NASA Technical Paper 2089

October 1982

The Pinhole/Occulter Facility

Executive Summary

J. R. Dabbs,
E. A. Tandberg-Hanssen,
and H. S. Hudson

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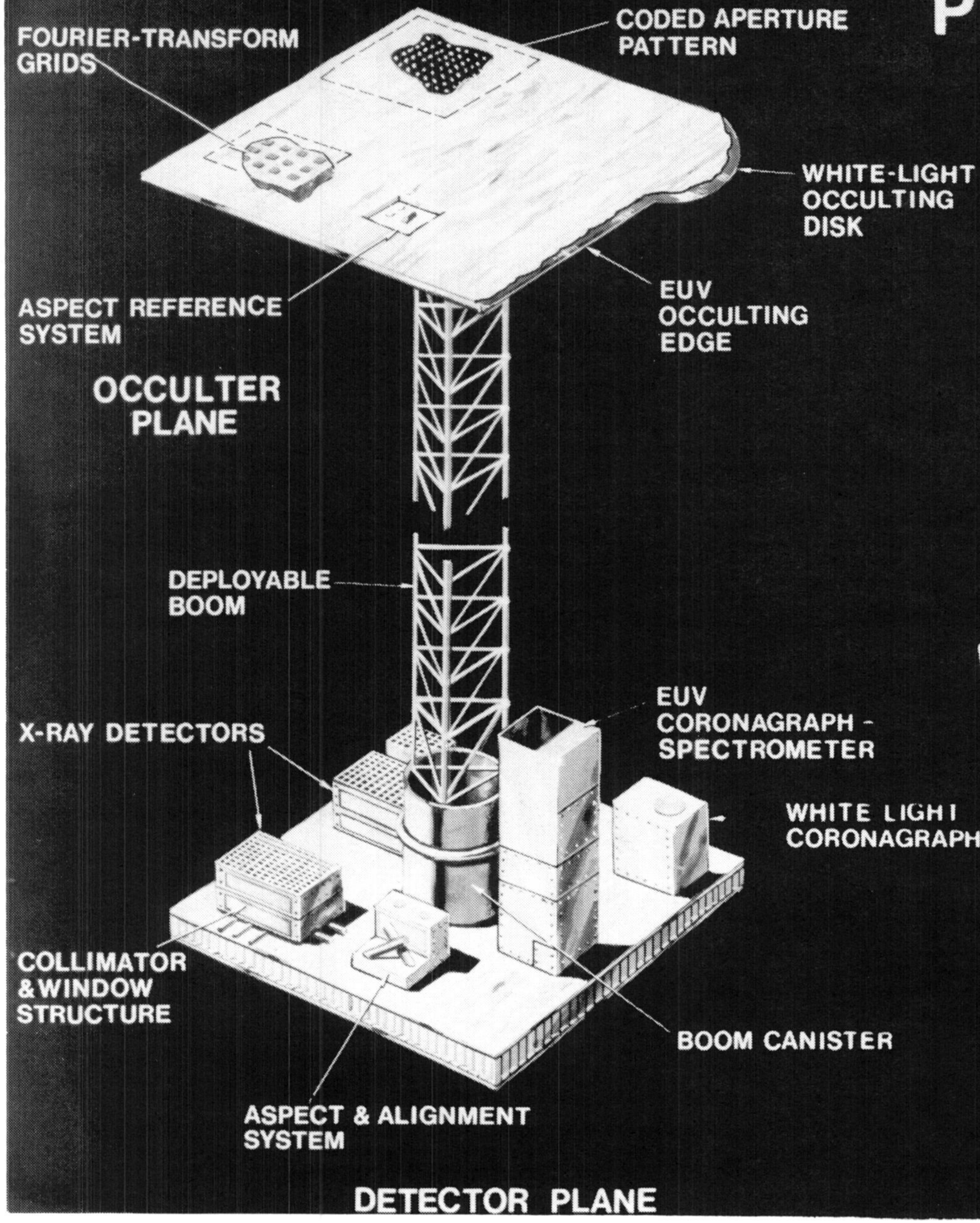
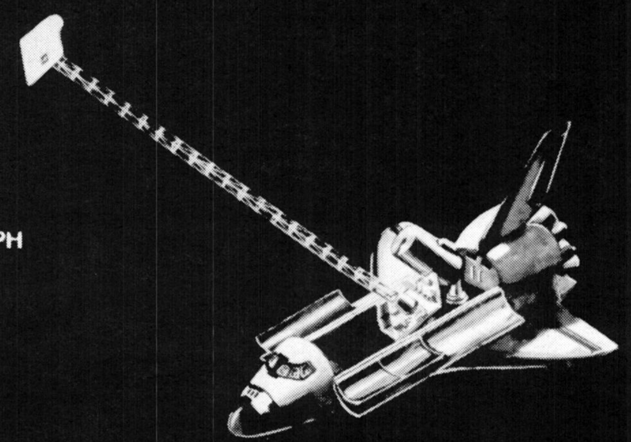
The frontispiece for NASA TP-2089 was inadvertently omitted in its recent publication. The attached photograph of the PINHOLE/OCCULTER FACILITY should be included as a frontispiece in your copy/copies of the report.

Date issued: 12-16-82

PINHOLE/OCCULTER FACILITY





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Executive Summary

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**Scientific and Technical
Information Branch**

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Executive Summary

Foreword

The outer solar atmosphere exhibits a great variety of dynamic and energetic plasma phenomena, from the catastrophic energy release of solar flares to the steady acceleration of the solar wind. Observations from space in the past two maxima of the solar activity cycle have more than whetted the appetite for understanding the physics of the solar corona. The Pinhole/Occulter Facility contains the instruments necessary for achieving fuller knowledge: broad-band X-ray imaging, combined with simultaneous ultraviolet and white-light spectroscopy and imaging.

X-ray astronomy has progressed, through the surveys by small satellites and the "deep" observations of soft X-rays by the *Einstein* Observatory, to a level at which it has become a major component of astronomical investigation. The Pinhole/Occulter represents the first serious effort to broaden the spectral band available to X-ray astronomers at high angular resolution (below one arc second), and it is thus an effective complement to AXAF and other future soft X-ray facilities.

Preface

The Pinhole/Occulter Facility originated as a concept during the discussions of the NASA Facility Definition Team for Hard X-ray Imaging, formed in response to an Announcement of Opportunity (AO #5) for the development of instrumentation for Spacelab. A full account of the proceedings of this Facility Definition Team is given in the document UCSD-SP-79-03 and in the minutes of its meetings, and in proposals for Spacelab instruments based upon the concept. Following this, an *ad hoc* committee to study the pinhole concept was formed. It was realized at the outset that the long focal length needed for hard X-ray imaging would make advanced coronal observation possible as well; the *ad hoc* committee therefore included representation in this discipline. The report of the *ad hoc* committee (NASA TM-82413, 1981) describes a strawman configuration of the facility and its instrumentation which largely matches that described below. In response to the activities of this committee, NASA in 1980 formed a Science Working Group for the study of the concept. This group includes X-ray astronomers as well as solar physicists. The present report summarizes the scientific and technical deliberations of the Science Working Group for the Pinhole/Occulter Facility. The present membership of the group is listed below.

The Working Group has now brought the Pinhole/Occulter Facility to a level of scientific and engineering definition at which a full systems analysis by an engineering organization should be undertaken.

R.L. Blake	Los Alamos Scientific Laboratories
J.R. Dabbs	NASA Marshall Space Flight Center
E.P. Fenimore	Los Alamos Scientific Laboratories
G.A. Garmire	Pennsylvania State University
J.E. Grindlay	Center for Astrophysics
H.S. Hudson	U.C. San Diego
G.J. Hurford	California Institute of Technology
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R.P. Lin	U.C. Berkeley
R.H. Munro	High Altitude Observatory
F.Q. Orrall	Institute of Astronomy, Honolulu
E.A. Tandberg-Hanssen	NASA Marshall Space Flight Center
H.F. van Beek	Space Research Laboratory Utrecht
A.P. Willmore	U. of Birmingham
K.S. Wood	Naval Research Laboratory

Table 1. Parameters of a Strawman Pinhole/Occulter Facility

X-ray Observations	
Angular resolution	0.2 arc sec
Field of view	1 degree
Total area	15000 cm^2
Time Resolution	1 msec
Spectral Range	2–120 keV
Sensitivity @ 20 keV	10^{-5} ph/cm^2sec keV
Mass	450 kg
Power	250 watts
Telemetry	250 kbps
Coronal Observations	
Ultraviolet Emission-line Spectrograph	
Angular resolution	1 arc sec
Aperture	44 cm
Time resolution	10 sec
Spectral range	300–1700 Å
Spectral resolution $\lambda/\Delta\lambda$	20000
Sensitivity	10^8 ph/cm^2sec sr
Magnetic sensitivity	< 2 gauss
Deployed Size	1.3 m × 1.3 m × 5.5 m
Mass	280 kg
Power	140 watts
Telemetry	120 kbps
White-light Coronagraph	
Angular resolution	1 arc sec
Telescope aperture	50 cm
Time resolution	5 sec
Spectral range	1100 Å–1.1 μ
Spectral resolution	broad-band and line filters
Size	1 m × 1 m × 2.5 m
Mass	200 kg
Power	130 w
Telemetry	1 Mbps
Overall System	
Mass of occulter	50 kg
Total mass	4200 kg
Total volume	1.5 pallets
Power	570 watts
Telemetry	1.4 Mbps

Introduction and Summary

The Pinhole/Occulter Facility is a novel instrumentation concept that will provide a major improvement in sensitivity and resolution for both X-ray and coronagraphic observations of the nonthermal phenomena central to understanding solar activity. It will also make possible high-energy cosmic X-ray observations with unprecedented angular resolution (0.2 arc sec) and will provide hard X-ray information complementary to the soft X-ray data from AXAF. In essence, the Pinhole/Occulter Facility consists of a 50-m boom erected from the Shuttle bay or other platform; the boom serves the function of separating an X-ray mask/occulting disk from the detectors and coronagraph optics. The long baseline permits very high angular resolution and sensitivity.

The Pinhole/Occulter is designed to study the nonthermal phenomena that lie at the heart of plasma dynamics in the solar corona. These include the acceleration of nonthermal particles in solar flares and in disturbances of the corona, as well as the basic physics of the corona itself as it expands into interplanetary space to form the solar wind. The Pinhole/Occulter will provide key information regarding the energetics of solar flares, with diagnostic information that can relate flare phenomena to the powerful acceleration of 10—200 keV electrons in the energy-release phase. The corona, as revealed by observation over the last solar cycle, consists of a tangled network of complex elements organized by electrodynamic processes. In and among the magnetic structures, the plasma exhibits a wide range of physical parameters. The interactions among these elements — and with the transition region which links the active corona with the chromosphere — produce the phenomena of solar activity and the solar wind. Diagnostic information on all spatial and temporal scales, including the smallest, is essential for an accurate description of these phenomena.

The Pinhole/Occulter also will provide a facility for X-ray astronomy that combines broad spectral response, excellent angular resolution, and high throughput into a large-area detector (1.5 m^2). Such an instrument will fruitfully observe a wide range of astronomical sources, ranging from extragalactic (active galaxies and clusters) to galactic (supernovae, obscured objects such as the galactic center, and stars). The stellar observations deserve particular mention because in many cases they involve similar physics to that of the solar observations.

In the following list we give the most important scientific questions addressed by the Pinhole/Occulter.

What are the mechanisms of particle acceleration in the corona?

What is the nature of energy release in solar flares?

What mechanisms deposit energy and momentum in the solar wind?

What propels coronal transients and flare ejecta?

How do active galactic nuclei couple with their environments?

What are the mechanisms of particle acceleration and propagation within supernova remnants?

What are the physical conditions in the acceleration regions of jets?

The instrumentation necessary to confront these questions must provide a long baseline — 50 meters in the strawman configuration — separating the occulter from the detector-plane instruments. For X-ray observations, this long baseline permits high angular resolution (0.2 arc sec) by straightforward aperture-coding techniques, the classical pinhole camera being the simplest illustration of this concept. For coronal observations in white light and out to the extreme ultraviolet, the occulter provides a large-diameter shadow — as in a total eclipse of the sun — allowing large-diameter optics to achieve high angular resolution and great sensitivity. Such sensitivity also makes possible the high spectral resolution with which the physical parameters in the distant corona can be probed. For both X-radiation and for classical coronal observations, the Pinhole/Occulter technique provides *qualitatively* new observational capability. In the present solar cycle of activity, we therefore anticipate an even greater gain in knowledge than had been achieved in the past one.

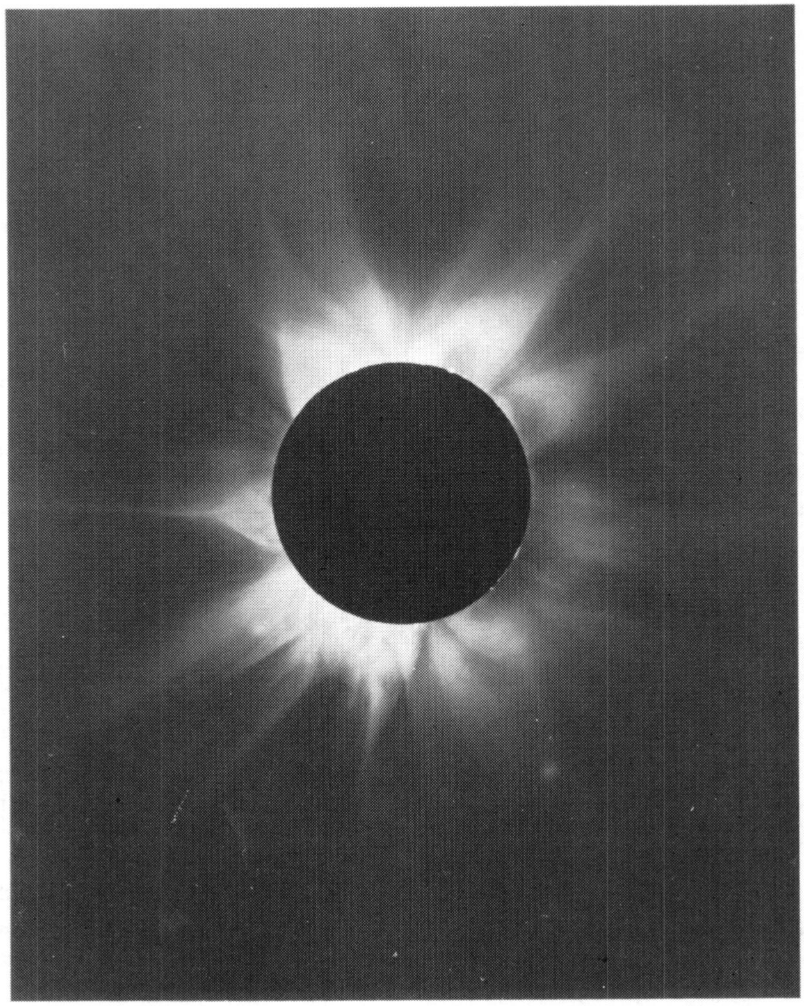

Figure 1. Solar corona: The solar eclipse of 1980 Feb. 16, photographed at Palem, India (courtesy High Altitude Observatory and Southwestern at Memphis).

Scientific Background

The solar corona represents a frontier for solar astrophysics: it is faint, so observations have been difficult, and it contains many puzzles and problems not answered by traditional astronomical theories. We know that the solar wind blows, but not how it obtains its mass and energy from the cooler layers of the atmosphere. We know many effects of transient phenomena in the corona — including some felt on the surface of the Earth — but know little of the causes or mechanisms involved. We know that there is an intimate involvement of the corona with solar flares and with lesser demonstrations of solar activity, but we do not understand the plasma physics well enough to know how the energy is stored and released into spectacular forms. In the most striking energy release, the flare, we have not been able to trace the energy release in the impulsive phase from source to sink.

The image of the corona in Figure 1 shows fine structure at the resolution limit of the observations. *The physics of the solar corona depends in ways that are not understood upon the properties of this unresolved substructure.* The exploration of the physics of these structures is the main goal of the Pinhole/Occulter Facility.

The answers will explain energy transfer and deposition, the acceleration of energetic particles and of the solar wind itself, and the motion of the transients through the coronal structures.

Coronal physics has depended upon four major observational windows: white light, emission lines from the lowest corona in wavelengths down to the soft X-ray region, radio frequencies, and the *in situ* measurements possible in the solar wind. Adequate *diagnostic* information is not presently available — even on coarse angular scales — in vital spectral regions. The Pinhole/Occulter Facility will give the first detailed hard X-ray observations and will permit emission-line diagnostics throughout the corona, significantly expanding our diagnostic and remote-sensing knowledge of the dynamic coronal plasma.

The X-ray astronomy of the corona has much scientific matter in common with observations of galactic and extragalactic objects. The acceleration and transport of nonthermal electrons has not been studied adequately in supernova remnants, galactic nuclei (including our own), and clusters of galaxies. The Pinhole/Occulter Facility will greatly extend the spectral range over which some of these objects can be studied; more important, it will provide higher angular resolution than that which has been available to date.

Scientific Objectives

The scientific objectives of the Pinhole/Occulter Facility can be divided into four major areas: solar activity, coronal structure and solar-wind generation, coronal transients, and X-ray astronomy. The nonsolar observations may share much of the instrumentation, and many of the specific scientific problems are related to the solar ones. In the following we detail the primary scientific objectives.

Solar Activity

X-radiation is the natural emission medium for the bulk of the solar corona. The corona consists of million-degree plasmas interacting dynamically, with occasional intrusions of relatively cold matter. The plasmas are quite active, and the techniques of radio astronomy show that innumerable plasma instabilities, particle accelerations, and other essentially *nonthermal* phenomena characterize this activity. The observations of the corona to date have only partly explored its complexities, and vitally important observations (including those described briefly below) have not yet been possible.

The solar X-ray observations of the Pinhole/Occulter Facility will provide an angular resolution limited by diffraction at 0.2 arc sec. This angular resolution equals approximately the angle subtended by the density scale height in the coolest part of the solar atmosphere, a shortest characteristic distance scale of ~ 150 km. At the same time the use of large-area detectors will give unprecedented sensitivity for the study of faint coronal sources. Given these capabilities, two major observational areas are opened up: the study of fine structure in solar flares, especially the relationships among nonthermal and thermal phenomena in the lower corona, transition region, and chromosphere; and the study of coronal phenomena directly in the bremsstrahlung of freshly accelerated electrons.

Solar flares consist of at least two distinguishable phases of energy release: *impulsive* and *gradual*. The impulsive phase produces the striking microwave and hard X-ray bursts that show the presence of the intense acceleration of 10—100 keV electrons; this acceleration appears to occur in closed magnetic loops related to the soft X-ray sources of the gradual phase, which were shown by Skylab to exist in such loops. Figure 2 shows hard X-ray brightenings at the footpoints of such loops, whose intersection with the chromosphere is marked by Hα brightening.

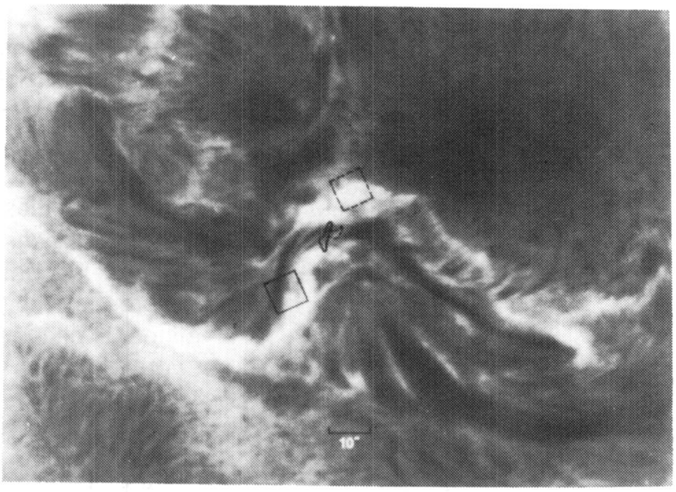

Figure 2. Hard X-ray, microwave, and Hα images of a two-ribbon solar flare. The hard X-ray sources (squares representing bright 8 arc sec pixels as observed from the Solar Maximum Mission) lie at opposite foot points of a magnetic flux tube. The microwave contours, from VLA observations, show the top of the tube.

Where does the impulsive-phase energy release occur? Theories of solar flares come in three broad categories that may be distinguished by their geometry: closed-loop, neutral sheet in an emerging-flux situation, or neutral sheet in an open configuration. The exact geometrical relationships between hard and soft X-ray sources — on the arc-sec level — will discriminate among these theories. Figure 2 shows the high-resolution microwave observations of the impulsive phase of a solar flare. No simple theory anticipated the simultaneous microwave brightening of the loop *tops* thus shown, with the hard X-ray brightening of the *footpoints* of the loops shown by the Solar Maximum Mission.

What is the source of "evaporated" material? A solar flare injects considerable new material into the corona, which can then appear as the classical coronal condensation or loop prominence system. This material presumably comes from the chromosphere, and the evaporation has a presently uncertain relationship with the impulsive-phase energy release. High-resolution observations are necessary to identify the source of the material.

What drives the evaporation? The precipitation of nonthermal electrons is one likely candidate for driving the impulsive-phase evaporation. This can be tested directly by hard X-ray observations, which will show the precise location of the energy deposition by these particles.

Coronal Structure and Solar-Wind Generation

Observations of the solar corona from space have reached a technological plateau in the exploitation of relatively small apertures in visible light. Future developments will emphasize spectroscopic observations over a broad range of wavelengths, large-aperture optics, and resonance-line diagnostic studies of the physical conditions in the solar-wind acceleration region of the corona. We have identified several specific problems:

What mechanisms deposit energy and momentum in the corona? The generation of the solar wind on open field lines and the heating of the solar corona in closed magnetic structures (especially in active regions) are two very considerable unsolved problems. The Pinhole/Occulter observations will provide the necessary diagnostic information to study the physical processes of energy and momentum transfer on angular scales small enough to resolve the interesting structure.

How do the physical properties of coronal magnetic loops depend upon their photospheric origin? As seen in Figure 3, both active and quiet regions of the sun contain elaborate networks of loops that link the photosphere with the corona. Such loops may connect different active regions or even different hemispheres. The Pinhole/Occulter observations will provide diagnostic information on these structures and the transition regions between hot and cool phases, or open and closed magnetic fields, of the coronal plasma.

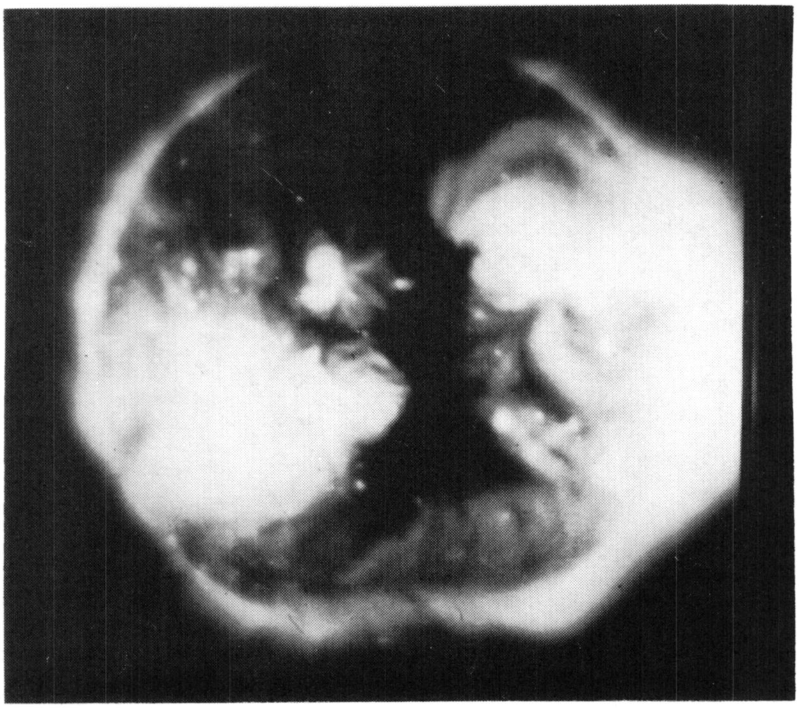

Figure 3. Skylab image of soft X-ray corona (courtesy American Science and Engineering).

Coronal Activity

The corona exhibits stable structures, but it also contains variations and transient phenomena of many types. The intense and highly organized radio emission shows that *nonthermal* processes accelerate particles to high energies during various types of transient perturbation. The plasma physics of these unstable regions is generally known only sketchily, since virtually no direct diagnostic observations exist. The active corona represents a true frontier for solar physics, with broad implications for many other astrophysical and laboratory investigations.

What propels coronal transients? The expulsion of a coronal transient requires a great deal of energy. For the flare-related transient, the energy in the coronal disturbance may exceed that in the other known forms of flare energy release. The source of this energy is presently unknown; the participation of the corona itself in stabilizing or energizing the material that forms the transient is not understood. The Pinhole/Occulter Facility will let us make diagnostic observations in the magnetic structure of these transients.

How are nonthermal particles accelerated in the corona? Each of the numerous types of radio burst known at meter wavelengths requires a different population of nonthermal electrons. The mapping of source regions in hard X-radiation, together with diagnostic information from the P/OF coronal instruments, will show us where and in what kind of medium the particle accelerator works.

X-ray Astronomy

The observational goals of X-ray astronomy match closely those desired for the solar corona: high sensitivity, high angular resolution, high time resolution, and broad spectral coverage. The Pinhole/Occulter is thus a general-purpose instrument suitable for a broad variety of objectives in X-ray astronomy. Specific targets for observation range from solar-type phenomena in stars to exotic objects such as neutron stars and black holes. For extended objects, including clusters of point sources, the Pinhole/Occulter will provide detailed images with unprecedented angular resolution.

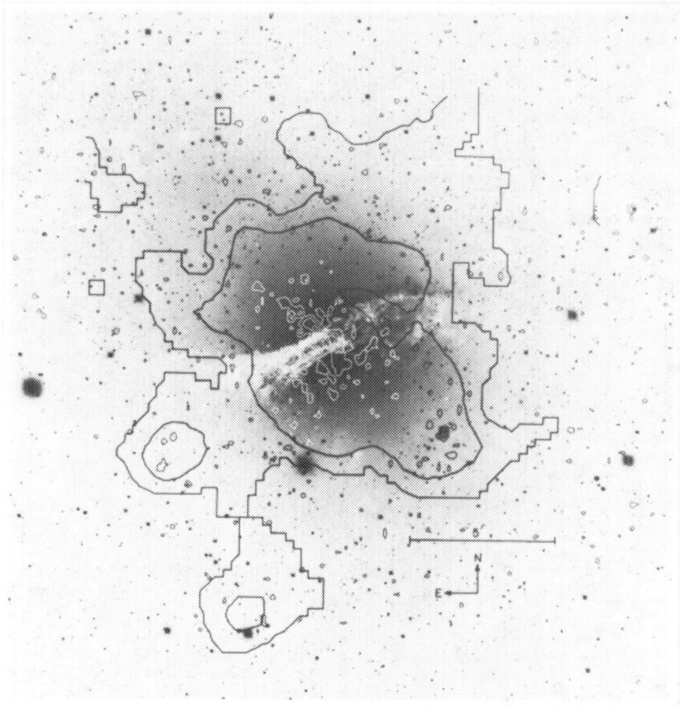

Figure 4. Superposed optical and X-ray (Einstein) images of the nearby radio galaxy Cen A. Black contours show *Einstein* data with arc-minute resolution; white contours (high-resolution X-ray data) show the jet emerging from the nucleus of the galaxy.

How do active galactic nuclei interact with their environments? X-radiation provides a tool for observing high-energy particles in the nuclei and jets found in active galaxies. The VLBI radio observations of these objects show that they contain angular structure on a wide variety of angular scales. The X-ray and radio observations are complementary probes of the distributions of matter and fields in the sources; the objective of the Pinhole/Occulter observations will be to discover the energetics and mechanisms of the jets. Figure 4 shows the *Einstein* image of the giant radio galaxy Cen A, indicating the existence of a barely resolved X-ray lobe structure oriented with the radio and optical jets. Response in the hard X-ray band will permit the Pinhole/Occulter to probe further into the acceleration regions of both galactic and extragalactic jets.

How do nonthermal particles propagate in supernova remnants? Supernova remnants may accelerate high-energy particles, perhaps by mechanisms resembling those found in the solar corona. The most spectacular example is the Crab Nebula (Fig. 5), in which the pulsar is directly responsible for particle acceleration. Pinhole/Occulter observations will reveal the details — at very high resolution — of the propagation of energetic electrons in the wisps and filaments.

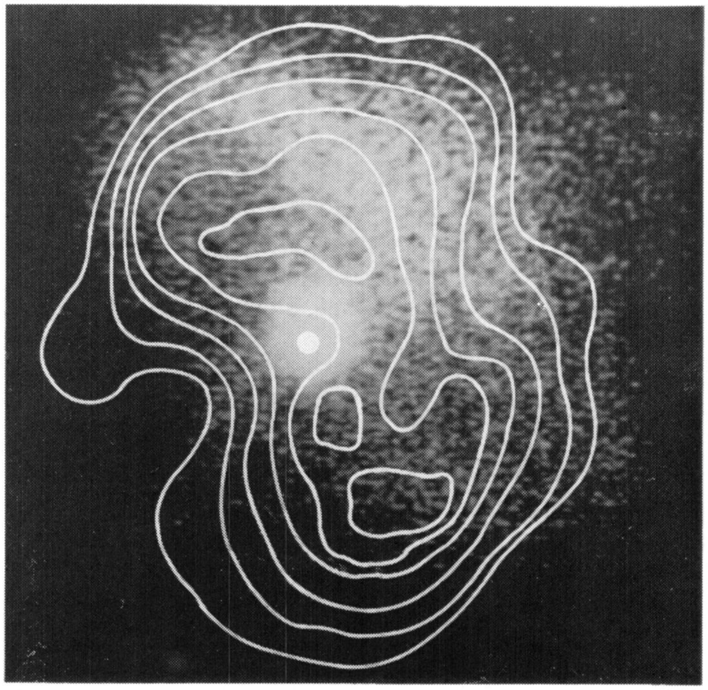

Figure 5. Soft X-ray (*Einstein*) and hard X-ray images of the Crab Nebula, the latter (contour lines) from balloon observations.

Strawman Configuration

The Pinhole/Occulter Facility consists of a self-deployed boom of 50 m length, which separates an *occulter plane* from a *detector plane*. The X-ray detectors and coronagraphic optics mounted on the detector plane are analogous to the focal-plane instrumentation of an ordinary telescope, except that they use the occulter only for providing a shadow pattern. The occulter plane is passive and has no electrical interface with the rest of the Facility. A standard Spacelab pointing-control system orients the boom to within a few arc sec of the point observed. The general layout is as shown in the frontispiece of this report. Table 1 gives general information about the Pinhole/Occulter Facility, together with the observational characteristics of the strawman detector-plane instruments.

Facility

The facility consists of the occulter plane, the retractable boom, the detector plane, and the alignment system. The boom is of a type used for deployment of spacecraft antennas and solar panels. Booms of comparable dimensions have been built and tested. The control of the boom requires active control of the lowest frequency resonant modes. The technology exists and can be tailored to the Pinhole/Occulter application, as shown by detailed modeling of the boom dynamics in the Shuttle mechanical environment.

Accurate aspect sensing and the internal transfer of the information is an important element of the Pinhole/Occulter system, because the desired angular resolution is comparable to that of the best at any other wavelength except for VLBI radio astronomy. The degree to which the development of aspect-sensing technology will be ready for the 0.2 arc sec resolution of the Pinhole/Occulter depends strongly upon progress in other programs: SOT, the Space Telescope, AXAF, or other high-resolution Spacelab experiments may establish the necessary technology within the time frame appropriate for the Pinhole/Occulter.

X-ray Instrumentation

There are two imaging X-ray systems: a *high-resolution imager*, with an angular resolution of 0.2 arc sec, and a *high-sensitivity imager*, with a large field of view and a total detector area of 1.2 m^2. The high-resolution imager uses Fourier-transform X-ray optics, a modern derivative of the modulation collimator, which requires a grid on the occulter plane and one at the detector itself. The field of view, 3.4 arc min, is small enough so that a form of image-motion compensation is necessary to track a given feature. The high-sensitivity imager is a straightforward coded-aperture system, with a single grid on the occulter plane and a large ($> 1°$) field of view.

The two X-ray detection systems have been designed to bring X-ray observational capability to a level matching that of the best optical (SOT) and microwave (VLA) facilities. The coronal hard X-ray observations of the Pinhole/Occulter will have substantially higher resolution (8 arc sec) than coronal observations at meter wavelengths (generally $\sim$ 1 arc min), our best guide heretofore on the nonthermal effects in the dynamic corona.

The total area (1.5 m^2 in five 3000 cm^2 modules) of the Pinhole/Occulter X-ray detectors makes it comparable to the largest earlier counter experiments, and its sensitivity is correspondingly good. An integration of 10^4 sec for an energy band of 2—10 keV would detect (5σ) a point source at 20 nJy (0.02 UFU). The counters themselves are xenon-filled position-sensitive multiwire proportional counters, based upon the technology established by HEAO-1.

Coronagraphic Instrumentation

Two separate telescopes on the detector plane use the occulter for sensitive white-light and ultraviolet coronal observations. These instruments are not coronagraphs of the types previously used for observations from space; they exploit the large-diameter shadow in a manner more nearly resembling eclipse observations. The white-light telescope has optics of 50-cm diameter, while the ultraviolet spectrograph has a 44-cm aperture. The ultraviolet coronagraph obtains spectroscopic information in the 300—1700 Å spectral range with a resolution of $\frac{\lambda}{\Delta\lambda} = 2 \times 10^4$. Stray-light suppression requires an internal occulter as well as the use of vignetting by the remote occulter. Each coronal telescope has an angular resolution of 1 arc sec and is capable of imaging a 90° sector of the corona.

Advanced Solar Observatory

The Pinhole/Occulter Facility is a stand-alone facility suitable for advanced studies of solar flares, the solar corona, and cosmic X-ray sources. In these areas a brief Spacelab exposure will generate an excellent scientific return, and the versatility of the Spacelab opportunities should make possible several problem-oriented flights. Ultimately, however, the Pinhole/Occulter should become a part of a longer-term space observatory. There are three essential reasons for this: observations of rare transient phenomena are needed; longer-term synoptic coverage is essential for understanding and monitoring other phenomena, including the generation of the solar wind; and long exposure times are required for certain faint sources.

The optimum step in the evolution of the Pinhole/Occulter Facility therefore appears to be the creation of an advanced, comprehensive observatory on a semi-permanent platform in space. For solar observations this would be the Advanced Solar Observatory, incorporating the Solar Optical Telescope along with advanced instrumentation in other wavelength regions. The Solar Maximum Mission has shown clearly that a coordinated battery of telescopes and detectors offers many advantages in probing the strongly inhomogeneous and time-varying phenomena found in the solar atmosphere. The construction of an Advanced Solar Observatory consisting of state-of-the-art solar instruments would represent an ideal exploitation of the flexibility inherent in the Space Shuttle systems.

For X-ray astronomy the Pinhole/Occulter would evolve differently. Improvements and augmentation of the detectors could proceed until a very large area X-ray observatory came into being. Again a space platform offering long exposure times would be an ideal home for such an evolved Pinhole/Occulter dedicated to X-ray astronomy.

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*Dr. Hudson is associated with the University of California at San Diego.

16. ABSTRACT

The outer solar atmosphere exhibits a great variety of dynamic and energetic plasma phenomena, from the catastrophic energy release of solar flares to the steady acceleration of the solar wind. Observations from space in the past two maxima of the solar activity cycle have more than whetted the appetite for understanding the physics of the solar corona. The Pinhole/Occulter Facility contains the instruments necessary for achieving fuller knowledge: broad-band X-ray imaging, combined with simultaneous ultraviolet and white-light spectroscopy and imaging.

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