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A HARD X-RAY IMAGING INSTRUMENT FOR SOLAR AND COSMIC SOURCES

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Abstract

A Hard X-Ray Imaging Instrument is described which is capable of high resolution imaging of solar and cosmic hard X-ray sources between 2 and 80 kev during Shuttle sortie flights. The properties of solar burst sources and the resulting instrument requirements are discussed. The instrument envelope of 1.2 x 1.2 x 3.0 meters includes a tungsten multigrid collimator which has 4" resolution, a 40' response envelope and a point source effective area of 26 cm^2. A combination of periodic fan beans and non-periodic pencil beams enable a unique deconvolution to be achieved within a 128" x 128" field without mechanical scanning. The detector system is a set of direct-readout 40 atm-cm Xenon-filled proportional counters, designed to minimize background. The instrument is capable of refurbishment to optimize the collimator configuration for specific solar or cosmic scientific objectives, to upgrade the angular resolution or to extend the high energy response.

Introduction

The last decade of high energy observations in space has shown that particle acceleration plays a major role in the energetics of solar flares. Energetic particles have been observed via their radio, X-ray and γ-ray emission and have been analyzed as solar cosmic rays. Because of the relatively simple physics of their propagation, X-rays can provide the most direct means by which to study the acceleration and propagation of energetic electrons in solar flares. Hard X-ray observations have provided valuable quantitative information on the spectrum and time evolution of accelerated electrons. This information has been limited, however, since no direct spatial information has been available to relate the location and spatial distribution of the high energy electrons to the optically observed magnetic field configurations in the acceleration region. Hard X-ray imaging with appropriate time, spatial and energy resolution would enable significant new insights to be obtained on particle acceleration in solar flares and cosmic phenomena.

The Hard X-Ray Imaging Facility Definition Team was constituted by NASA to define the scientific objectives, instrumental concepts and specifications, implementation and operation of a Shuttle-borne instrument to obtain hard X-ray images of the sun during solar flares. The work of this team has resulted in the design of an instrument to achieve these scientific goals and which represents a significant, yet practicable step forward in high resolution hard X-ray imaging.

Solar hard X-ray bursts provide a rather different set of constraints on the design of a hard X-ray instrument thatn those posed by other sources. The nature of these constraints will be described below, along with the collimator concepts chosen to adapt to them. A version of the instrument proposed for flight on Spacelab-2 in 1980 will be described.

This version, which requires an envelope of $\sim$1.2 x 1.2 x 3.0 m, is compatible with a number of proposed Spacelab pointing systems, including the Small Instrument Pointing System (SIPS). In the configuration described, HXII features 4 arc second resolution, a full sun field of view and an effective area of 26 cm^2. It is well suited for imaging of both solar burst and cosmic sources.

Characteristics of Solar X-Ray Bursts

Integrated characteristics of solar X-ray bursts have been well established over the last decade of observations(1). Figure 1 illustrates the spectrum of such a burst, which is characterized by two components. Above 20 kev, emission is due to bremsstrahlung of non-thermal electrons and is frequently parameterized by a power law in energy, $E^{-\gamma}$, where $2.5 \leqslant \gamma \leqslant 6$ and typically is $\sim$4. The thermal component which dominates at lower energies is parameterized by an emission measure and temperatures in the range 10 to 20 million degrees. The extreme steepness of the spectrum, which can cover up to 10 orders of magnitude between 1 and 100 kev, should be noted. The spectrum shown in Figure 1 represents the largest flare which might be observed in a year. Smaller flares have qualitatively similar spectra but much lower fluxes so that, for example, the peak 20 kev flux of a typical once-a-day flare is about 0.3 photons/cm^{2}sec kev (2). The spatial dependence of the spectral parameters is one of the key observational objectives of solar hard X-ray imaging.

The non-thermal component typically has rise and decay times in the range 2-5 seconds and 3-10 seconds respectively. Durations vary from <10 to ~10^3 seconds with the observed fine structure as short as 1 to 2 seconds. It is important to note that these time scales are the result of integrated sun measurements so that shorter time scales may be observed with imaging detectors.

Indirect evidence from soft X-ray, radio, and optical data suggest that much of the emission may come from kernels of emission with size scales of 2"-8" which are separated by distance up to 2 arc minutes. Thus the expected character of the images is that of high contrast, compact features viewed against a black sun.

In addition there are theoretical considerations which suggest that weak, extended X-ray emission, originating in the corona may also be observable. These X-ray analogues to Type II, III, and IV radio bursts would be several arc minutes in extent.

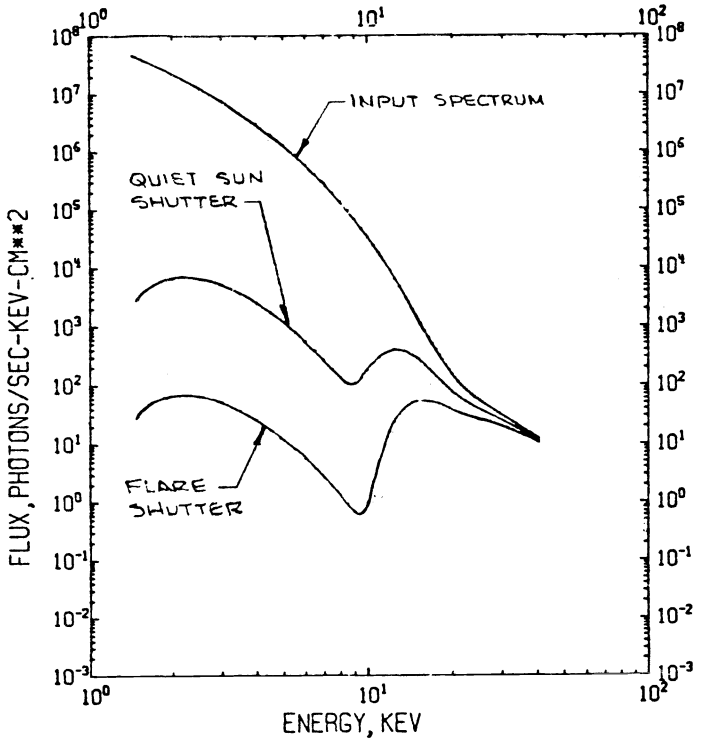

Fig. 1. Model solar X-ray spectrum for a large solar flare. The effect of shutter assemblies in modifying the pulse-height spectrum is also shown. The shutters consist of 0.2 gm/cm^2 of aluminum with appropriate apertures to permit a controlled fraction of low energy photons to be detected.

Instrument Parameters

In the design of any instrument, there is always a balance to be struck between what one would like to do and the limitations posed by physical considerations, current technology, externally imposed boundary conditions and cost. Table 1 indicates the HXII parameters, as configured for Spacelab 2, along with the scientific drivers and corresponding technical constraints.

Multigrid Collimators

The instrument parameters outlined below would appear in some respects to be incompatible with a collimator of the scale under consideration. For example the sensitivity and time resolution requirements imply the system must have an effective area of several tens of cm^2 while the field of view and resolution requirements imply that to view the full sun with 4 arc second resolution requires about 2×10^5 pixels. Such requirements are unachievable in a ∿1 m^2 collimator unless suitable multiplexing techniques are used.

One approach to this problem is to take advantage of the nature of solar burst sources. While in general one cannot predict with adequate assurance which solar active region will be the location of the next burst, it is expected that the maximum extent of the burst source, wherever it occurs, will be limited to less than 2 arc minutes. To see how this property is useful, it should be recalled that the response of conventional multigrid collimators (3) is characterized by three parameters: the FWHM angular resolution which is given by the ratio of aperture size to collimator length; the period (or angle between planes of maximum transmission), which for a given resolution is determined by the number of grids; and the envelope of the collimator response which is given by the ratio of the collimator width to its length. If the period of the collimator is comparable to the envelope, there is only one transmission maximum and the collimator may be termed non-periodic. In this work, a collimator will be considered non-periodic if its period is greater than the solar diameter of 32 arc minutes. For unambiguous imaging of solar bursts it is not necessary to have such a non-periodic collimator, but rather it is only necessary to ensure that the period exceed the maximum burst extent of 2'. Although the source

Table 1: Instrument Parameters

		Scientific Drivers	Constraints
Low Energy Limit	2 kev	* Quantitative imaging of thermal component * Overlap with focussing telescopes	* Pulse pileup * Diffraction * Window/detector
Upper Energy Limit	80 kev	* Quantitative imaging and spectra of non-thermal component	* Detector efficiency * Grid transparency * Sensitivity * Background
Energy Resolution	7-30%	* Parameterization of thermal and non-thermal spectra	* Detector
Dynamic Range	10^{-4} to 10^{8} photons $(cm^2 sec\ kev)^{-1}$	* Imaging large bursts without pulse pileup * Sensitivity to low fluxes at high energies	* Detector count rate limits * Window/shutter response * Background
Time Resolution	< 1 second	* Time scale of solar X-ray bursts	* Photon statistics
Angular Resolution	4"	* Inferred size scale of solar hard X-ray sources	* Grid fabrication * Metering structure * Sensitivity tradeoff * Diffraction
Field of View	40' 2'	* Full sun coverage * Maximum extent of individual burst sources	 * Sensitivity tradeoff
Sensitivity	0.1 ph $(cm^2 sec\ kev)^{-1}$ at 20 kev	* Need to image several non-thermal bursts during a 7 day sortie mission	* Instrument envelope

location is ambiguous to integral multiples of the period, this ambiguitiy can easily be removed with auxiliary coarse imaging or with simultaneous optical data. The use of collimators with periods of $\sim$2' rather than $\sim$32' can ease but not eliminate the sensitivity problem.

A second technique well suited to solar burst imaging is the use of phased arrays of subcollimators rather than mechanical modulation of a single collimator. Figure 2 illustrates the concept of the phased array of subcollimators. Each grid of a multigrid collimator is divided into a number of regions, each separated by a few millimeters while within each region or subcollimator, an appropriate pattern of apertures is etched. A number of properties of such a set of subcollimators should be noted:

1. The angular response of each subcollimator need not necessarily be related to the response of other subcollimators.
2. If the design and fabrication of the grids is done correctly, alignment of the grid implies alignment of all the subcollimators within the grid.
3. The coalignment of all subcollimators within a grid is determined by the design and fabrication and is relatively immune to subsequent changes.
4. Intercalibrated detectors of moderate spatial resolution are required to provide clean identification of which subcollimator a detected photon passed through.

A particulaly useful special case, also illustrated in Figure 2, is the phased array of subcollimators where (in one dimension) the central response peak in one subcollimator is displaced from the previous subcollimator by an angle equal to its FWHM resolution. If N subcollimators are provided where N = (Period/Resolution), then each source point is viewed by at least one subcollimator , with the additional property that (subject to envelope restrictions) all such source points are viewed with the same total effective area. Compared to the alternative of a mechanically scanned single collimator, phased arrays have comparable sensitivity plus immunity to ambiguities due to rapid source changes. Dynamic range is improved since they do not have the count rate variations of scanning systems.

Tradeoffs Among Collimator Systems

Over the last decade many collimator concepts have been developed in response to specific problems in hard X-ray imaging. When viewed, however, in the light of the instrument parameters outlined above, each involves a different compromise in sensitivity, time, energy and/or angular resolution, image reconstruction or technical feasibility.

For example, a phased array of $\sim 10^3$ 4"x4" two-dimensional collimators with a period of ~ 2 arc minutes would satisfy all the requirements described above except for sensitivity which would be low by over an order of magnitude. Such an approach which nevertheless has the advantage of direct imaging, is inherently inefficient in its use of collimator frontal area. Since almost all the emission is expected to be in highly compact knots, loops, etc., the vast majority of subcollimators are looking at black sun.

One way around this is the use of a foveal system which consists of a much smaller phased array of non-periodic, two dimensional subcollimators supplemented by a small number of coarse resolution elements. Collectively the system views the whole sun, although the high resolution elements view only a small area of perhaps 32 arc seconds square. When a burst occurring anywhere on the sun is detected by the coarse elements, a microprocessor control system then issues commands to the pointing system so as to direct the high resolution elements to the location of the burst within 1 to 2 seconds. Should the burst be larger than the 32"x32" high resolution field of view, this would be sensed by the coarse elements and the pointing system directed to 'time share' the high resolution elements among the different regions of interest. Although the system would always be alert to the full sun, only the center of its field of view would be imaged with the highest resolution. It is analogous to the human eye which responds by turning to look directly at objects of interest which are first sensed by peripheral vision. The use of a foveal system could provide direct imaging with marginally adequate sensitivity but with some susceptibility to rapid changes in sources larger than 32".

Phased arrays of fan beams can meet virtually all the requirements but have the drawback of requiring a deconvolution step to recreate the two dimensional image. Although their sensitivity is good, very complex source configurations could lead to ambiguities in the deconvolution step.

The rotating modulation collimator (4) with adequate period and resolution does not provide a significant sensitivity advantage over the fan beam approach. In addition to the mechanical complexity of the rotation drive, it also requires a deconvolution step of comparable or greater complexity.

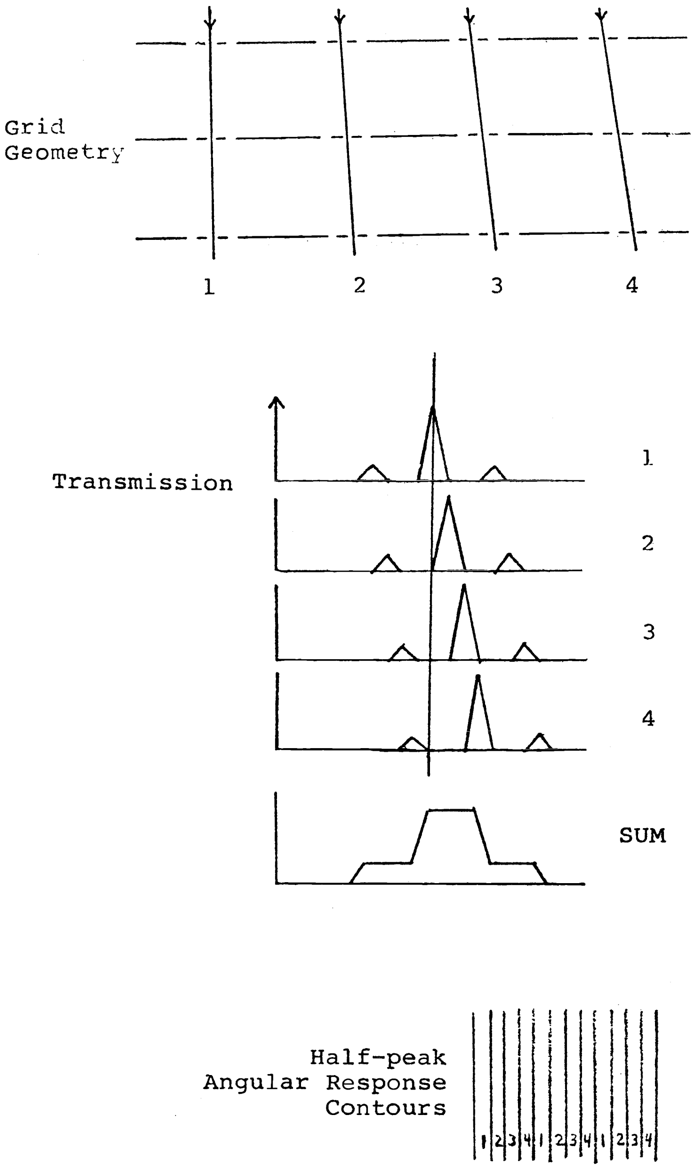

Fig. 2. A Phased Array of Subcollimators. The top panel shows the geometry of a three grid collimator divided into 4 subcollimators, each with a period four times the resolution FWHM. The second panel shows the transmission of each subcollimator and their sum, illustrating the "uniformity of field" property whereby subject to the envelope, the summed transmission over all subcollimators is uniform. The bottom panel shows how the angular half peak contours repeat to give wide field, high resolution coverage. These properties of phased arrays are retained in two dimensions if square apertures are used.

Random array systems (5), in both their one and two dimensional forms, offer outstanding sensitivity and simplicity of construction over multigrid approaches, but the angular resolution of 4" requires a detector spatial resolution of about 50 microns, which is not within the state of the art for a detector with the required energy resolution. Although techniques have been identified by which this spatial resolution requirement could be eased, the penalty in sensitivity is too great to make this a viable alternative.

A detailed tradeoff study among these and other collimator approaches indicated that the foveal system and phased arrays of fan beams were best suited to the instrument requirements. Both of these systems require similar metering structures and detectors and so can be flexibly combined within a given instrument. The combination has the additional advantage that the fan beams provide the continuous full sun, high resolution coverage that the foveal system lacks, while the foveal system is direct imaging and so can provide a guide to fan beam deconvolution, if necessary.

The Hard X-Ray Imaging Instrument

The Hard X-Ray Imaging Instrument (HXII), as proposed for Spacelab 2, is illustrated in Figure 3. The actual layout is determined by structural, thermal, and detector considerations. The basic metering structure identified as a working concept is a truss structure, divided into four quadrants, each of which supports grid planes and counter elements independently. Each grid plane is further divided into four collimator areas, called frames. The sixteen collimator frames are utilized as follows: 6 high-resolution fan beam arrays; 4 low resolution fan beam arrays; 4 two-dimentional foveal arrays; 2 reserved for auxiliary instruments such as full sun monitors and aspect sensors.

The high resolution fan beams and foveal elements have a combined point source effective area of 26 cm^2. The additional 20 cm^2 of effective area provided by the low resolution fan beams is used to image the extended coronal sources as well as to direct the foveal elements to the solar burst location. Grids within each frame are fabricated from sheets of 50 micron thick tungsten. Their 22 x 22 cm area is divided into subcollimators, 3.4 or 5 cm on a side and separated by 0.5 cm. The total number of subcollimators is 376, not including those reserved for background and alignment monitoring. Table 2 shows the allocation of subcollimators and their properties.

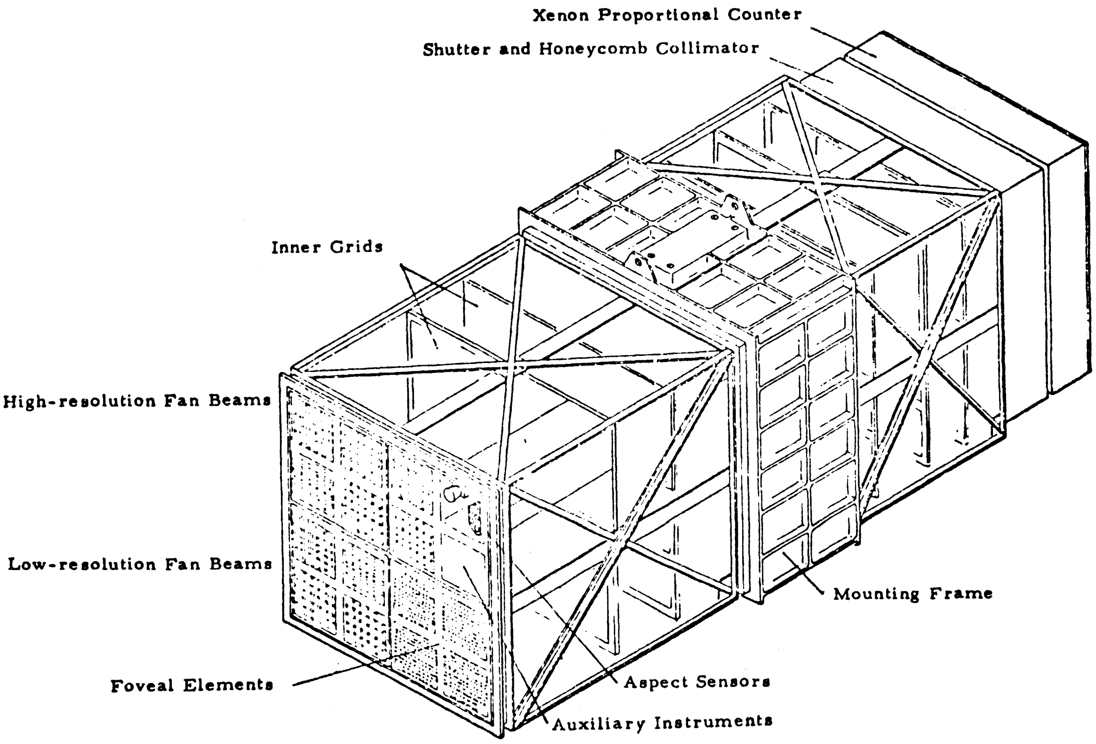

Fig. 3. Schematic layout of the Hard X-Ray Imaging Instrument. Shown is a unitary metering structure/integrating structure that supports several grid planes. The instrument points to the left.

Table 2. Subcollimator Layout

Elements	FWHM Resolution	Period	Envelope	Number of grids	Effective Area per pixel(cm^2)
High-resolution Fan Beams (6x32)	4"	128"	40'	6	3.8
Low-resolution Fan Beams (4x32)	64"	34.1'	40'	6	5.0
Foveal (56 total)	4x4"	-	-	10	3.4

The multigrid collimators are designed so that some misalignment of the inner grids is possible without any effect on the angular response. This is illustrated in Figure 4 for the high resolution fan beams. Although coalignment of subcollimators within a frame (i.e. within a given phased array) is relatively stable, frame to frame coalignment and coalignment to an optical reference axis of the aspect sensor must be reestablished in flight by viewing a known cosmic X-ray point source such as Cygnus X-1.

A significant dynamic range problem for solar X-rays arises from the steepness of the flare spectrum. Good efficiency at the lowest energies is a requirement to observe cosmic X-ray sources. but the thin counter window thereby required creates an extremely high count rate during flares. This imposes the need for a variable geometry such as a moveable shutter system to be operated during flares. The effect is illustrated in Figure 1. A simple mechanical activator is controlled by software in the digital electronics.

Three possibilities exist for the large area multi-element detector array: position-sensitive proportional counters; an array of thin crystal NaI/CsI detectors of the "phoswich" variety (7); or an array of cooled Li or Ge solid-state devices. Although each has its advantages in terms of efficiency, dynamic range, energy resolution, complexity, and engineering problems, cost considerations dictate proportional counters with direct spatial readout as an initial choice.

Obtaining large spectral and dynamic ranges requires careful consideration of counters, window thickness and area, and electronics. The objectives can be met by a Xenon proportional counter with moveable shutters to reduce the effective area during large flares. Each quadrant has a physically distinct proportional counter, with four independent internal elements consisting of two cathode planes with orthogonal wire directions, read out in four or six groups each, to provide the spatial resolution. The anode plane is used for energy and pulse shape discrimination. Figure 5 shows the layout of each of the counters.

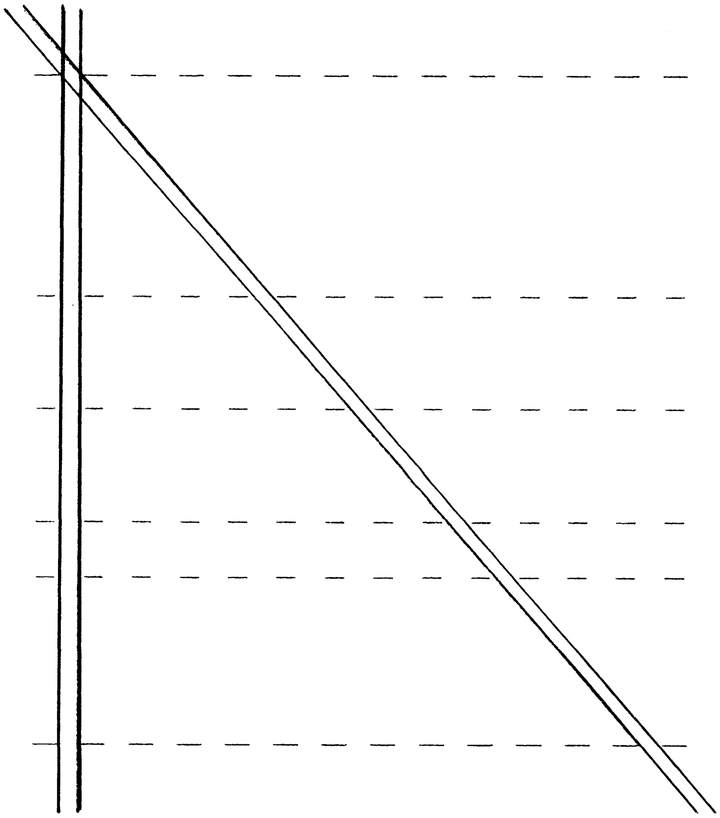

Fig. 4. Example of a periodic multigrid collimatof in which the angular response is unaffected by modest misalignments of the inner grids (6). FWHM resolution and period are 4" and 128" respectively. The transmission is 37.5%. Apertures of the inner and outer grids are 52.4 and 69.8 microns respectively so that a misalignment error budget of ±8.7 microns is available. Note that the inner grids are located at L/2, L/4, L/3 and 2L/3, where the total collimator length, L is 2.7 m.

A spatial resolution of 0.5 cm gives unambiguaous identification of the element in which the X-ray photon registers.

The anode wire spacing of 1-2 mm leads to a maximum anode-to-cathode wire plane spacing of 5 to 10 mm. Therefore the bulk of the counter thickness is a drift volume with the proportional region on the order of 1 to 2 cm thick. The proportional region is located in the centre of the counter to reduce spatial uncertainties due to diffusion, and to permit a symmetric field configuration with lower voltages. At a fill pressure of 2 atm, each drift volume has a thickness of ~10 cm for a total absorbtion efficiency of >70% throughout most of the 2-80 kev range.

A low background is important for cosmic sources and for solar imaging at higher energies. Graded-Z honeycomb collimators, whose field of view is on the order of 5° FWHM, reduce photon background due to production in the grids and support structure. The background is further reduced by wall-anticoincidence anodes, not shown in Figure 5. Finally, each subcollimator area of the detectors provides anticoincidence rejection for other subcollimator areas. The resulting background levels should be below 10^{-3} counts $(\mathrm{cm}^2 \text{ sec kev})^{-1}$.

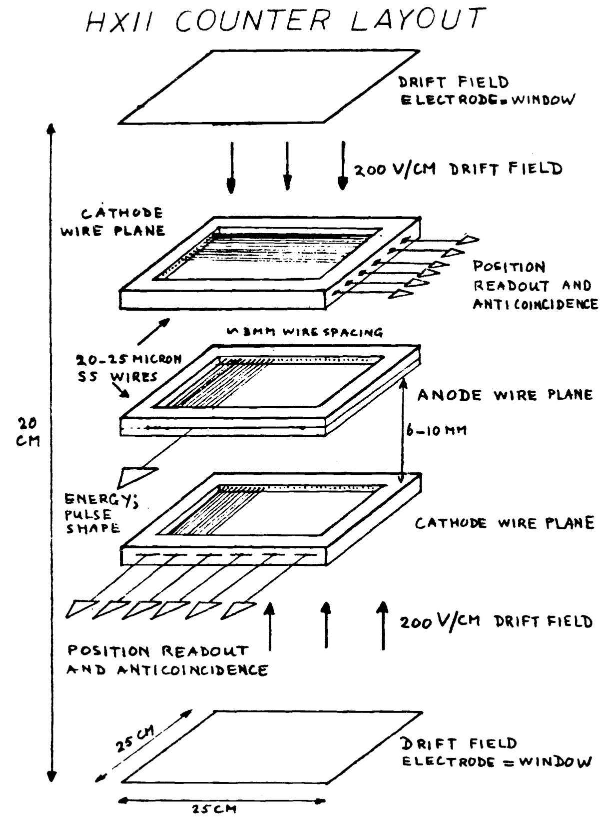

Fig. 5. Layout of the position-sensitive, Xenon-filled proportional conters.

Discussion

Although the Hard X-Ray Imaging Instrument described above was optimized to meet the unique problems posed by solar burst imaging, it is well suited to determining the size, structure and location of a wide range of cosmic X-ray sources such as the Crab nebula, extragalactic and galactic compact sources, discrete sources at the galactic centre, X-ray burst sources, etc. The instrument can also evolve so as to significantly extend its energy and angular resolution capabilities. Stacking several layers of grids and the use of intrinsic Germanium detectors could extend the imaging energy range to 130 kev. Such a system would simultaneously provide a large volume gamma ray detector at energies above 200 kev where the grids would be transparent. Angular resolution can also be upgraded to ~1 arc second at intermediate energies where diffraction is not a concern.

The instrument concept provides excellent refurbishment potential in view of its modular construction, replaceable grid planes and pointing system capabilities. Mere substitution of different grid planes, for example, would permit a wide range of configurations optimized for specific cosmic or solar objectives. Thus HXII could become part of an evolutionary program of quantitative imaging of solar and cosmic hard X-ray sources where the instrument parameters for each reflight were adapted to reflect the experience and discoveries of previous missions.

Acknowledgements

The work described above was due in large part to the efforts of the NASA Hard X-Ray Imaging Facility Definition Team whose membership consists of: L. E. Peterson (team leader), University of California, San Diego; R. L. Blake, Los Alamos Scientific Laboratory; C. J. Crannell, Goddard Space Flight Center; G. Garmire, California Institute of Technology; H. S. Hudson, University of California, San Diego; R. P. Lin, University of California, Berkeley; Z. Svestka, American Science and Engineering; H. F. van Beek, Space Research Laboratory, Utrecht.

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Question submitted by Joseph L. Wiza, Galileo Electro-Optics:

What is the field of view defined by the Honeycomb Collimators? Are they also metallic?

Answer: The honeycomb collimators limit the field of view of the proportional counters to 5° FWHM to minimize background. The collimator walls are a multilayer, metallic 'sandwich' of graded -Z materials (7).

Question submitted by Robert H. Price, Lawrence Livermore Laboratory:

What is the total thickness of tungsten in the grid structure between the source and the proportional counter?

Answer: Each of the 6 or 10 grids in a given collimator frame has a thickness of 50 microns of tungsten. This is the relevant number for evaluating the angular response at high energies where grid transparency becomes a consideration. The total mass of tungsten involved is 4.2 kg which translates into an average of 0.5 g/cm^2 in front of the proportional counters.