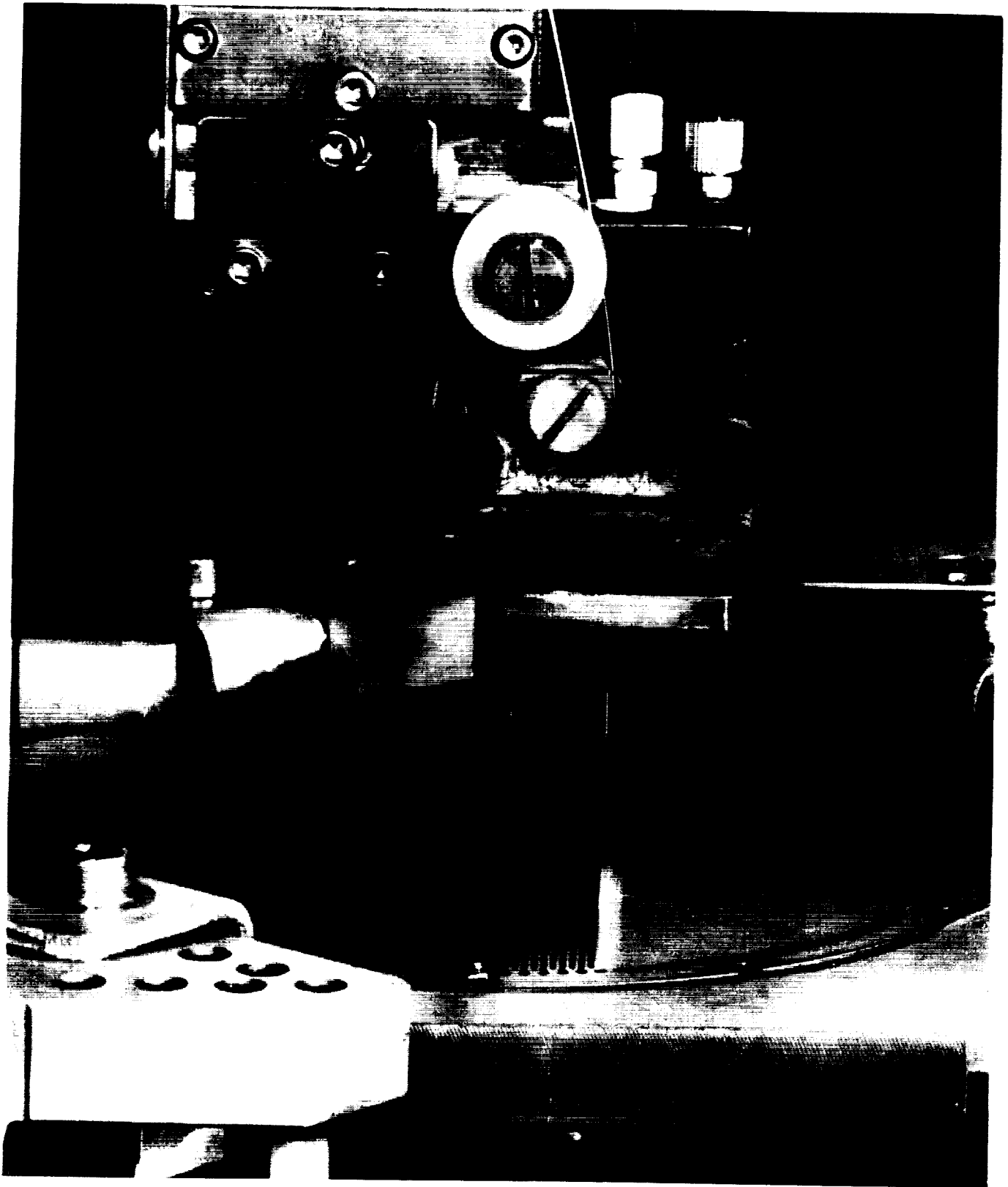
Figure 4.5. Photograph of 620-micron-wide slits being cut in a tungsten-alloy blank using an Electric Discharge Machine (EDM).
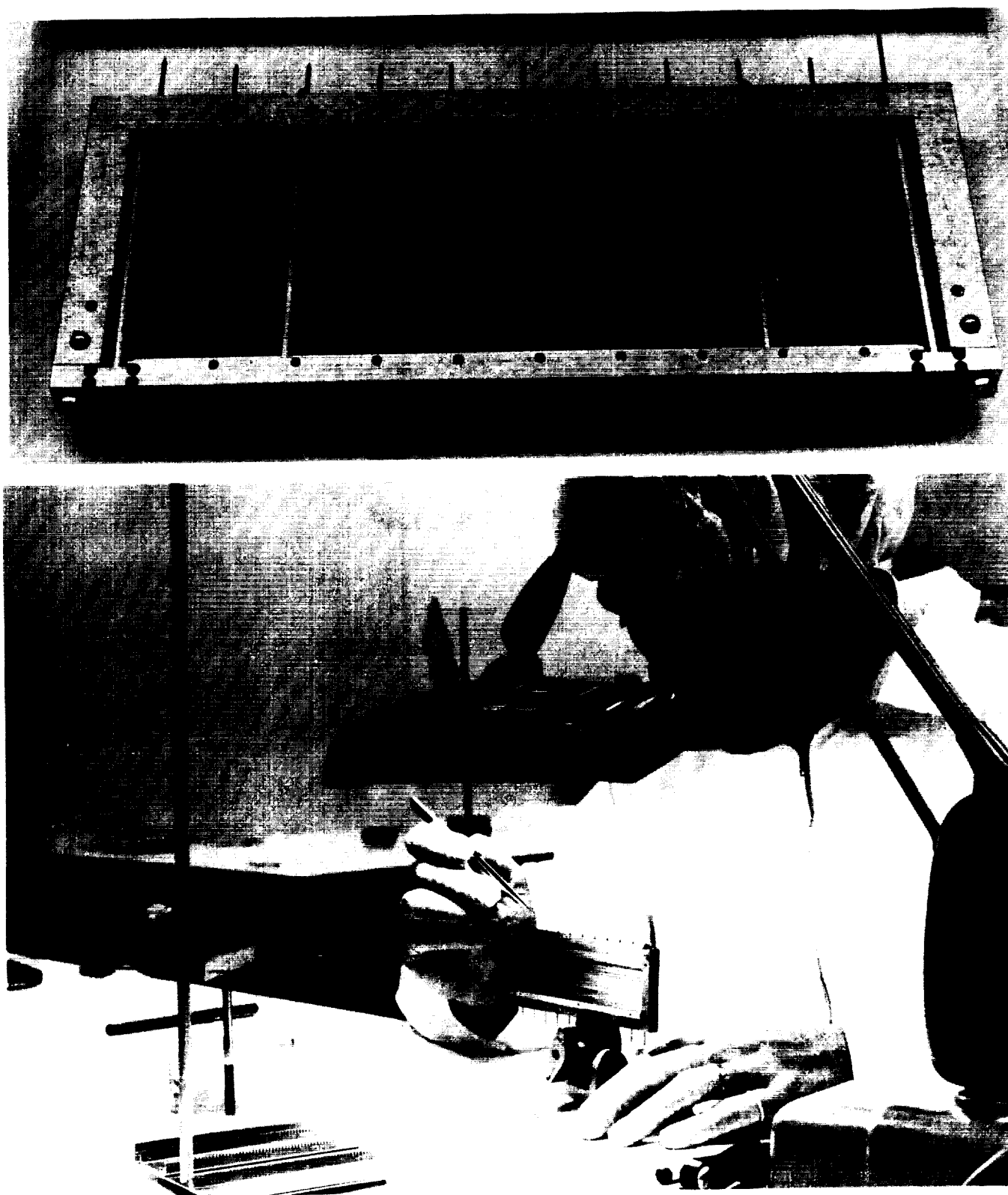
Figure 4.6. Top: Photograph of a fine grid with slit widths of 50 microns made at the Technical University of Delft by stacking tantalum blades and stainless steel separators. Bottom: Grid being assembled.
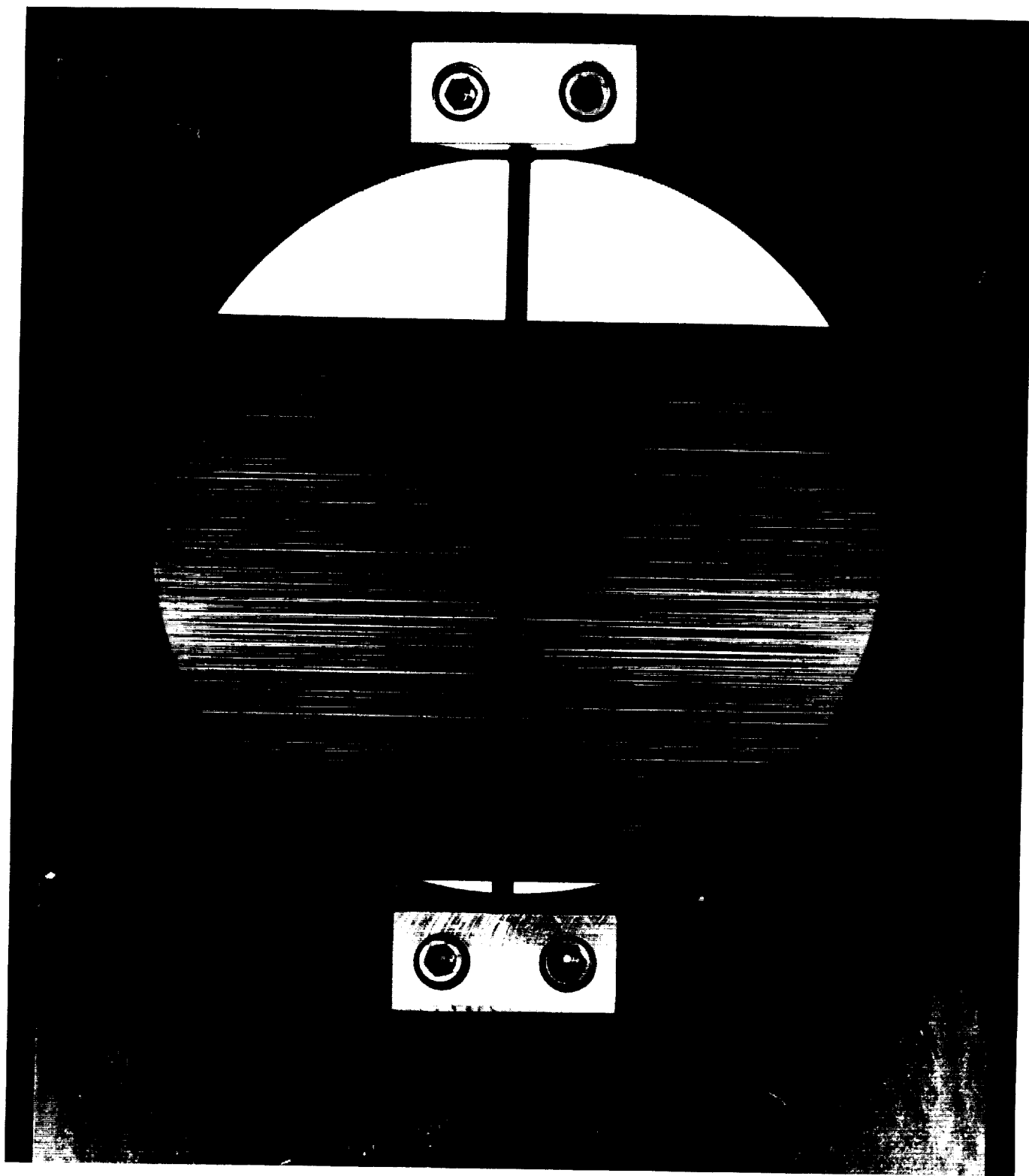
Figure 4.7. Photograph of fine grid with slit widths of 100 microns made at GSFC by inserting tungsten blades into a pre-slotted tungsten frame to maintain pitch registration across the full diameter. A pre-slotted "comb" over the blades helps to maintain the blade spacing.

exploiting the uniform rotation of the spacecraft. Accurate coalignment of the star-tracker to the X-ray optics is not required. Absolute roll calibration is provided every few minutes by the random passage of a sunspot over a preselected pixel on the solar aspect system. The sunspot locations are sufficiently well-known from ground-based data that the timing of these passages can be used to provide an occasional but absolute indication of roll aspect.

Despite the fact that **HESP** will produce arcsecond-class images, control of instrument pointing and alignment to arcsecond tolerances is not required. The pointing requirement of 6 arcminutes rms is set by the fields of view of the X-ray and aspect-system optics, and is independent of the instrument resolution. Since each detected photon is individually time-tagged, it is only necessary to have aspect knowledge of the pointing direction at the time of detection. In effect, the system has inherent image-motion-compensation. Pointing stability requirements are correspondingly modest because of the 250 Hz bandwidth of the aspect system.

The most critical alignment of **HESP** is the maintenance of the relative twist of the front and rear grid pairs in each subcollimator. Any subcollimator for which the twist requirement is substantially violated suffers an irrecoverable loss of modulation amplitude. This requirement, which scales with grid pitch, is 0.7 arcminutes for the finest grids.

From structural considerations, the primary requirement is the maintenance of the relative orientation of the front and rear grid plates. This, however, is continuously monitored to a few arcseconds by the dual solar aspect system. The relative orientation can be adjusted in-orbit by rotating the lower grid plate on command from the ground using an actuator with about 1 mm of travel. Given the stable thermal environment, such an adjustment should only be required occasionally, if at all, after launch. Small residual errors can be fully compensated during data analysis.

The structure of the telescope is remarkable in that all the X-ray and aspect hardware (except for the star sensor) is confined to two planes. Within each plane, coalignment reduces to accurate mapping with an x-y table. Coalignment between planes is intrinsically indicated by the solar aspect system.

4.2 Detectors

4.2.1 *Germanium Detectors*

HEISPEC will use the largest, readily available, hyperpure (n-type) germanium coaxial detectors, presently 7.5-cm diameter x 8-cm long. The Ge detectors were chosen to be n-type because of their relative immunity to radiation damage.

The dominant source of damaging radiation is trapped protons (primarily from the South Atlantic Anomaly) which penetrate the BGO shield (protons entering through the aperture are negligible in comparison). Protons must have $\gtrsim 200$ MeV energy to penetrate the BGO shield. Primary cosmic rays which penetrate the BGO shield contribute $\lesssim 0.1$ to 0.2 of the trapped radiation. Solar flare protons over a solar cycle account for the equivalent of ~ 0.2 to 1 year of the primary cosmic ray fluence.

Figure 4.8 shows the effect of radiation damage on the FWHM resolution for germanium detectors based on laboratory measurements. The 3, 5, and 10 year expected dosages for **HESP** are indicated. There is no noticeable radiation damage to the Ge detectors for a mission lifetime of 3 years, and barely noticeable resolution broadening after ~10 years. Thus, no provision for detector annealing is required.

Each Ge detector has two inner electrodes which divide it into two distinct volumes, or segments, according to the electric field pattern (Figure 4.9). In the central 1.0-cm diameter hole, the top contact collects charge from the front ~1.5-cm thick segment of the detector, and the lower contact collects charge from the rear ~6.5-cm long coaxial segment. The curved outer surface and top surfaces are metallized for the high voltage contact and implanted with boron to make a very thin (~0.3-micron) window for X-rays.

The Ge detectors operate in three spectroscopy modes. Photons of low energies (~15 to 150 keV), where photoelectric absorption dominates, are mainly absorbed in the front ~1.5-cm segment, while Compton-scattered photons and detector background are rejected by anticoincidence with the adjacent rear segment of the detector. Therefore, this mode has the excellent background rejection properties of a phoswich-type scintillation detector (Matteson et al., 1977).

Higher energy ($\gtrsim$ 150 keV) photons are detected primarily in the thick rear segment but those that stop in the front sector and those that deposit part of their energy in both the front and rear segments are also recorded and tagged accordingly.

The main advantage of the dual-segment configuration of the detectors is that the bottom segment is shielded by the top segment from low energy, $\lesssim$ 150 keV photons. This shielding, together with the entirely separate electronics for each segment, is crucial for obtaining undistorted high-resolution gamma-ray line measurements with high efficiency in the presence of intense solar flare hard X-ray fluxes. The analog electronics for the Ge detectors are designed to operate over a very wide energy range (~10 keV to 250 MeV) and to accommodate the wide range of counting rates expected from flares while maintaining high spectral resolution.

The Ge detectors are cooled to their operating temperature of ~85 K by a combination of mechanical, radiative, and thermoelectric coolers (see report of the Ball study). Alternatively, a solid-cryogen refrigerator (methane/ammonia), similar to that flown on the HEAO-3 and EINSTEIN, could be used. Sufficient volume and weight is available in both the Ball and Goddard spacecraft designs to allow for such a fall-back cooling system if mechanical coolers do not become available in time for **HESP**.

4.2.2. Bismuth Germanate (BGO) Shield

The BGO anticoincidence shield and collimator play important roles in reducing background, rejecting Compton scattered photons, and, together with the HPGe detectors, extending the response of **HESP** to high energy ($\gtrsim$ 20 MeV) gamma-rays and neutrons. A comparison of commonly used scintillators (CsI, NaI, and BGO) clearly demonstrates that BGO is not only the most cost-effective anticoincidence material but also the most mass- and volume-effective (i.e., it minimizes the number of grams and cc's per photon absorbed).
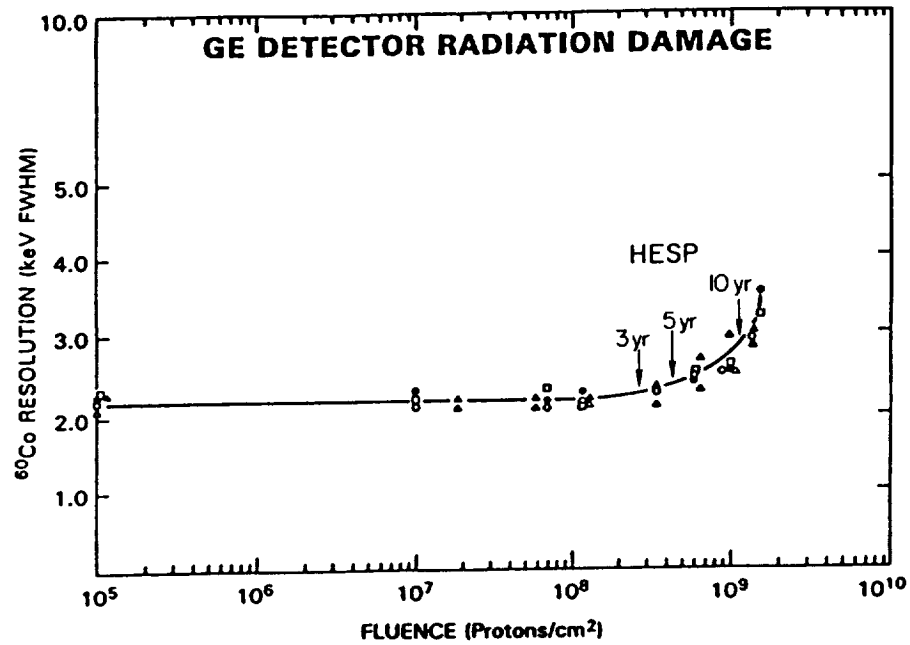
Figure 4.8. Change in the energy resolution of germanium detectors under irradiation by 150-MeV protons (Friesel 1987). The estimated total fluences for the **HESP** orbit are indicated for a 3-, 5-, and 10-year lifetime.
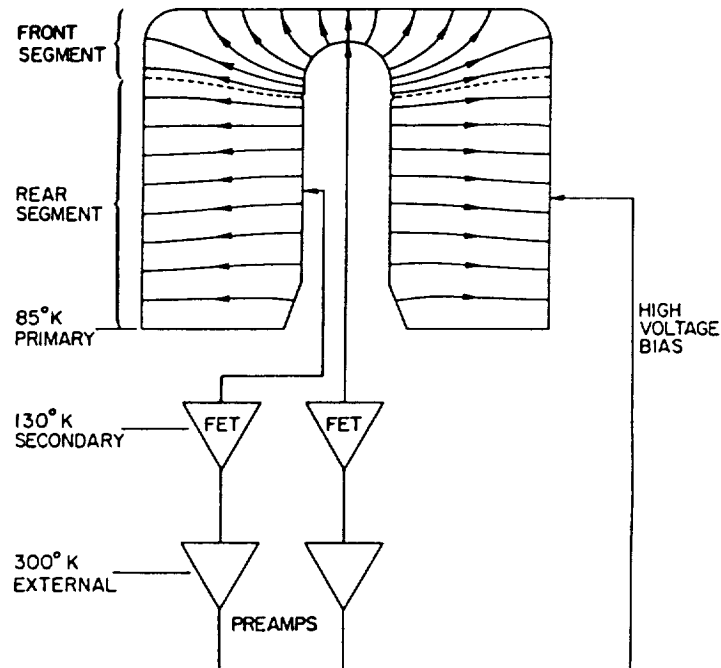

Figure 4.9. Schematic cross-section of a two-segment co-axial germanium detector. The lines with arrows inside the detector show the electric field pattern; the dashed line shows the separation between the upper and lower segments.

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The BGO shield is made up of a 5-cm thick well covering the sides and bottom of the cryostat and a drilled BGO collimator above it. Similar BGO shields are used for the Max '91 **HIREGS** balloon-borne germanium spectrometer and the **HEXAGONE** spectrometer for cosmic sources. Since BGO is presently available in crystals ~5 inches in diameter, the shield will be built up out of multiple sections. This architecture was also used for the balloon spectrometers and poses no particular problems. The nominal design calls for one photomultiplier tube to be associated with each BGO piece. The electronic design used places a high-voltage power supply and preamplifier at the base of each tube. The low-energy threshold of ~50 keV achieved with this configuration provides excellent background rejection.

A 3-mm thick passive lead shield in front of the BGO collimator and well absorbs the solar flare $\lesssim$ 300 keV hard X-rays to minimize the active BGO shield counting rate in an intense flare. Fast anticoincidence circuitry (~1 microsecond overlap time) limits the dead time to $\lesssim$ 20%, even in the largest flares.

The output of the BGO is pulse-height analyzed for energies from 0.3 MeV to ~1 GeV. The back BGO plate is divided into hexagonal sections (each with its individual photomultiplier tube), with one such section behind each RMC and Ge detector. The combination of the front and rear Ge segments and the corresponding back BGO section is utilized as a multi-layer detector for measurement and identification of high energy gamma-rays and neutrons (Forrest *et al.* 1985).

4.2.3 *Soft X-ray Detectors*

The imaging spectroscopy will be extended down to the flare thermal range by adding soft X-ray detectors to the germanium detectors behind the RMC's. Diffraction in the finest RMC grids becomes important at ~3 keV although energy "windows" are available at lower energies. The soft X-ray measurements will extend up to $\geq$20 keV to overlap with the germanium detector range.

Several different types of detectors are available that could cover the required energy range. These include various forms of silicon solid-state detectors and gas proportional counters.

Lithium-drifted silicon detectors cooled to -40 C can provide energy resolution of ~0.3 keV FWHM, and thick detectors $\gtrsim$ 1 mm, are available to cover energies up to 20 keV. These have been flown previously. The cooling could be provided by thermoelectric coolers.

Recent developments of passivated ion-implanted silicon detectors with very low leakage current at room temperature provide a possible alternative. At present, however, PIP detectors which can achieve 2 keV threshold at room temperatures are generally much smaller than 1 cm^2 area and PIP thicknesses are limited to ~0.5 mm.

Finally, standard xenon-filled gas proportional counters, which have flown in many space experiments and are known to be highly reliable and long-lived, could be used. Typical energy resolution is ~20% at 6 keV.

4.3 Electronics

The analog electronics for the HPGe detectors is essentially the same as that used in the **Max '91 HIREGS** and the **HEXAGONE** gamma-ray balloon systems. Each Ge detector has independent signal paths for the front and rear segments. Each signal path (Landis et al., 1970) includes a cooled FET, a wide-bandwidth charge-sensitive preamplifier, and dual shaping amplifiers – a slow shaping amplifier with a time constant of $\sim$4 microsecond used for pulse height analysis, and a fast shaper-amplifier-discriminator with a time constant of $\sim$400 ns to supply fast pulses for coincidence, pileup rejection, timing, and rate accumulations. The pile-up rejection system, together with a gated baseline restorer, allows operation at incoming photon rates up to $\gtrsim 3 \times 10^5 \ s^{-1}$ per detector without resolution degradation. The maximum rate at which these photon events can be pulse-height analyzed is $\sim 5 \times 10^4 \ s^{-1}$. Similar analog electronics are used for the silicon soft X-ray detectors. The shaped pulses from the slow shaping amplifier go to a 13-bit (8192-channel) pulse height analyzer (PHA). For energies below 2.8 MeV, the PHA provides a resolution of $\sim$0.34 keV per channel. For energies in the range from 2.8 to 20 MeV, where essentially all the lines are broad ($\gtrsim$ 100 keV FWHM), a 7-times lower gain output of the shaper amplifier is passed to the PHA, resulting in $\sim$2.4 keV per channel.

For energies above 20 MeV, an upper level discriminator inhibits the 13-bit PHA and triggers a separate 8-bit flash PHA. This PHA covers the energy range from 20 to 250 MeV. The BGO collimator and shield photomultiplier outputs are also connected to 8-bit flash PHAs to cover the $\gtrsim$ 0.3 MeV to $\gtrsim$ 1 GeV energy range. Similarly, the silicon soft X-ray detectors use 8-bit flash PHAs to provide $\sim$0.1 keV/channel over the 2 to 20 keV energy range.

Gain and coincidence status bits at the time of the event trigger are included in the data stream together with detector identification for each PHA word. Timing information to 50 microseconds is included so the temporal modulation produced by the RMC's can be accurately measured.

4.4 Data Handling

Full information for every detected photon during flare events is stored in RAM memory. The largest flares will drive the Ge detectors to their maximum photon throughput rate ($\sim 5 \times 10^4$ c/s per detector) and result in a data rate as high as $\sim$1 or 2 Megabytes s^{-1}. For a 10^3-s flare FWHM duration typical of large flares, a total of $\sim$1 or 2 Gigabytes of data will be generated and must be stored on board. Presently available Dense-Pak memory (used in the FAST Small Explorer program) can provide this storage capacity, although denser memory is being developed. Also, a variety of data compression techniques can reduce this data volume if required. This volume of data can be telemetered down to ground stations in one or two days (see the Goddard report on the **HESP** spacecraft design study). The normal average daily data rate is a factor of 5-10 lower.

5. THE HESP SPACECRAFT

Two studies, one at GSFC and the other by the Ball Aerospace Systems Group, have resulted in similar spacecraft designs. The results of these studies are presented in the following two reports:

(i) "Pre-Phase A Study Report on the High Energy Solar Physics Mission (HESP) - Spacecraft Study Report " by the Advance Missions Analysis Office at GSFC.

(ii) "Preliminary Mission Study for NASA Space Physics Division (Code SS) High Energy Solar Physics (HESP) Addendum I" by the Ball Aerospace Systems Group.

Here, only the GSFC concept, illustrated in Figure 5.1, is briefly described. More detailed information can be found in the above reports.

The spacecraft is designed to accommodate a single instrument, **HEISPEC**, as described in Section 4 of this report. **HEISPEC** must be pointed at the Sun and must spin about the telescope tube center-line. Key mission requirements, as driven by the science objectives and the instrument pointing requirements, are as follows:

- Mission lifetime, ≥ 3 years

- Spin rate, ~ 15 rpm

- Total mass of instrument, ~ 900 kg

- Maximum power for instrument, ~ 300 watts continuous.

- Field of view (FOV), 36 arcminutes

- Pointing accuracy, 2 arcminutes

- Pointing stability, 0.1 arcseconds over 4 ms

The data collection and transmission requirements are as follows:

- 16 Gbits collected over a period of 1000 s during solar flare activity.

- Dump a maximum of 16 Gbits to the ground in 24 to 48 hours.

- Orbital average data rate of 20 kbps when there is no solar flare activity.

The 4800-pound spacecraft shown in Figure 5.1 consists of three subsystem modules surrounding the 5-m long x 0.94-m diameter telescope tube. These spacecraft modules are deployed immediately after launch to allow stable rotation about the long axis of the instrument telescope tube. The instrument detectors, cooling systems, and electronics are contained within a cylindrical volume 2.2 m in diameter x 1.2 m long located below the telescope tube. In addition, this volume contains the launch vehicle interface structure, the primary spacecraft structure, and the module deployment mechanisms. The complete instrument and spacecraft in its launch configuration fits comfortably within the standard Delta fairing.

The electrical power subsystem is a direct energy transfer (DET) system composed of conventional silicon solar cells, nickel-cadmium batteries, power subsystem electronics (PSE), and a battery reconditioning unit (BRU). The solar cells are mounted to honeycomb panels
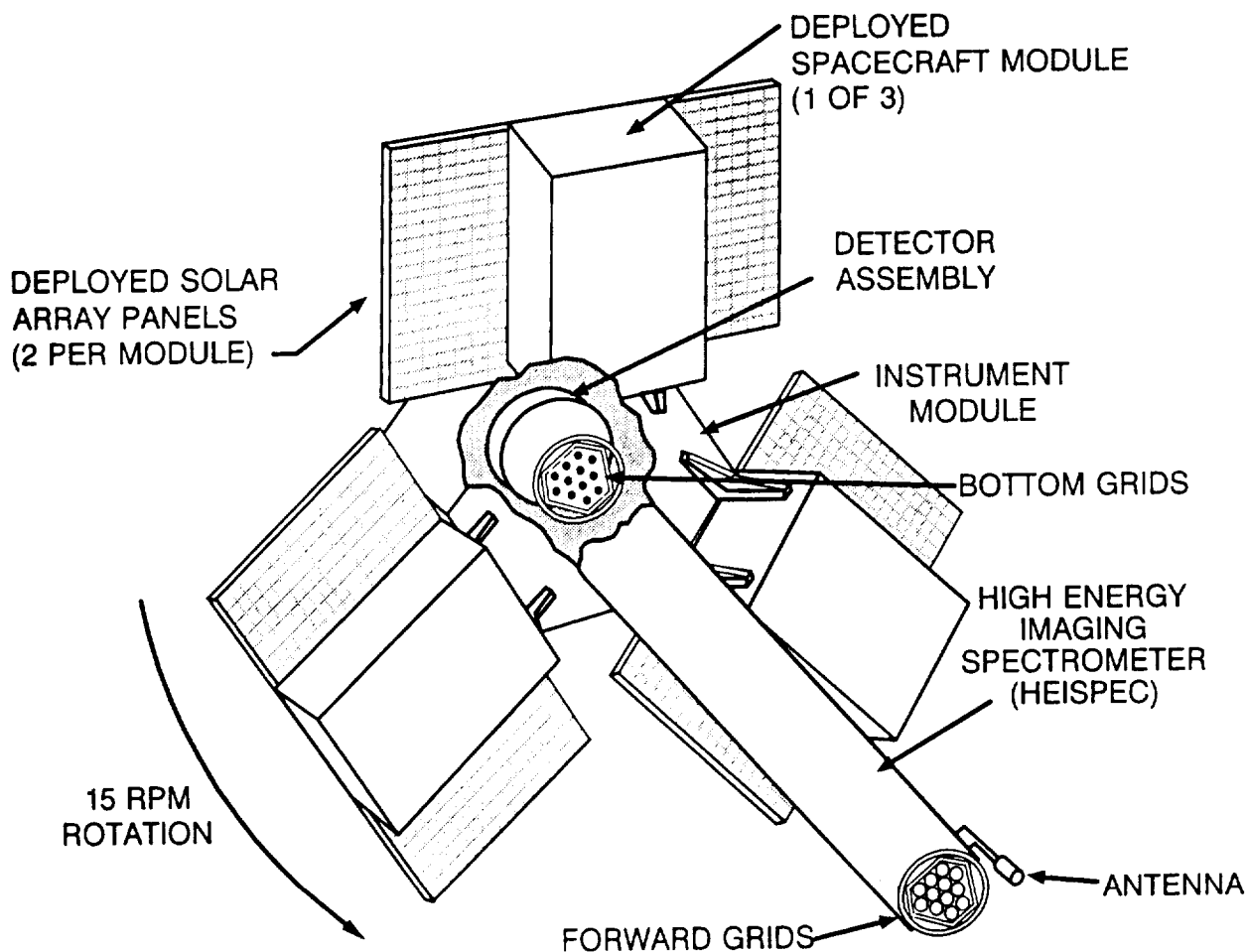
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HESP ON-ORBIT CONFIGURATION

Figure 5.1. On-orbit configuration of the spacecraft concept developed for **HESP** by the Advance Missions Anlysis Office (AMAO) at GSFC. Full details of this concept are given in the AMAO **HESP** spacecraft study report.

that are deployed perpendicular to the Sun immediately following launch-vehicle separation. The total solar array size is 1080 ft² to give 600 watts after 3 years in orbit. There is ample room within the Delta fairing to substantially increase the size of these arrays, if necessary.

The **HESP** Data Flow concept is similar to the one employed by **COBE**, which utilized the Tracking Data Relay Satellite System (**TDRSS**), Wallops Island Orbital Tracking Station (**WPS**), Domestic Satellite (**DOMSAT**), and GSFC. Science data stored in the **HEIS-PEC** solid-state recorder is played back through the **HESP** communications subsystem (at 6.6 Mbps) and delivered to GSFC through WPS and DOMSAT. Spacecraft engineering and housekeeping command and telemetry with GSFC is supported by **TDRSS** (multiple access at 1 kbps continuous), and **DOMSAT**.

The **HESP** communications subsystem is also similar to the **COBE** system, consisting of two transponders, RF switches, diplexers, RF amplifiers, and antennas. To ensure full coverage, one antenna is located on the top of the telescope and one is located on the bottom of the instrument module as shown in Figure 5.1.

The **HESP** spacecraft will be launched by a Delta 7920 into a 600-km, Sun-synchronous, 98-degree orbit from the Western Test Range (**WTR**). Following orbit injection and separation from the Delta second stage (approximately 55 minutes after lift-off), the spacecraft modules are deployed, the spacecraft is oriented so that the instrument is pointed at the Sun, and the entire spacecraft is spun up to 15 rpm. Pointing maneuvers, spin rate, and nutation control are all autonomously accomplished using magnetic torquer bars, reaction wheels, and attitude sensors. Because the attitude control system (ACS) does not use gas jets and there is no propulsion required for orbit adjustments, spacecraft life will not be limited by the use of any propellant. Orbital analysis indicates a lifetime of at least 15 years.

The **HESP** on-orbit spacecraft geometric configuration (Figure 5.1) is driven by the fundamental physical principle that passively stable spacecraft always spin about the axis with the maximum principal moment of inertia. The long and narrow Delta fairing together with the **HEISPEC** mass properties and geometry are constraints that make it physically impossible to configure **HESP** so that it is passively stable in the launch configuration with the spacecraft modules and solar paddles folded up around the telescope tube. If the spacecraft were to be spun-up about the telescope center-line in this launch configuration, it would eventually spin about one of its transverse axes. In order to solve this problem, the following two approaches were investigated: tip masses on the end of deployable solar arrays or deployable spacecraft modules. It was determined that the deployable module concept had several significant advantages over the deployable tip mass approach and these are discussed in the GSFC spacecraft study report.

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6. BUDGET AND SCHEDULE

6.1 Cost Estimates

Cost estimates for **HESP** have been made by both the Resource Analysis Office (RAO) at GSFC and Ball Aerospace Group (BASG). In both cases, the total costs were estimated through launch plus 30 days. The breakdown of these estimates are given below with all costs in millions of FY 1991 dollars.

RAO GSFC Estimate

	Cost Plus 10% Fee	Contingency	Total Cost
Spacecraft	62	20%	74
Instrument	46	30%	60
MSI&T	28	30%	37
Code S Development	5	25%	6
Code O Development	18	25%	22
Total	159		199

Ball Aerospace Estimate

	Cost Plus 10% Fee	Contingency	Total Cost
Spacecraft	61	20%	73
Instrument and MSI&T	67	60%	108
Ground Support	10	60%	16
Total	138		197

In both cases, the cost estimates were based on system weight and complexity and on the costs for similar systems for which data are available. In the Goddard analysis, the heritage included **GRO, SMM,** and **NAE**, with the instrument analogs being **EGRET** and **OSSE** on **GRO** and the Gamma Ray Spectrometer on **HEAO-3**. The spacecraft costs were based on a proto-flight approach using the spacecraft concept discussed in the GSFC **HESP** spacecraft pre-phase-A study report. In the BASG analysis, the **OSSE** instrument was taken as the analog for **HEISPEC**, with historical data from similar Ball spacecraft programs used to develop the spacecraft cost estimate.

6.2 Schedule

Figure 6.1 shows a schedule for **HESP** based on achieving a launch in 1999, in time for the next period of high solar activity at the turn of the century. Note that this period of high activity is expected to extend until about 1995. Thus, a two-year slip in the schedule would still allow **HESP** to obtain three years of flare observations. Also, it may be possible to reduce the length of Phase B and/or Phase C/D in order to achieve an earlier launch.
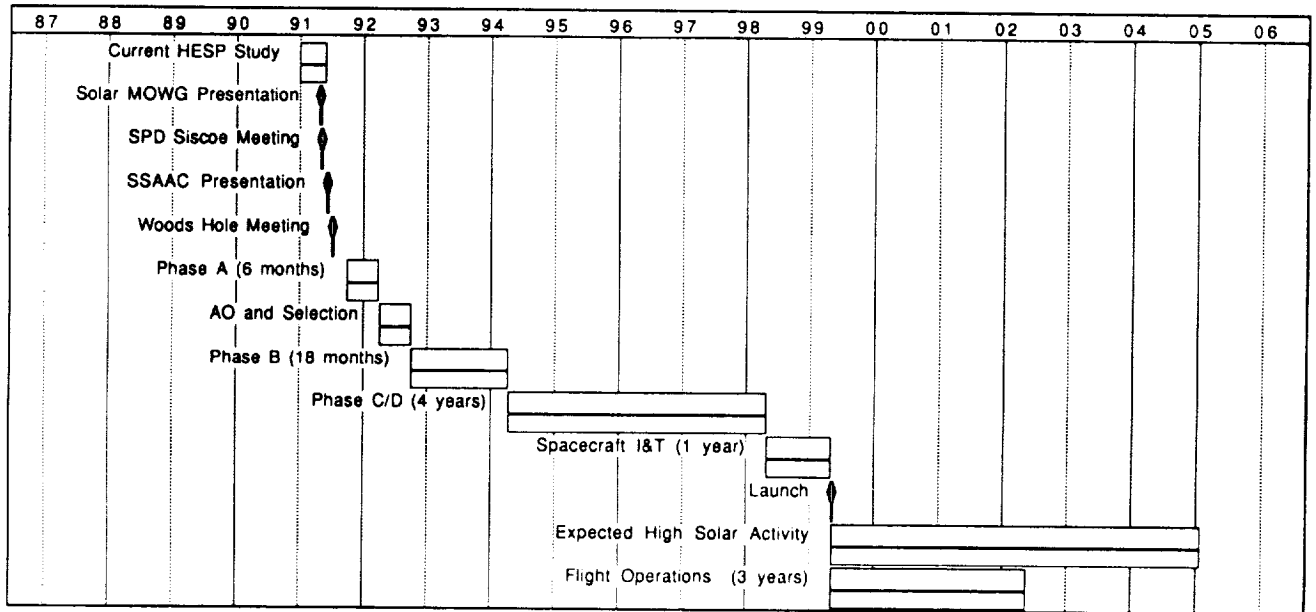

Figure 6.1. A schedule for **HESP** based on achieving a launch in 1999.

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APPENDIX

SPACE SCIENCE AND APPLICATIONS ADVISORY COMMITTEE

DETAILED CRITERIA FOR SELECTION:

THE HIGH ENERGY SOLAR PHYSICS MISSION (HESP)

I. SCIENTIFIC MERIT

A. Scientific Objectives and Significance

1) What are the key scientific issues being addressed by the mission or initiative?

The overarching scientific objective of the High Energy Solar Physics mission is to explore the processes of impulsive energy release and particle acceleration in the magnetized plasmas of the solar atmosphere. The fundamental importance of these high-energy processes transcends their significance in solar physics since they are found to play a major role throughout the universe at sites ranging from magnetospheres to active galaxies. The detailed understanding of these processes is one of the major goals of astrophysics, but in essentially all cases, we are only just beginning to perceive the relevant basic physics.

Nowhere can one pursue the study of this basic physics better than in the active Sun, where solar flares are the direct result of impulsive energy release and particle acceleration. The accelerated particles, notably the electrons with energies of tens of keV, appear to contain a major fraction of the total flare energy, thus indicating the fundamental role of the high-energy processes. The acceleration of electrons is revealed by hard X-ray and gamma-ray bremsstrahlung; the acceleration of protons and nuclei is revealed by nuclear gamma-rays, pion-decay radiation, and neutrons. The proximity of the Sun means that these high-energy emissions appear orders of magnitude more intense than from any other cosmic source, plus they can be better resolved, both spatially and temporally. Consequently, only on the Sun can the phenomena be studied with the detail necessary to understand the fundamental processes.

The principal scientific objective of HESP is to study these high-energy processes through observations of the X-ray, gamma-ray, and neutron emissions from solar flares. The processes of interest include the rapid release of energy stored in unstable magnetic configurations, the equally rapid conversion of this energy into kinetic energy of accelerated particles and hot plasma, the transport of these particles, and the subsequent heating of the ambient solar atmosphere. These processes involve energies, temperatures, densities, spatial scales, and magnetic containment times that are impossible to duplicate in laboratories on the Earth or to resolve at astronomical distances.

To achieve this overall objective, HESP will address the following scientific questions:

- What are the processes that release the stored magnetic energy to produce a flare and where in the solar atmosphere does this energy release take place?

- How are electrons and ions accelerated so rapidly and efficiently to sub-relativistic and relativistic energies?

- What are the mechanisms that transport the flare energy and accelerated particles away from the energy release site?

- What is the composition of the accelerated particles and of the solar atmosphere with which they interact?

- Are all flares, large and small, manifestations of the same basic processes? In particular, what are the characteristics of microflares and what is their contribution to coronal heating?

Imaging and spectroscopic observations of hard X-rays, gamma-rays, and neutrons serve as the best diagnostic of the underlying physics of flares. The necessary spatial and temporal resolving powers must match the spatial and temporal scales that characterize the processes of energy release, acceleration, and transport. The observations must be sufficiently sensitive to detect the initial energy release and particle acceleration, and they must have adequate dynamic range to span events from microflares, with an energy release of $\lesssim 10^{26}$ ergs, to the largest flares, with an energy release of $\gtrsim 10^{32}$ ergs. Equally important, the spectral resolving power must be sufficiently fine to allow the deciphering of the rich and detailed information encoded in both the gamma-ray lines and the highly structured photon continuum. The primary goal of HESP is to provide, for the first time, such high-resolution imaging spectroscopy observations over the entire photon energy range from soft X-rays through hard X-rays to gamma-rays. Imaging spectroscopy observations of high-energy gamma rays and energetic neutrons will also be obtained with HESP for the first time.

In addition to the solar observations, HESP will also provide the first high resolution spectra of the many cosmic X-ray and gamma-ray sources within ± 25 degrees of the ecliptic plane, as well as fine imaging of extended sources such as the Crab Nebula and the quasar 3C273. Many cosmic gamma-ray bursts will also be detected by HESP with high temporal and spectral resolution.

Key General Objectives:

HESP will be capable of high-resolution X-ray and gamma-ray imaging spectroscopy, i.e., high-resolution spectroscopy at each point of the image. This will allow the spectral evolution of the emissions to be traced in both space and time throughout a flare. It represents an important new capability not available in any other instrument in this wavelength range. Furthermore, the Sun is the only astrophysical X-ray or gamma-ray source bright enough and close enough to allow such observations to be made with present instrumentation.

With this powerful technique of imaging spectroscopy, HESP has the following solar objectives:

- To obtain **hard X-ray images** with an angular resolution of 2 arcseconds and a temporal resolution of tens of milliseconds, commensurate with the known size scales of the flaring magnetic structures and the stopping distances and times of the accelerated electrons. The images will be obtained with sufficient sensitivity to detect the initial flare energy release and to study microflares. Such images will enable us, not only to locate the energy release site or sites for the first time, but also to evaluate, both qualitatively and quantitatively, the evolution of the released energy as a result of interactions with the ambient atmosphere during the impulsive and gradual phases of many solar flares of different types.

- To obtain **gamma-ray images** with an angular resolution of 4 to 8 arcseconds. It will be possible to obtain images in specific gamma-ray lines or in continuum regions such that, for example, the proton- and alpha-induced lines could be imaged separately, as could the 4-to-7 MeV gamma-ray continuum that is primarily from accelerated heavy nuclei. Comparisons of images in the ion-produced gamma-rays with images in the electron-produced hard X-rays offer the exciting possibility of demonstrating the existence of large-scale electric fields in flare loops.

- To obtain **high-resolution X-ray spectra** with 1-to-2-keV resolution down to energies as low as 2 keV. The measurement of the precise shape of the X-ray continuum made possible with such fine energy resolution will provide unique information on the spectrum of the accelerated electrons and on the heated plasma, thus allowing the thermal and non-thermal aspects of individual flares to be clearly distinguished.

- To obtain **high-resolution gamma-ray spectra** with a few keV resolution to energies as high as 20 MeV. This resolution is sufficient to resolve the gamma-ray lines and to measure their shapes, thus allowing the full potential of gamma-ray line spectroscopy to be realized for the first time. The Sun is the only astrophysical gamma-ray source bright enough to allow such studies to be carried out with present instrumentation and the HESP observations would provide the first true astrophysical gamma-ray spectroscopy. Such high-resolution spectra would provide unique information on the directionality of the interacting particles, the composition of both the ambient gas and the accelerated ions, and the temperature, density, and state of ionization of the ambient gas.

- To obtain **high-energy gamma-ray spectra and images** for large flares at energies from 20 MeV to ≳200 MeV. With an energy resolution of ~5% and 4- to 8-arcseconds angular resolution, these observations will provide information on the acceleration of electrons (through the bremsstrahlung gamma-rays) and ions (through the pion-decay gamma rays) to the highest energies.

- To obtain **high-energy neutron spectra and images** for large flares at energies from 20 MeV to ≳1 GeV. These measurements will have an energy resolution of ~5% and an angular resolution of ~40 arcseconds, and as with the gamma-ray observations, will provide information on the acceleration of ions to the highest energies.

HESP also has the following non-solar objectives:

- To obtain high resolution spectra of hard X-ray and gamma-ray sources within ± 25 degrees of the ecliptic plane that have intensities as small as one thousandth that of the Crab Nebula. These spectra can be used to search for such features as cyclotron line emission or absorption from magnetized neutron star sources.

- To obtain high resolution spectra of the large-scale structure of the diffuse galactic emissions in the positron annihilation line and the ^{26}Al line, both of which have been attributed to nucleosynthesis in supernovae and novae. For about a month every year, HESP will be able to follow the evolution of the variable 511 keV line emission from what is believed to be a few solar mass black hole source near the galactic center.

- To obtain high resolution spectra for the tens of cosmic gamma-ray bursts that will occur in its 50 degree FWHM field of view each year. These spectra can be used for the detailed study of cyclotron lines, gravitationally red-shifted positron annihilation line features, and other nuclear lines which may be present.

- To obtain hard X-ray and gamma-ray images with a few arcseconds resolution of the galactic-center region and of extended cosmic sources such as the Crab Nebula and 3C273 that come within 5 to 10 degrees of the Sun. These images will provide individual source spectra and arcsecond positions for the multiple sources in the galactic-center region and will give detailed information on the distribution of energetic electrons in the extended sources.

Representative Specific Objectives of HESP:

- Locate and determine the characteristics of the energy release site.

- Locate and identify the particle acceleration mechanisms at work during the different phases of solar flares and other coronal disturbances.

- Determine the contributions of high-energy particles to flare energetics, specifically by following the detailed spectra of electron-ion bremsstrahlung continuum and nuclear gamma-ray line radiations, both spatially and temporally.

- Study energy and particle transport during flares and other coronal disturbances.

- Determine the spectrum of the accelerated electrons and ions.

- Study abundances and abundance variations in the solar plasma and in the interacting accelerated ions as revealed by nuclear gamma-ray line intensities.

- Study the energetic processes in both steady and transient cosmic sources, indirectly by analogy with the corresponding solar flare phenomena and directly through detailed measurements of their hard X-ray and gamma-ray emissions.

2) How significant are these issues in the context of science?

The physics of the high-energy processes occurring in solar flares is highly complex and involves many disciplines including plasma physics, magneto-hydrodynamics, kinetic theory, particle and radiation transport, and atomic and nuclear physics. It is fundamental to many key astrophysical problems since these same processes of energy release and particle acceleration occur routinely in cosmic plasmas at many sites throughout the universe from magnetospheres to flare stars, cosmic X-ray and gamma-ray bursters, supernovae, accretion discs around black holes and neutron stars, the galactic center, and active galaxies. These processes are the most energetic that we observe but all of the astronomical sources are remote, many of them extremely so, and the emissions appear exceedingly weak. It is only with the active Sun that one can pursue the study of this basic physics with the spatial, spectral, and temporal resolutions required to reveal the nature of these processes. Thus, the HESP results will impact research in many branches of astrophysics, not only because of the direct observations of the hard X-ray and gamma-ray emissions from cosmic sources, but also because of the solar flare observations themselves.

3) To what extent is the mission or initiative expected to resolve them?

HESP will produce hard X-ray, gamma-ray, and neutron observations of many solar flares over a significant fraction of a solar cycle with unprecedented spatial, spectral, and temporal resolutions - resolutions that are required to reveal the nature of the high-energy processes. An evaluation of our current understanding of solar flares strongly suggests that the availability of X-ray and gamma-ray spectra, with keV resolution, arcsecond size scales and on timescales of order 0.1 s, will provide key information leading to the elucidation of the operable physics. Similarly, HESP will also provide direct high-resolution observations of many cosmic hard X-ray and gamma-ray sources. Thus, HESP will provide the opportunity for major new breakthroughs in understanding the fundamental energy release and particle acceleration processes that occur in solar flares and at many sites throughout the universe. Based on results from earlier space missions with much more modest capabilities, new discoveries can be confidently expected from HESP, and the solutions to many of the outstanding problems of contemporary high-energy solar astrophysics will be within our grasp.

B. Generality of Interest

1) Why is the mission or initiative important or critical to the proposing scientific discipline?

2) What impacts will the science accomplished by the mission or initiative have on other disciplines?

3) Is there potential for closing the major gap in knowledge, either within an important discipline or in areas bridging disciplines?

- Much previous effort has been expended in observing and understanding the thermal aspects of solar flares. Optical, UV, EUV, and soft X-ray spectra have been obtained with exquisite resolution such that the temperature,

velocity, and, in some cases, density distributions can be estimated during the impulsive and gradual phases of solar flares. It has become obvious, however, that only by observing the evidence of the high-energy non-thermal processes at the core of solar flares can we hope to understand the fundamental questions that remain unanswered:

- How is the flare energy released on such short time scales?

- How are the electrons and ions accelerated to such high energies on similar time scales?

Unfortunately, there are few direct observational indicators of the energy release and particle acceleration processes. Of the many available signatures of the later consequences of these processes, hard X-rays, gamma-rays, and neutrons, along with radio and microwave emissions, form a distinct class in that they are produced before the accelerated particles are thermalized in the ambient atmosphere. Thus, they provide the most direct information available on the energy release and particle acceleration processes.

• Contemporary solar-flare physics came of age with the pioneering observations carried out with instruments flown during the active phase of the last solar cycle (1978 to 1984) on the NASA Solar Maximum Mission (SMM) and the International Sun-Earth Explorer 3 (ISEE-3), the Japanese Hinotori satellite, and the DoD P78-1 spacecraft. Of the many results obtained, the first imaging of solar flares in hard X-rays and the detection of gamma-ray lines from many flares are particularly significant.

However, none of these spacecraft was able to obtain imaging at energies above 40 keV, and even at lower energies, the ≳8-arcsecond angular resolution and ≳10-s time resolution were not adequate to resolve the flaring magnetic structures either spatially or temporally. Furthermore, none of the gamma-ray lines detected with the Gamma Ray Spectrometer on SMM could be resolved and much of the observed nuclear emission was not decomposed into its individual lines. Thus, it was not possible to measure line widths or line shapes and only a small fraction of the potential of nuclear gamma-ray line spectroscopy could be realized.

In contrast, HESP is the first solar mission designed to make all of these measurements simultaneously with the requisite high spatial, spectral, and temporal resolutions, thereby allowing definitive studies of the most fundamental high-energy physical processes occurring in the solar atmosphere.

• Solar flare physics, like all sciences, requires both experiment and theory to work together. However, the theoretical models being currently advanced in this discipline cannot be critically tested owing to the lack of observations with sufficiently fine spectral, spatial, and temporal resolutions. HESP will provide such observations on the relevant scales to provide stringent tests of these models.

• The primary objective of HESP is to make the necessary measurements to understand the processes of impulsive energy release and particle

acceleration in solar flares. These processes occur at many sites throughout the universe, such as magnetospheres, flare stars, cosmic gamma-ray burst sources, supernovae, X-ray bursters, the galactic center, and active galaxies. As a result, HESP will have a direct impact on research in many subdisciplines of astrophysics.

- It is believed that the energy released during a flare comes from the dissipation of the non-potential components of strong magnetic fields in the solar atmosphere, possibly through magnetic reconnection, a process that is common to laboratory, space, solar and astrophysical magnetized plasmas. However, it can be radically different in each environment depending on the magnetic topology and the collisionality of the plasma within each environment. For example, the Sun permits the study of reconnection involving magnetic topologies that are both closed, such as occurs in magnetic fusion devices, and open, such as occurs in the Earth's magnetosphere.

C. Potential for New discoveries and Understanding

1) *Does the mission or initiative provide powerful new techniques for probing nature? What advances can be expected beyond previous measurements with respect to accuracy, sensitivity, comprehensiveness, and spectral or dynamic range?*

2) *Is there a potential for revealing previously unknown phenomena, processes, or interactions?*

3) *In what ways will the mission or initiative answer fundamental questions or stimulate theoretical understanding of fundamental structures or processes related to the origins and evolution of the universe, the solar system, the planet Earth, or of life on Earth?*

4) *In what ways will the mission or initiative advance understanding of important and widely-occurring natural processes and stimulate modeling and theoretical description of those processes?*

5) *Is there potential for discovering new laws of science, new interpretations of laws, or new theories concerning fundamental processes?*

- No previous space mission has obtained hard X-ray imaging with better than 8-arcsecond resolution at energies below about 40 keV and no imaging at all has been obtained at higher energies. Thus, our direct observational information for understanding the high-energy radiations has been limited primarily to spatially integrated spectra and time variations. Even at energies below 40 keV, HESP will have a factor of at least 5 better angular resolution than previous hard X-ray imagers, a factor of >10 larger sensitive area, and sub-second time resolution compared to the ≳10-s effective time resolution of previous imaging observations.

- No previous space mission has obtained solar gamma-ray spectra with better than the tens of keV resolution possible with NaI(Tl) scintillators. None of the nuclear gamma-ray lines detected with the Gamma Ray Spectrometer on the Solar Maximum Mission (SMM) were resolved by that instrument so that no information on line widths or line shapes could be obtained.

- Of particular importance is the expected long lifetime of this mission so that many flares, including the largest gamma-ray flares, will be observed, thus allowing the highest instrument resolutions to be achieved without the degradation of poor statistics inherent with the weaker but more numerous flares. Because of these factors, major new discoveries are not only expected, they are almost guaranteed.

- Since HESP can image a flare no matter where on the visible solar disk it occurs, no flares will be missed because of the difficulty of predicting which of several active regions may flare next, a problem that plagued the pointed SMM instruments with their limited fields of view. This attribute will greatly simplify operations since HESP can be continuously pointing close to Sun center, independent of the locations of the active regions.

- Understanding solar flares, particularly the acceleration of particles to high energies, is an essential first step in predicting solar activity and its affect on mankind. Since this predictive capability is becoming increasingly important for anticipating problems in the terrestrial environment and for warning astronauts of the potential for high radiation doses in interplanetary space and on the surfaces of the Moon and Mars, HESP will provide important contributions to the national purpose in this area.

- HESP will make observations of plasma phenomena in conditions that cannot be duplicated in ground-based laboratories. For example, the plasma beta (the ratio between the magnetic and the dynamic pressure) varies along a flux tube from much greater than one in the photosphere to much less than one in the corona. Similarly, the plasma collisionality varies along a flux tube from a weakly ionized plasma to a fully ionized plasma, and during flares the plasma within the flux tube can become collisionless over a substantial fraction of its length.

- A close interaction of theorists and observers is essential to achieving the HESP objectives. Accordingly, the HESP program will include a strong component of theoretical support prior to and during the mission.

D. Uniqueness

1) What are the special reasons for proposing this investigation as a mission in space or as an OSSA initiative? Are there other ways that the desired knowledge could be obtained?

HESP is exploring several new areas of solar high energy physics not previously studied; the proposed measurements have never been carried out before. Their importance to advancing our understanding of solar flares lies in the fact that they address the fundamental unanswered questions concerning energy release and particle acceleration in ways that, given our current understanding of solar flares, are generally deemed to be potentially the most rewarding. The accelerated electrons and ions are believed to contain a major fraction of the flare energy and they provide the most direct link available to the energy release process itself. They can best be studied by making high precision X-ray and gamma-ray observations as proposed with HESP.

A second reason for proposing HESP at this time comes from the fact that understanding solar activity in general and solar flares in particular is taking on a new level of urgency within the Agency if we are to proceed with the President's plans for long-term manned presence in space called for by his Space Exploration Initiative. The catastrophic consequences of astronaut exposure to the large fluxes of high-energy particles resulting from an energetic solar flare make the understanding of how, and which, flares produce high energy particles imperative if we are to predict the occurrence of flares and the corresponding fluxes of energetic particles that they produce. As pointed out by the National Research Council, the ability to make accurate predictions of solar flares is of crucial importance to the future of the manned space program. These flares occur most frequently during periods of five or six years around the maxima in solar activity every ~11 years. Thus, it is crucial that full advantage be taken of the next opportunity for studying flares during the maximum expected at the turn of the century, less than ten years from now. Only by observing flares with the very best instrumentation that we can now envision can we hope to understand the basic physics involved in order to optimize our predictive capabilities. Consequently, it is imperative that X-ray and gamma-ray observations be made of many solar flares during the next period of high solar activity with the high spatial, spectral, and temporal resolution of HESP.

- The proposed observations can only be done from space since these radiations do not penetrate the Earth's atmosphere. Observations can be made from high-altitude balloons but sufficient observing time to catch the unpredictable large flares that typically occur as infrequently as once per year, even during solar maximum, is impossible to obtain. Furthermore, X-rays below about 30 keV suffer significant attenuation at balloon altitudes. Consequently, it is impossible to obtain the crucial information concerning the lower energy end of the X-ray spectrum which comes from the energetically most significant electron population below about 50 keV. Also, the context information about the thermal plasma generated during the flare at temperatures as high as 20 or 30 million K cannot be obtained from a balloon. HESP will provide this information from observations extending down to 2 keV with similar spatial, spectral, and temporal resolutions as at higher energies.

2) Is there a special requirement for launching the mission or starting the initiative on a particular time schedule?

- Since HESP is a solar flare mission, it is imperative that it be in space during periods of high solar activity that occur on an 11-year cycle. The next maximum is expected to occur around the year 2001 with usefully high activity levels occurring from 1998 to 2005. Thus, ideally, HESP would be in space for this 7-year interval to be sure to catch all of the most important events of the next solar cycle. Currently, HESP is baselined for a 3-year operations lifetime during this 7-year period.

- There are long-range proposals being considered for manned polar orbiting missions, lunar bases, and Mars missions by the early 2000's. However, large solar flares can result in particle and radiation fluxes that could prove fatal to astronauts on such missions unless they were able to take pharmacological countermeasures in advance or were warned in time to

enter shielded enclosures. HESP and OSL are the only solar spacecraft presently planned that are capable of providing the new understanding of flares that will be required to develop a predictive capability before these missions are undertaken. HESP is particularly useful in this respect since it will provide direct information on the acceleration of the high-energy particles that are of the greatest danger to the astronauts.

- The United States has always held a commanding lead in solar astrophysics. There is no other country or foreign agency that can execute a mission with the capabilities of HESP because of the unique HPGe technology required and the experience gained by US scientists using balloon-borne instrumentation. Therefore, the international solar community looks to the U.S. to take this next major step in flare observations.

II. PROGRAMMATIC CONSIDERATIONS

A. Feasibility and Readiness

1) Is the mission or initiative technologically feasible?

2) Are substantial new technological developments required for success?

- The detector and imaging technologies required for the HESP instrument have already been developed for the following balloon instruments: the High REsolution Gamma-ray and hard X-ray Spectrometer (HIREGS) and the High Energy Imaging Device (HEIDI) to be flown next year. HIREGS consists of an array of twelve, large, segmented, germanium detectors surrounded by a bismuth germanate (BGO) shield, very similar to HESP. HEIDI utilizes rotating modulation collimators similar to those baselined for HESP, and its solar aspect system is identical to that planned for HESP. Grids with finer resolution than currently being fabricated for HEIDI, down to 50-micron slit widths, must be developed for HESP. Parallel research efforts are now being carried on at Goddard Space Flight Center and in The Netherlands to achieve this goal.

- The simple spinning HESP spacecraft concept developed at Goddard requires no new technology development. The mechanical coolers baselined for the germanium detectors are already space qualified, with the first flight on the UARS spacecraft scheduled for launch this fall. Thus, the HESP mission is technologically feasible and ready for implementation with essentially no new development required.

- The proposed Sun-synchronous polar orbit for HESP has inherently eliminated many difficulties usually associated with low-inclination Earth-orbiting spacecraft. In particular:

  - There will be no day/night thermal extremes since the Sun-synchronous polar orbit provides constant sunlight (except for periods of short eclipses for part of the year).

  - There will be no need for reacquisition of the Sun since there is no day/night cycle.

  These factors lead to greatly reduced challenges, hence costs, for spacecraft engineering and mission operations.

3) Are there adequate plans and facilities to receive, process, store and distribute data at the expected rate of acquisition?

- Yes. On the assumption that HESP is assigned to GSFC, the following data handling and ground-support facilities will be used:

  - The GSFC Information Processing Division (IPD)) will provide data capture from the NASA Communications Network;

- A HESP Science Data Operations Center at GSFC will include a Data Management Facility (DMF), a Data Processing Facility (DPF), and a Data Analysis Facility (DAF); and

- Remote DAF's at the PI institutions will provide off-center data access and analysis capabilities.

4) Are there adequate plans and funding identified for scientific analysis of the data?

• If HESP is assigned to Goddard, the Space and Earth Sciences Directorate would be responsible for the management of science data processing, distribution and archiving. In particular, the HESP Data Processing Facility (DPF) will:

- Store, copy and distribute raw data in digital formats

- Create electronic catalogs of all data from the mission

- Generate and distribute calibrated data products

- Store and distribute correlative data products

- Distribute analysis software (generally produced by the investigators)

• Data analysis itself will be supported either at the HESP DAF at GSFC or from remote stations at the investigators' institutions. The HESP Project Office will have an identified budget line for data analysis.

5) Is there an adequate management and administrative structure to develop and operate the mission or initiative and to stimulate optimum use of the results?

• Yes. GSFC has developed data systems for data processing during flight operations for missions such as IUE, SMM, COBE, GRO, and ROSAT, all similar to that required for HESP's science data processing requirements:

- IUE is the model for the "Facility-mode" science data processing for HESP data. SMM is similar to the Principal Investigator-mode of operations planned for the initial period of HESP science (i.e., following checkout/verification, but before Guest Investigations).

- Both Guest Investigator and Theory Programs will be budgeted as integral parts of the HESP program.

- Finally, following the process pioneered by the solar community after Skylab, a series of workshops will be directed and funded from Headquarters to ensure the widest possible access to the HESP data by the astrophysics community.

B. Space Operations and Infrastructure

1) What are the long-term requirements for space operations, including launches, replacement and maintenance of instruments, and data acquisition and transfer?

- According to the Goddard spacecraft concept study completed in May, 1991, HESP will be launched on a Delta rocket into a Sun-synchronous, dawn-dusk, polar orbit with an altitude of 600 km.

- HESP has no consumables and hence is expected to operate for the full three-year mission lifetime with no requirement for on-orbit replacement or servicing of the instrument.

- Because HESP consists of a single, multi-function, instrument with a single basic mode of operation and with full-Sun coverage, operations support will be extremely simple. Regular monitoring of the health and safety of the mission will be required but very few commands are anticipated to keep the instrument operating and automatically recording background and solar flare data and storing it in the on-board memory. The data will be played back on command to a ground station on a few orbits per day. Other stored commands will be uplinked periodically to control the instrument operations so as to prevent degradations due to passages through the high-charged particle fluxes in the trapped radiation belts.

- Data acquisition and transfer will be covered by the HESP Data Management Plan.

    - GSFC already routinely provides such services for comparable missions, like IUE and COBE, and for vastly more complex missions such as HST.

    - Likewise, GSFC operates the NSSDC data archival system with high speed networks (e.g., a 1.3 Mbps line to universities and intercenter networks up to 100 Mbps, in addition to low speed electronics networks such as SPAN).

2) What current and long-term infrastructure is required to support the mission or initiative and the associated data processing and analysis?

- See answers to II.A. 3), 4), & 5) above.

C. Community Commitments and Readiness

1) Is there a community of outstanding scientists committed to the success of the mission or initiative?

- A dedicated group of US solar physicists have, over the last seventeen years, doggedly pursued a high-energy solar imaging mission as a follow-on to the highly successful Solar Maximum Mission. This effort has been focussed by a series of NASA committees starting with the Hard X-ray Imaging Facility Definition Team convened in 1974, followed by the Pinhole/Occulter Facility Science Working Group, the Max '91 Science

Study Committee, the Solar High-Energy Astrophysical Plasmas Explorer proposal in 1986, the Max '91 Solar Balloon program, and culminating with the current HESP Science Study Group.

- The Solar Maximum Mission, during its almost 10-years of observations, was supported by a large community of solar physicists numbering close to 1000. Over 100 people attended the international SMM workshops series in the 1980's that resulted in a comprehensive publication outlining the then current status of the field.

- The international FLARES 22 and the US Max '91 programs, established to coordinate solar observations during the current maximum, regularly have close to 100 people attending their workshops and over 50 groups around the world participate in the observing campaigns that are called periodically to obtain coordinated observations of solar activity.

- There are extensive communities of solar physicists in many countries around the world, including Germany, the United Kingdom, France, The Netherlands, Norway, Switzerland, Italy, the Soviet Union, Japan, India, China, and Brazil.

- There is an increasing interest on the part of plasma physicists who recognize that the solar atmosphere contains many phenomena for study involving regimes of temperatures, densities, and/or spatial scales unavailable in the laboratory.

2) In what ways will the community participate in the operation of the mission or initiative and in the analysis of the results?

- It is anticipated that a significant number of Guest Investigators will be involved in the reduction and analysis of HESP data in addition to the members of the PI teams. Starting about three months after launch, it is expected that HESP will be available to selected Guest Investigators.

- An extensive program of ground-based optical and radio observations is planned involving a world-wide network of observatories. These observers will have access to the HESP observations and they will be involved in the joint analysis of the data.

- GI's will also be selected to provide complementary data from other spacecraft, and from rocket- and balloon-borne instruments. These GI's will also have access to the HESP data from observations that coincided with or complemented their own and they will be involved in the joint analysis of the respective data sets.

- Several years prior to launch, a HESP Theory Program will be initiated to directly support the development of advanced theoretical models that can be directly tested with HESP observations, and to suggest observations not otherwise planned.

D. Institutional Implications

1) In what ways will the mission or initiative stimulate research and education?

- The availability of new observations at the frontier of any area of science has always led to the involvement of bright new students as well as established research personnel; the same is expected of HESP. Students have participated extensively in previous solar missions, particularly Skylab and SMM, and they are heavily involved in the development of the balloon-borne forerunners to HESP. Such hands-on participation will continue to be encouraged throughout the development phase of the HESP instrumentation. In addition, a Student Investigator Program (SIP) will be proposed prior to launch to ensure that the newest generation of researchers can participate directly in the observation and data analysis phases.

2) What opportunities and challenges will be presented to NASA Centers, contractors, and universities?

- HESP will stimulate all involved institutions to develop capabilities for carrying out high resolution X-ray and gamma-ray imaging spectroscopy in space. For the imaging aspects, this will include developing optical and mechanical technologies for fabricating the collimator grids from high-Z materials (e. g., tungsten or tantalum) down to the finest slit widths of 50 microns. In addition, the characterization of these grids and their alignment both on the ground and in orbit must be accomplished to achieve arcsecond imaging. For the spectroscopy aspects, techniques for handling the cooled germanium detectors, including maintaining their temperature at ≤ 85 K for long periods in space, must be perfected. Also, computational techniques must be developed to analyze, display, and interpret the detailed imaging spectroscopy data from HESP. This challenge will be especially true for the NASA Center assigned the responsibility for carrying out the HESP mission and being responsible for the project and science management.

- HESP will also stimulate complementary ground-based solar observations at optical and radio wavelengths. Such observations will provide the photospheric magnetic field and the context within the solar atmosphere for the HESP high-energy flare observations. Furthermore, the spatially and spectrally resolved radio observations give complementary magnetic-field-weighted indications of the high-energy electrons accelerated during the flare for direct comparison with the density-weighted indications obtained from the HESP X-ray and gamma-ray observations.

3) What will be the impact of the mission or initiative on OSSA activities? Will new elements be required? Can some current activities be curtailed if the mission or initiative is successful?

- HESP, as an intermediate-class mission, would provide a much-needed NASA focus for the next peak in solar activity expected at the turn of the century. In the same way that SMM provided a focus during the last

cycle, HESP will allow NASA to reestablish a strong program of solar activity research after the relatively small Max '91 effort during the current solar maximum.

- For HESP to be fully successful, a program of coordinated and complementary observations must be organized along the same lines as for SMM and the Max '91 program. HESP will benefit greatly from joint observations made at other wavelengths with instruments on other spacecraft, on rocket- and balloon-borne payloads, and at ground-based observatories. It is particularly important that rocket and balloon flights be continued since they are the proving grounds for new instrumentation, some of which will be used on HESP, and they will provide the opportunity to obtain observations with the latest, state-of-the-art instrumentation during the HESP operational lifetime.

E. Collaborative Involvement by Other Agencies or Nations

1) Does the mission or initiative provide attractive opportunities for involving leading scientists or scientific teams from other agencies or other nations?

- Yes. Strong interest has been expressed in the HESP mission by solar physicists in several other countries including France, The Netherlands, Germany, England, the Soviet Union, and Japan. Scientists from several of these countries are part of the HESP Science Study Group.

- Scientists from several European countries (United Kingdom, Germany, Switzerland, France, The Netherlands) are likely to become involved as Co-Investigators of the U.S. investigations.

2) Are there commitments for programmatic support from other nations, agencies, or international organizations?

- This is not possible at this stage of the planning process but, as stated above, there is strong interest in several countries.

F. Costs of the Proposed Mission or Initiative

1) What are the total direct costs, by year, to the OSSA budgets?

2) What are the total direct costs, by year, to the NASA budgets?

Cost estimates for HESP have been made by both the Resource Analysis Office (RAO) at GSFC and Ball Aerospace Systems Group (BASG). The two estimates are based on independent studies and include the total cost for the mission through launch plus 30 days. The breakdown of these estimates is given below with all costs given in millions of FY 1991 dollars.

RAO GSFC Estimate

	Cost Plus 10% Fee	Contingency (%)	Total Cost
Spacecraft	62	20%	74
Instrument	46	30%	60
MSI&T	28	30%	37
Code S Development	5	25%	6
Code O Development	18	25%	22
Total	159		199

Ball Aerospace Estimate

	Cost Plus 10% Fee	Contingency (%)	Total Cost
Spacecraft	61	20%	73
Instrument and MSI&T	67	60%	108
Ground Support	10	60%	16
Total	138		197

The breakdown of the costs by year has not been made at this time since it will depend on when HESP is begun and how quickly it can be readied for launch during the next solar maximum. Also, the MO&DA costs have not been estimated although they will be comparable to a relatively simple Explorer-class mission baselined for a three-year lifetime. Costs for the launch vehicle and launch operations will be typical for a Delta rocket.

3) What portion of the total costs of the mission or initiative will be borne by other agencies or nations?

• Other funding sources, representing approximately 15% of the science facility and instrumentation costs, can be expected from foreign sources although no definite commitment can be made at this time. As indicated in Section E above, it is expected that significant contributions will be made both to the hardware and to the scientific data analysis.

III. SOCIETAL AND OTHER IMPLICATIONS

A. Contribution to Scientific Awareness or Improvement of the Human Condition

1) Are the goals of the mission or initiative related to broader public policy objectives such as human welfare, economic growth, or national security?

- Understanding energetic solar activity to the point of having a reliable predictive capability is important to national and international interests because of its effects, in a wide variety of ways, within the Earth's aerospace environment. Examples of such effects are as follows:

  - Interference in space-based communications and control systems

  - Anomalous perturbations to satellite orbits

  - False signatures in space-based detection systems

  - Threats to astronaut safety

  - Interference in geomagnetic navigational and detection sensors

  - Induced currents in high geographic latitude pipeline and power grids.

  - Threats to passenger and crew safety on the National Aerospace Plane on over-the-pole flights.

2) What is the potential for stimulating technological developments that have application beyond this particular mission initiative?

- The development of mechanical coolers and adapting them to maintain the HPGe detectors at temperatures of ≤ 85 K for extended periods of time in space.

- The development of fine collimation grids and the capability for making X-ray, gamma-ray, and neutron images with high-sensitivity and arc-second angular resolution in space.

- Analysis software and display techniques to quantitatively analyze and interrelate the essential flare data such as the X-ray, gamma-ray, and neutron images at different energies, the photon energy spectra as a function of time and space, and the corresponding parameters of the electron and ion spectral distributions.

3) How will the mission initiative contribute to public understanding of the physical world and appreciation of the goals and accomplishments of science?

- The Sun is the most important of all celestial objects to life on the Earth. Display of the incredible range of activity in the solar atmosphere, down to the limits of spatial resolution to be achieved with HESP, will certainly demonstrate that our physical universe never ceases to offer new challenges

and knowledge as we develop new observational techniques that open up new spatial, spectral, and temporal ranges never previously explored.

- A better understanding of the fundamental physics that gives rise to high-energy solar phenomena will lead to better predictors of the solar cycle and solar flares, and to enhanced predictions of solar-terrestrial-effects, a number of which are of keen interest to the public (see III.A. 1)).

B. Contribution to International Understanding

1) Will the mission or initiative contribute to international collaboration and understanding?

- Yes. See II.E. above.

2) Do any aspects of the mission or initiative require sensitivity to the concerns of other nations?

- HESP will provide observations that are highly complementary to the measurements planned with the European Space Agency's Solar and Heliospheric Observatory (SOHO). Also, HESP will benefit from the pioneering observations to be made with the high-energy instruments on the Japanese Solar-A spacecraft, due to be launched in August, 1991. It will be important to coordinate HESP with the ESA and Japanese follow-on solar missions.

C. Contribution to National Pride and Prestige

1) How will the mission or initiative contribute to national pride in U.S. accomplishments and to the image of the United States as a scientific and technological leader?

- The United States has lead the world in the scientific exploration of space, but the only instruments that have ever obtained hard X-ray images of solar flares have been non-US: the Hard X-ray Imaging Spectrometer on SMM was built by a Dutch/UK collaboration and the Hard X-ray Telescope was built and flown by the Japanese on their Hinotori spacecraft. The latter is shortly to be followed by a second-generation Japanese hard X-ray imager on Solar-A. However, the US is now embarked on the development of a balloon-borne payload that will provide the finest spatial resolution and will cover the highest energy range of any imager that has been flown to date or is currently planned. HESP is a mission of world-class caliber that will build on this experience; it is an imager with order-of-magnitude improvements over currently planned hard X-ray capabilities and it will cover the gamma-ray range for the first time. Furthermore, the United States is the only country with the requisite germanium detector technology to allow high-resolution spectroscopy to be incorporated. Consequently, implementation of the HESP mission will afford America the opportunity to regain supremacy in this field, thus contributing to its stature as the leading nation in space science.

2) Will the mission or initiative create public pride because of the magnitude of the challenge, the excitement of the endeavor, or the nature of the expected results?

• The U.S. public has consistently shown great interest and pride in our space science programs. There is every reason to think that HESP will continue to engender such interest. The American public is generally aware of sunspots, solar activity, and solar flares. HESP results should be of great interest to public television and American science education programs of all levels, especially since it will produce graphic movies of solar flares as revealed for the first time in the highest energy emissions.