THE CONCEPT OF THE PINHOLE/OCCULTER FACILITY

(Invited)

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ABSTRACT

The Pinhole/Occulter Facility is based upon a simple idea for obtaining high angular resolution in astronomical X-ray observations, for example for solar flares at energies >10 keV. The scheme uses a coded aperture device (multiple pinhole camera) with a large separation between the aperture encoder and the detector. Such an imaging device can have an angular resolution much better than 1 arc s if desired.

A large structure would also make it possible to have a large external occulter, which would have powerful applications, notably for high-sensitivity observations of the corona in EUV and white light. This capability leads to the definition of the Pinhole/Occulter Facility, which combines both X-ray and coronal observations. The present concept is based upon a 35-m deployable boom, erected in the cargo bay of the Space Shuttle and pointed in the solar direction by the Instrument Pointing System of Spacelab.

I. INTRODUCTION

It is possible to make images of high-energy radiations – X rays, γ-rays, and material particles – by using the coded-aperture method. If the aperture is a large distance from the detector, such images can have excellent angular resolution, limited only by diffraction if problems of fabrication and deployment be solved. The simplest example of such a coded-aperture telescope is the pinhole camera, which forms a real inverted image on any plane behind the pinhole. More complex aperture patterns can also be used, with a great increase in image brightness. Hudson and Lin (1978) described the application of these ideas to high-energy astrophysics.

The idea for a Pinhole/Occulter Facility (P/OF) began during studies of methods for observing solar hard X-ray emission with high angular resolution. These studies aimed at producing instruments to be deployed from the Space Shuttle. A Facility Definition Team for Hard X-Ray Imaging assessed the technology available for such observations, and in the course of these studies realized that very high angular resolution could be achieved.

This paper reviews the concept of the Pinhole/Occulter Facility from the point of view of its capability for X-ray observations; the other "half" of the instrumentation planned at present for P/OF aims at making revolutionary new EUV and visible-light observations of the corona. Further information appears elsewhere in this volume on the science in these areas of P/OF (Withbroe, 1985) and from the important phenomena that need both X-ray and coronal observations.

The non-solar capability of a large-area X-ray detector array with sub-arc-second imaging capability is great. This aspect too will not be discussed here, but is the subject of a separate paper by Wood (1985).

II. SCIENTIFIC OBJECTIVES

When dynamical phenomena occur in the magnetized plasma of the solar atmosphere, particle acceleration results. The mechanisms of this particle acceleration are interesting in themselves, but the particles also give us information about the energy release – its timing, geometry, modality, and magnitude. Thus, since the initial hard X-ray observations of solar flares (Peterson and Winckler, 1959; for a review, see Kane et al., 1980), we have known that sensitive imaging observations of the hard X-ray bremsstrahlung production by the accelerated electrons would make the next major observational step in flare research.

The Pinhole/Occulter Facility takes major steps in improving the angular resolution and the sensitivity over prior observations. In angular resolution, P/OF will give 0.3 arc s as opposed to the 8 arc s of the Solar Maximum Mission (Van Beek et al., 1980); in sensitivity, P/OF has a total area of 1.5 m^2, far larger than any previous solar instrument, or any non-solar hard X-ray instrument for that matter. Its sensitivity will be great enough to observe many cosmic X-ray sources as they transit through the solar corona, and thus P/OF will observe solar phenomena at low flux levels never before observed.

The first major scientific objective is illustrated in Figure 1, which shows microwave and hard X-ray observations from a flare of November 5, 1980 (Duijveman and Hoyng, 1983). These data can only suggest relationships between the hard X-ray emissions and the microwave and Hα observations but certainly reinforce our ideas about the close relationship between the accelerated particles and the flare effects that occur at all levels of the flaring atmosphere.

In the corona the situation remains even more obscure. We know that dramatic effects take place: the launching of coronal mass ejections, the acceleration of "solar cosmic rays," and rearrangements of the magnetic field that require large amounts of energy. Figure 2 shows the Hinotori observations of a coronal hard X-ray source accompanying a flare of May 13, 1981, from which little impulsive emission occurred. Thus it seems as though the coronal particle acceleration can take place semi-independently of the acceleration on the compact, closed magnetic loops that flare up in the impulsive phase. The observational requirement here is for sensitivity, rather than high resolution particularly since the coronal plasma is more tenuous and thus produces bremsstrahlung more weakly.

III. CODED-APERTURE IMAGING

The basic idea of coded-aperture imaging for high-energy astrophysics was proposed independently in different forms by Oda (1965; the modulation collimator) and by Dicke (1968; the random aperture γ-ray imager). A general discussion of these imaging techniques had already been given by Mertz (1965), but the first practical application of the methods in astrophysics was with Oda's ideas: modulation collimators mounted on rocket-borne X-ray detectors succeeded in locating the bright cosmic X-ray source Sco X-1 well enough so that ground-based telescopes could identify its optical counterpart (Sandage et al., 1966), the first identified stellar X-ray source beyond the Sun.

We can now identify three classes of coded-aperture imagers, which have many, two, and one aperture masks, respectively:

1. Grid collimators (Soller collimators) in which several grids are placed at specific distances in front of a detector to define a narrow field of view. The HXIS instrument from the Solar Maximum Mission (Van Beek et al., 1980) is the most sophisticated example of this type.

2. Modulation collimators (Oda, 1965) in which two grids – one at the front, and one at the detector at the back of the instrument – cause shadow bands to sweep across the sky with the motion of the telescope. Recent variants of this, which we call "Fourier Transform Telescopes," do not require scanning motion (Makishima et al., 1978; Hurford and Hudson, 1985).

3. Coded-aperture imagers (Mertz, 1965; Dicke, 1968) in which a single aperture mask at the front of the instrument makes an intermediate image on a position-sensitive detector. The final image is produced by deconvolution, essentially by a correlation analysis. There are specific aperture codes that result in flat sidelobes (Gunson and Polychronopulos, 1976; Fenimore and Cannon, 1978), so that complete image information can be obtained.

These three approaches each have merit in specific applications. The third type has the advantages of high throughput and complete image formation, but its angular resolution is limited by the position resolution of the detector and by the mask-detector separation.

IV. X-RAY CAPABILITY OF THE PINHOLE/OCCULTER FACILITY

The Pinhole/Occulter Facility incorporates two hard x-ray imaging systems: a coded-aperture imager for sensitive observations of the whole Sun, with moderate angular resolution (8 arc s FWHM); and a Fourier-transform imager for high-resolution observations on the smallest scales (0.3 arc s FWHM). Both imagers use tungsten grids (aperture-encoding masks) with precise patterns of holes used to create the image on a position-sensitive detector.

Table 1 summarizes the tentative parameters of these two X-ray imagers on the Pinhole/Occulter Facility. We describe each instrument briefly here:

Fourier-Transform Imager. The Fourier-transform approach to image formation divides the total area of detector into "subcollimators," each one of which measures one Fourier component of the source angular structure. To make a complete image requires a large number Fourier components; on the other hand, for a given detector area, the area per subcollimator drops as the number increases. This presents a tradeoff problem: sensitivity versus image completeness. Unfortunately this tradeoff depends upon the source angular structure itself, and also is hard to analyze, so the optimization of the number of subcollimators will require numerical modeling. Figure 3 shows how the subcollimators produce individual Fourier scans of the source angular structure.

The field of view decreases as the number of subcollimators increases and their dimensions decrease. For the 100-subcollimator layout given in Table 1, the field of view is only sufficient to image a single active region at high resolution. This implies that an "image motion compensator," an X-Y translation of the detector or of the grids, is required to image a given solar active region.

Coded-Aperture Imager. The simple coded aperture requires only a single grid, and then relies upon the position-sensing capability of the detector to form an image. If the pattern of the aperture code is physically large enough, the field of view can cover the whole Sun. The angular resolution is limited by the ratio of position resolution in the detector to mask distance, which corresponds in the data of Table 1 to about 4 arc s (FWHM, assuming oversampling by a factor of two and a position resolution of 0.5 mm). Figure 4 shows the hole pattern of a typical "uniformly redundant array" (Fenimore and Cannon, 1978).

V. CORONAL CAPABILITY OF THE PINHOLE/OCCULTER FACILITY

The existence of an occulter at some great distance from a telescope has real advantages for the observation of faint objects (e.g., the corona) in the presence of bright objects (e.g., the solar photosphere). The improvement in the diffraction pattern relative to that of a normal external occulter makes it possible to observe closer to the limb of the Sun. Even more important, the large shadow of the distant occulter makes it possible to have large-aperture optics; all previous space-borne coronagraphs have had small apertures with resulting poor angular resolution and low sensitivity. The Pinhole/Occulter Facility includes one coronal telescope – essentially an all-reflecting coronagraph – and an EUV spectrometer capable of imaging resonance-scattered solar light in various EUV emission lines.

VI. OTHER APPLICATIONS

The Pinhole/Occulter Facility has its own scientific program, but there are other potential applications of the basic idea – the use of large structures in space (or no structures at all) to create new observational capabilities. For interest, we review some of these ideas here with the caveat that none of them might have any relationship to the Pinhole/Occulter Facility.

Sun-Grazing Comets. The successful detection of Sun-grazing comets by coronagraphs (Michels et al., 1982; Sheeley et al., 1982) represents an interesting application of sensitive photometry of diffuse objects near the solar limb. The low diffracted light level of a remote external occulter not only reduces the diffuse background light, but also allows one to observe closer to the limb of the Sun. Both advantages should aid in the detection of comets that approach or strike the solar surface.

Planetary Detection. A remote external occulter provides a sharp Fresnel diffraction pattern, and this can aid in suppressing a bright stellar image in a search (for example) for a planet orbiting a nearby star. Spitzer (1962) may have proposed this originally in the context of space astronomy, having in mind an independent occulter subsatellite navigating around the Space Telescope. Elliot (1978) has given an analysis of grazing lunar occultation as a realization of this idea.

Solar Occultation. Elliot (private communication) has pointed out that sufficient control of scattered and diffracted light levels, together with high-resolution, stable stellar images from space, should permit observations of the actual occultation of a star by the outer layers of the solar atmosphere. This would provide a totally new means for studying atmospheric structure and also give high resolution.

Interferometric Detection of Gravitational Radiation. The deformation of large structures in space, or else perturbations of the relative positions of two independent satellites, might provide a means of detecting gravitational radiation via precise geometrical measurements (Faller and Bender, 1984).

Stellar Interferometry. At present there are ideas for multiple-component optical interferometers in space that would use one or more subsatellites (e.g., Stachnik et al., 1984; Labeyrie et al., 1984). The control of these subsatellties for interferometry resembles the control problem for X-ray imaging, but is much more demanding since position information at some small fraction of an optical wavelength would be required.

VII. EVOLUTION OF THE P/OF CONCEPT

A reasonable plan for developing the Pinhole/Occulter Facility would use Spacelab as a stepping-stone to an eventual deployment on the Space Station. The great sensitivity of P/OF means that it can obtain interesting results even in its initial brief observations, but the major fruits will come only from systematic observations as the Sun displays its whole range of phenomena. Non-solar observations naturally are limited only by the total number of photons detected, so that the long exposures possible from the Space Station will be essential.

The key technology needed for making coded-aperture telescopes of high resolution lies in stably defining the geometrical geometric relationship between the components of the instrument. A rigid structure can do this, as it does in a classical telescope. Relying on a rigid structure may pose problems for the highest resolution, however, since any structure will exhibit geometrical instability at some level. In "conventional" telescopes such as AXAF (the Advanced X-Ray Astrophysics Facility), one now finds designs in which some structural flexibility can be tolerated; essentially the motions of the image are reconstructed and removed after its detection by using accurate knowledge of the image motion.

In the initial formulation of the Pinhole/Occulter approach we envisioned the use of separate subsatellites, one carrying the coded aperture and the other carrying the detectors. Each subsatellite would carry components of a system for determining the pointing direction of the telescope. This information then would provide the precise knowledge needed to restore the image after the detection process. The use of such subsatellites in near-Earth orbit would require considerable maneuvering capability because of the need to maintain non-Keplerian orbits for a given view direction. This is analogous to the use of subsatellites for optical interferometry mentioned above, but with less severe requirements on relative position information.

The basic concept of the Pinhole/Occulter Facility offers us a chance to make revolutionary observations in important areas of solar observation without the need for very much technology development. In a sense the P/OF concept is a "brute force" solution to the problem of improving observations in this area, simply by having a very long "focal" length. This kind of idea can be considered in an era when large-scale construction can be done in space. The structures required are not massive ones, and their alignment is not particularly critical in view of the possibility of reconstructing an image photon-by-photon in the presence of substantial pointing jitter. Nevertheless, active damping control by the IPS would be necessary to stabilize the boom adequately.

On Spacelab, the deployment of the P/OF structure would be by use of a self-extending boom. On the Space Station, the longer time in orbit and access to the astronauts' aid in assembling a large structure make it possible to think more imaginatively. A permanent three-dimensional structure with excellent rigidity but low mass could easily be designed and assembled in orbit. This should make it possible to have a simpler pointing-control actuator than the IPS. Finally, one should look forward to the eventual evolution of this concept to include a maneuverable subsatellite capable of circulating around the detector array mounted on the Space Station. Such a facility would make it possible to achieve angular resolution well below 0.1 arc s.

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TABLE 1. X-RAY IMAGING SYSTEMS FOR P/OF

Fourier-Transform Imager	
Angular Resolution	0.3 arc s
Field of View	4 arc min
Total Area	3000 cm^2
Energy Range	2 – 120 keV
Number of Subcollimators	100
Time Resolution	< 1 ms
Coded-Aperture Imager	
Angular Resolution	4 arc s
Field of View	whole Sun
Total Area	12 000 cm^2
Energy Range	2 – 50 keV
Time Resolution	< 1 ms
Sensitivity @ 5 keV	0.03 μJy

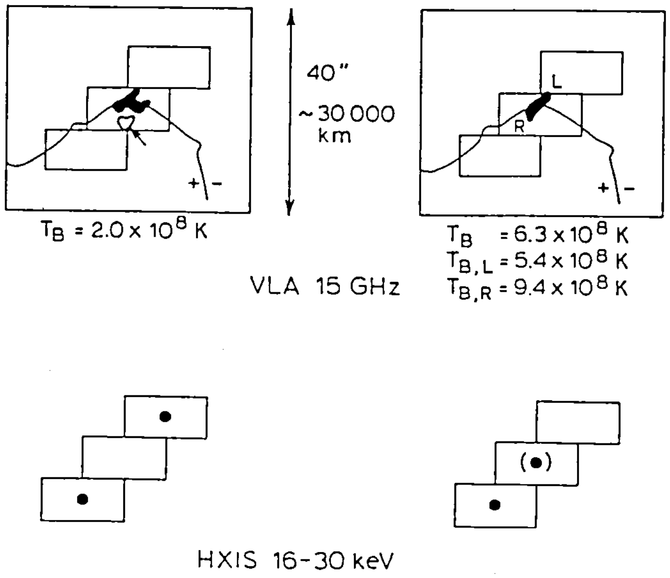

Figure 1. Observations of hard X rays (lower panels) and microwaves (upper panels) from a flare of November 5, 1980 (Duijveman and Hoyng, 1983). The two epochs in the flare represent (left) an impulsive spike, and (right) the peak of gradual hard X-ray emission. The dots in the rectangular pixels (8 arc s X 16 arc s) indicate that the spectrum in those pixels deviated significantly from a single-temperature thermal fit. Thus, this observation shows – at a marginal level of image quality – that the foot-points of the flux tube shown by the microwave source tend to show thick-target hard X-ray emission.

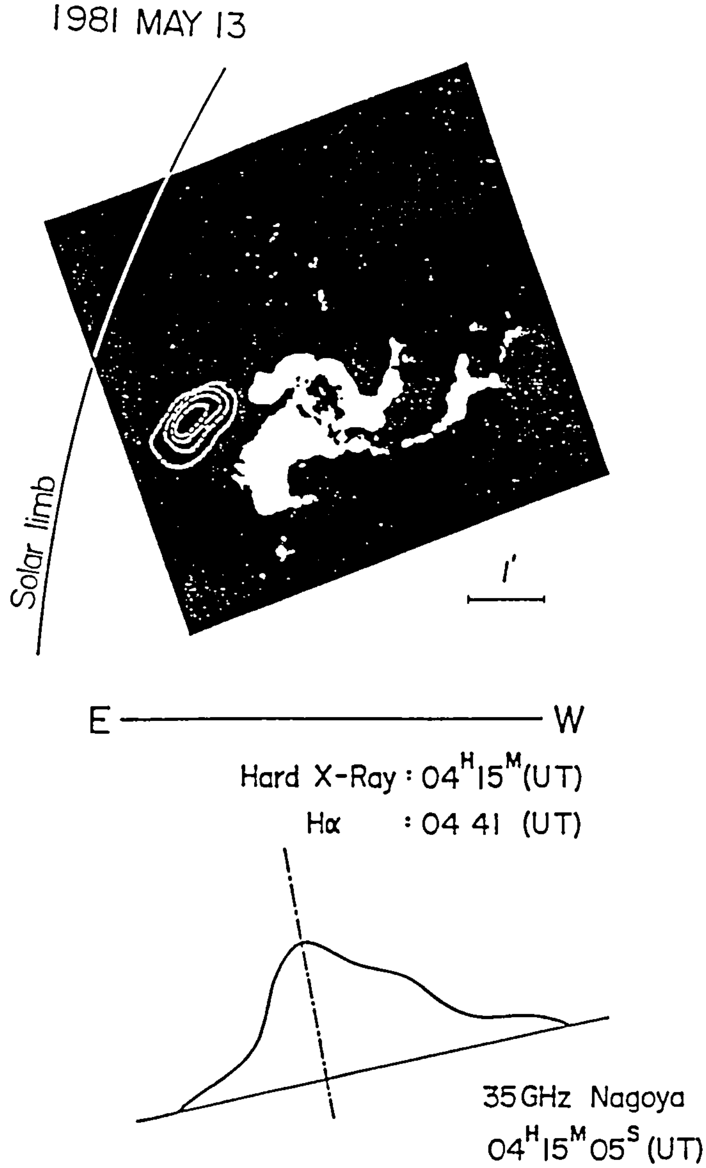

Figure 2. Hard X-ray coronal source during a flare on May 13, 1981 (Tsuneta et al., 1983). The lower part of the figure shows a one-dimensional image at 35 GHz. The observations show that stable trapping of a large population of non-thermal electrons can occur on extended magnetic loops.

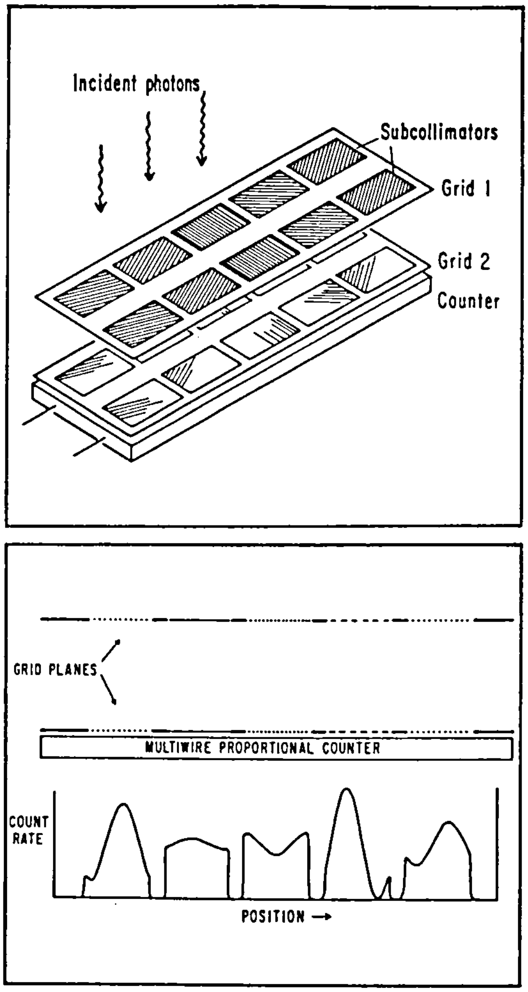

Figure 3. Principle of Fourier-transform imaging (Hurford and Hudson, 1985). Each subcollimator, or separate grid area, corresponds to one Fourier component of the source spatial distribution. A position-sensitive detector of moderate resolution (~10% of the subcollimator dimension) is necessary to read out the image.

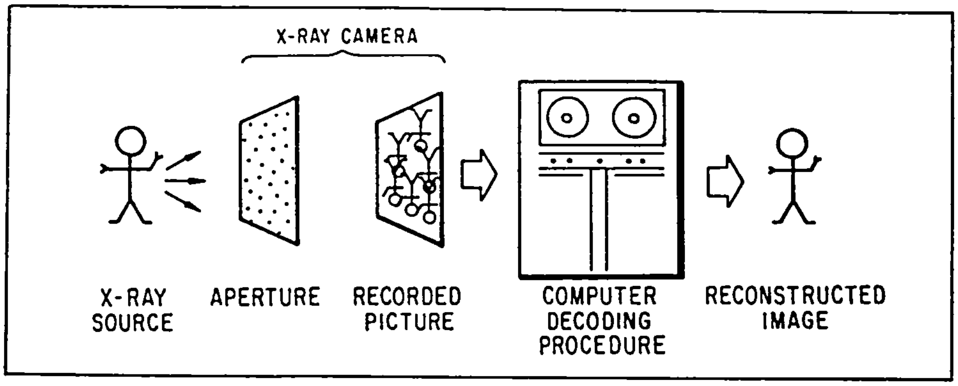

Figure 4. Example of a "uniformly redundant array" pattern for a coded-aperture imaging instrument (Fenimore and Cannon, 1978). Such mask patterns have the property that their autocorrelation function is flat, so that no spurious sidelobes appear in the resulting image.