THE PINHOLE/OCCULTER AS A TOOL FOR X-RAY ASTRONOMY

(Invited)

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ABSTRACT

The two X-ray transform telescopes on the Pinhole/Occulter Facility (P/OF) will provide sub-arcsecond angular resolution, high sensitivity imaging in hard X-rays for the first time, as well as improved capabilities for timing studies and spectroscopy. Although the design was driven by solar observing requirements, the result is an instrument of major importance for astronomical as well as solar observations. Fundamental astrophysical measurements could be made on supernova remnants, clusters of galaxies, active galaxy cores, accreting binary systems, and active coronae of nearby stars. Ways in which astronomical observations will benefit solar research are discussed.

INTRODUCTION

The Pinhole/Occulter Facility (P/OF) is proposed to carry a complement of two hard X-ray imaging instruments and two coronagraphic instruments that together will provide new capabilities for solar observations. This discussion concerns itself solely with the X-ray instruments, and looks at them primarily from the standpoint of their suitability as tools for celestial, rather than solar, observations. Descriptions of the P/OF instrumentation may be found in Tandberg-Hanssen et al. (1983) and in Hurford and Hudson (1980). These references should be consulted for details, but a brief description is as follows: one of the X-ray instruments, the coded-aperture imaging (CAI) telescope, has a 50% transparent mask with a coded pattern of "pinholes," placed 50 m from a detector that records positions, times, and energies of X-rays transmitted by the mask. The other instrument is a Fourier-transform telescope (FTT) employing two sets of grids, an upper one on the mask platform and a lower one directly in front of a detector similar to that in the CAI. Upper and lower grids consist of ~100 "subcollimators"; each subcollimator consists of a set of fine, parallel slits. Slit spacing and orientation vary from one subcollimator to the next, so that each subcollimator measures a different Fourier component of the spatial image. In both the CAI and FTT designs, the pattern recorded in the detector is not the source image but rather a transform of that image that must be inverted to recover the source brightness distribution. Both designs belong to the class of transform telescopes.

Two main points will be stressed here. The major theme is that P/OF will be a powerful instrument for high energy astrophysics, in the first rank of X-ray astronomy facilities now foreseen. A second point is that inclusion of the astronomical observations in the P/OF program will benefit the solar program conducted with the facility, as well as solar physics generally.

Capabilities of the X-ray instruments on P/OF will be assessed from the astronomical perspective, in part through comparison with other major astronomical instruments now planned or under discussion. The estimated performance characteristics of P/OF will then be used as a basis for characterizing the expected scientific results. Applications will be described in several areas including source population studies, imaging of extended sources, photometry, and spectroscopy.

I. PERFORMANCE CHARACTERISTICS OF P/OF IN CELESTIAL OBSERVATIONS

In 1979, the Naval Research Laboratory, the University of Birmingham, and the Los Alamos Scientific Laboratory submitted a proposal to NASA for a large-area coded aperture instrument, to be used exclusively for astronomical observations in hard X-rays. It is interesting and instructive to note that this instrument as proposed was roughly similar to the coded aperture X-ray telescope on P/OF, in its energy range, size, and angular resolution, as well as in design. This coincidence in parameters means that a single basic instrument concept is able to serve as a frontier research tool in both solar physics and X-ray astronomy. How does this happen? Naively, the roughly 12 orders of magnitude difference in flux between bright solar flares and celestial sources at 1 keV would seem to raise serious questions about feasibility.

It turns out that there is no single answer, but rather a combination of several factors that disposes of these orders of magnitude. Comparison must be made not in units of flux but rather in terms of the fluence per pixel in a typical image. Several aspects of typical solar flare imaging in hard X-rays collectively create a requirement for extremely high sensitivity, which in turn makes celestial work possible. First, P/OF is not designed solely for the brightest flares, but rather for the ones that would be seen during a typical Shuttle mission at solar maximum. Hence, it must detect flares $\sim 10^3$ times fainter than the brightest ones. Second, the solar flares are to be imaged at $E > 20$ keV. The highest priority solar goals, such as imaging bright X-ray regions near loop footpoints, fall in this energy range. This means that the very steep solar spectrum (typically E^{-4}) in hard X-rays will drastically reduce the photons available in the band of greatest interest, relative to energies near 2 to 10 keV. In contrast, celestial observations will cover a range of 2 to 120 keV. The celestial spectra of interest are much harder than E^{-4}, and sometimes harder than E^{-1}, so that the relative attrition of count rates with increasing energy is far less severe. In addition, integration times for solar applications are, very conservatively, less than 1 s, in contrast with celestial sources, wherein 10^4 or 10^5 s integrations are appropriate and longer ones are feasible if the task warrants it. Each of the factors just mentioned disposes of 3 to 5 orders of magnitude in the naive flux discrepancy. A fourth factor is image complexity. The solar flare flux, integrated over a typical observing integration time, must ultimately be assigned to a number of pixels, distributed in a complex way, whereas the faintest objects dealt with in celestial work are point sources. When all four factors are combined, there is great overlap in the expected range in fluence per pixel used in typical solar and cosmic observations made with the P/OF.

Granting that the celestial observations are feasible with P/OF, it is still necessary to understand how data from P/OF would compare with those from other X-ray astronomy instruments.

Sensitivity for a coded aperture instrument such as P/OF depends on detector area and background in a manner similar to other X-ray instruments, to within factors of 2. It improves as the square root of integration time for faint sources, because the dominant consideration is detection of a signal in the presence of Poisson noise. Typically, the detector background per unit area is much larger than the diffuse X-ray background, and also much larger than the flux from the source. In this case the minimum detectable flux, F_{lim}, is given by

$$F_{lim} = 2\,\eta\,(B/\epsilon\ A\ \delta E\ \tau)^{1/2} \quad , \tag{1}$$

where

δE = energy range, e.g., 2 to 10 keV

B = background, e. g., 3×10^{-4} cts cm^{-2} s^{-1} keV^{-1}

A = effective area, $\sim 10^4$ cm^2

τ = integration time, 10^4 - 10^5 s

η = detection significance = 5σ

ϵ = efficiency.

Typical values are, at 5 keV, $F = 0.03\ (10^4\ \mathrm{s}/\tau)^{1/2}$ microjansky and, for δE = 15 to 30 keV, $F = 1.3 \times 10^{-5}\ (10^4\ \mathrm{s}/\tau)$ cts cm^{-2} s^{-1}. These numbers compare favorably with most X-ray astronomical instruments that have flown or are now planned, with the single exception that AXAF will achieve substantially greater sensitivity at energies well below the cutoff energy of its X-ray mirror, ~10 keV. For many hard X-ray observations, P/OF has no equal in sensitivity.

Figure 1 is a spectral sensitivity curve comparing P/OF with instruments from the first two decades of X-ray astronomy as well as AXAF. The P/OF curve, taken for a 10^5 s integration, represents the CAI and Fourier-transform telescope instruments taken together. It is clearly more sensitive than the HEAO-1 instruments and aligns roughly with the upper end of the Einstein Observatory HRI spectral sensitivity curve. All curves, including P/OF, refer to point sources detected at 5σ.

In considering Figure 1, it should be recognized that the sensitivity advantage conferred by grazing incidence optics does not exist beyond ~10 keV. Hard X-ray instruments must rely on some nonfocussing technique in order to have imaging at all. The other hard X-ray instruments shown in Figure 1, UHURU and the HEAO-1 experiments, had coarse pencil beam angular responses (a few square degrees) achieved with mechanical collimators. Unlike these, P/OF enjoys true high-resolution imaging.

Table 1 summarizes parameters besides sensitivity that affect imaging and timing performance. The P/OF field of view is comparable to that of the Einstein Observatory IPC, while the angular resolution is substantially better than the HRI, 0.2 arc s. The timing resolution is 1 ms. The total collecting area excellently supports fast timing observations even in the millisecond domain, as does the large telemetry allocation.

Table 2 gives key parameters of several major X-ray astronomy missions expected over the next few years. Comparing areas, P/OF is seen to be larger than these future payloads, two of which have grazing incidence optics (ROSAT, AXAF) and two of which (ASTRO-C, XTE) do not. The sensitivity advantage of focussing optics pertains to sources at very low flux levels. For sources whose flux exceeds the background per unit area in the detector, the sensitivity advantage lies with the instrument having greater collecting area, whether or not it has optics. For P/OF this crossover would fall near UHURU flux unit (1 UFU = 2.4×10^{-11} erg cm^{-2} s^{-1}, 2^{-10} keV, or roughly 1.1 microjansky at 5 keV, for a Crab-like spectrum) so that the area advantage of P/OF would be an unqualified performance asset over the focussing instruments above that flux level. P/OF's area would be (within a factor of 2) the same as ASTRO-C and XTE, but it would gain in performance by virtue of its imaging and higher bit rate. On fainter sources, ROSAT and AXAF would perform far better than P/OF, but only up to the cutoff of their X-ray optics. At higher energies, where P/OF's most novel capabilities lie, it is simultaneously superior in collecting area, sensitivity, and angular resolution.

It would thus be reasonable to characterize P/OF as being roughly the hard X-ray counterpart to AXAF, with angular resolution comparable to that instrument and with superior capabilities for timing and low-resolution spectral work on bright sources. Its sensitivity for faint sources would be roughly like that of the Einstein HRI, the detector that has reached the lowest flux levels of any X-ray astronomical instrument to the present time.

II. THE X-RAY SKY: SOURCE COUNTS AND CLASSES

P/OF will have the power of a general purpose X-ray astronomy facility; hence, complete discussion of all observations it could perform would entail a prohibitively vast survey of X-ray astronomy. The most important thing is to assess where its unique features – hard X-ray imaging and high sensitivity in hard X-rays – will be effective. This will be undertaken in a brief survey emphasizing bright X-ray sources. The survey will analyze X-ray astrophysics from several standpoints: by source populations, by type of observation (imaging, photometric, etc.), and by the astrophysical problems addressed.

A convenient way to begin is with the full-sky surveys from HEAO-1. The lower portion of Figure 2 shows the HEAO A-1 full-sky survey (Wood et al., 1984), which covers energies from 0.5 to 25 keV. Although the flux limit varies in a systematic way with position on the sky because of variations in sky exposure, it is typically at least 1 UFU, and ~450 sources are seen above this level. The display is in galactic coordinates, with the size of the dot representing a source proportional to the logarithm of its intensity in counts cm^{-2} s^{-1}. Five major source populations are encountered among the identified objects: clusters of galaxies, active galactic nuclei, accreting binaries, supernova remnants, and stellar coronae.

The upper portion of Figure 2 shows the HEAO A-4 catalog (Levine et al., 1984) displayed in the same mode. The energy range is now higher, 13 to 120 keV. The epoch observation over which this high-energy map was accumulated includes that of the other map, but is roughly three times as long. The sources seen here are a subset of the previous sample, mainly the brighter objects. None is unidentified, and most of the major classes are again represented. All sources have lower flux at this higher energy, but they do not all scale the same way because of differences in spectral hardness. Improving the flux limit tenfold would reveal many more objects in all classes, particularly the extragalactic ones. It is noteworthy that despite the lower full-sky source count at higher energies, the regions that were crowded at low energies remain crowded. Since collimators used in most high-energy designs other than P/OF are comparatively coarse, this crowding becomes a very serious problem. Ultimately, some imaging is needed as limiting flux decreases, from source confusion considerations alone.

The most fundamental sense in which confusion provides a limitation is in the fluctuations from pixel to pixel in the number of unresolved sources. The problem is exemplified by Figure 3, which shows source counts obtained with HEAO A-1 using two different collimators. The points at higher flux levels are obtained with 1 deg x 4 deg collimators, and reach a level of roughly 1 UFU. The lowest point is obtainable only by using a collimator eight times finer, 1/2 deg x 1 deg, on a small field of sky where a long integration time was obtained. Instrumental source confusion has been analyzed formally in several studies, many of them prompted by the early sky surveys done with radio pencil beams. It can be shown that in work with a particular point source response function ("beam width"), it is not possible to isolate more than one source in every few tens of beam widths. The collimator that obtained the lowest point in Figure 3 had the smallest field of view of any pencil beam design that has yet flown. To go below this limit requires imaging or modulation collimator designs to achieve smaller effective beam sizes.

The Pinhole/Occulter Facility would never encounter source confusion within practical integration times, even up to a few weeks. This is essentially because the very fine resolution places its confusion limit at a flux level too low to be reached in practical integrations. Accessibility of sources would depend mainly on integration time and energy. Table 3 estimates the number of sources that would be accessible at various energies. These are extrapolated from surveys, particularly those shown in Figures 2 and 3, according to expected number-flux relations.

It is clear that all major source classes would be available. There would not be time to observe all accessible sources, because it would require at least 10^4 seconds on each of about 40 000 fields, i.e., well over 10 years. A feasible observing program would be to look at bright targets of special interest, sampling each class, and to conduct statistical studies based on random sampling with long integrations. This tactic was used with the Einstein Observatory and could be extremely effective with P/OF.

With overall source accessibility thus characterized, it is appropriate to survey particular classes and objects. In appreciating P/OF's role, it may help to recall that, in contrast to the optical sky, virtually every source known to X-ray astronomy has proven to be either extended or variable, so that the combination of high-resolution imaging, high sensitivity, and fast timing available with P/OF necessarily finds wide application. As X-ray astronomy matures, measurements needed to advance understanding become more subtle and difficult, creating demand for advanced instrumental capabilities.

III. IMAGING APPLICATIONS

Supernova remnants, active galactic nuclei, and clusters of galaxies are the major X-ray source classes having extended X-ray components in which surface brightness mapping with P/OF would be of great value.

Supernova Remnants (SNR)

The Crab Nebula was the first X-ray source discovered to be extended, a fact determined originally using lunar occultations (Bowyer et al., 1964; Wolff et al., 1975). This nebula and the pulsar within it present a wealth of astrophysical phenomena, over radio to gamma-ray wavelengths. The pulsar is thought to be the energy supply for the entire nebula, but details of energy transport remain a challenge to high-energy astrophysics. Insights gained here, for example concerning particle acceleration and transport, may well transfer to other astrophysical situations.

The angular structure as a function of energy can be used to discriminate between diffusion and bulk transport models of the energy flow. Diffusion predicts a specific relation for shrinkage of the nebula as energy increases into hard X-rays. P/OF can precisely determine the nebular size to high energies. It can also tell whether there are localized fine features in X-rays, corresponding perhaps to optical wisps that move appreciably over the course of time.

The combination of high angular resolution and high timing resolution available on P/OF makes possible a very basic measurement, namely determination of the continuum flux from the Crab Pulsar (PSR 0532+21). The observation is difficult because the pulsar must be seen against the nebular background, and must be imaged using data strobed at the pulse period, accepting only portions of the cycle when the pulsar is at its minimum. Such an image shows whether there is excess steady flux at the pulsar position. No excess has been detectable with previous instruments (Harnden and Seward, 1984), but feasibility of the measurement is strongly dependent on the angular resolution available. P/OF, with resolution roughly 25 times finer than the Einstein Observatory's HRI, should provide a definitive measurement. The intent behind this measurement is determination of the neutron star cooling timescale. Since it is known that the supernova that produced the Crab Pulsar occurred in AD 1054, determination of the surface temperature at the present epoch fixes the cooling time; an upper limit on current temperature sets a limit on the cooling time. The cooling time is sensitive to the constituents of the neutron star interior and the processes whereby they contribute to heat loss.

P/OF is also suited to mapping other bright, young SNR such as Cas A, that contain regions of high temperature and high surface brightness. Angular size scales are such that arcsecond or better imaging is required. From Einstein observations (Murray et al., 1979) one estimates that Cas A would give a flux/pixel ratio of 4×10^{-12} erg cm^{-2} s^{-1} $pixel^{-1}$, for pixels 10 arcseconds on a side, so that imaging should be possible up to 10 to 15 keV. The Tycho and Kepler supernova remnants should also be detectable and possibly some SNR in the large Magellanic Cloud. Hard X-ray imaging will supplement data from lower energy instruments, such as AXAF, providing improved knowledge of temperature gradients or of how kinetic energy in the expanding remnant is thermalized.

Active Galactic Nuclei: Jets and Extended Features

Active galactic nuclei (AGN) are a broad class that includes a number of distinct kinds of bright, compact, variable galaxy cores, including highly luminous (10^{43} to 10^{47} erg s^{-1}) quasars and BL Lacertae objects, as well as less luminous (10^{42} to 10^{45} erg s^{-1}) Seyfert I galaxies and emission line galaxies. Much of the total power in these sources is radiated at high energies. The central power source may be a supermassive black hole, of mass 10^6 to 10^8 solar masses. Many of these sources have outer radio lobes, powered by jets of material ejected from the central object.

In NGC 5128 (Cen A) an X-ray jet has been detected using the Einstein Observatory (Schreier et al., 1979; Feigelson et al., 1981). This jet includes small knots, interpreted as regions of synchrotron emission. Jets are also seen in radio wavelengths, and are evidence for transfer of energy from the nucleus to outer radio lobes. Much of the lifetime energy output of the source may be in such ejecta, and imaging at high energies is crucial to developing physical models. Known X-ray jets range in size from a few arc seconds to several arc minutes, but the total number detected remains small: only in 3C273, M87, and Cen A have jets been seen (Schreier, Gorenstein, and Feigelson, 1982). The jet in Cen A has an intensity of 3×10^{-12} erg cm^{-2} s^{-1}, or about 0.1 microjansky; hence, P/OF could detect it. The X-ray spectrum of the jet would be determined from, for the first time, P/OF observations. A jet like that in Cen A should be observable with P/OF at greater distances because of its high angular resolution. If it were ten times farther away, its surface brightness would be unchanged, and it would still be resolvable. P/OF will thus be able to range over a larger volume of space in searching for jets, and should enlarge the list of X-ray jets.

Clusters of Galaxies: Imaging the Hot Intercluster Medium

Previous work has shown that most clusters of galaxies contain X-ray-emitting gas, usually at temperatures exceeding 8 keV. The surface brightness has been mapped using the Einstein Observatory for at least 30 clusters, revealing a variety of structures rather than a single recurrent morphology. In addition, spectral measurements indicate that there is in some clusters a nonthermal component extending to hard X-ray energies (Lea et al., 1981), although the relative location of this component is unknown. Locating such features is one example of a task that P/OF could perform on clusters of galaxies. Another would be imaging of clusters in iron lines near 6.7 keV. Iron line images need to be combined with temperature maps determined from continuum observations to be maximally useful in modeling the gas distribution and its dynamics. In combination with a hydrostatic model, mapping of the gas temperature provides a way to measure the total mass enclosed within a particular radius; this has been used to demonstrate that there is considerable "missing mass" in M87 (Fabricant, Lecar, and Gorenstein, 1980), that is, nonluminous matter that contributes to the gravitational mass.

Resolving Multiple Point Sources in Crowded Fields

In several parts of the sky, bright X-ray sources become so crowded that resolving confusion becomes a major aspect of any observation. Below ~1 UFU, serious confusion exists everywhere in the sky for most conventional collimators and imaging becomes essential, but confusion is encountered at much higher flux levels in the central part of our galaxy, in the Magellanic Clouds, and elsewhere. The role of imaging in these situations is to resolve point sources from one another, rather than to map surface brightness.

The galactic center contains 6 X-ray sources within 1 square degree (Watson et al., 1982) and interstellar absorption restricts observations to energies above about 3 keV. There may be unusually frequent bursting in this region (Proctor, Skinner, and Willmore, 1978). This is also the region where 511-keV line emission has been seen (Leventhal, MacCallum, and Stang, 1978), and P/OF could well play a role in positioning the source of that emission through simultaneous observations with gamma-ray instruments. P/OF can survey the galactic center region carefully, going 2 to 3 orders of magnitude fainter than previous surveys above 4 keV.

Crowded field regions also exist in other galaxies of the Local Group. The Large Magellanic Cloud has several sources at small angular separations, and some of them so close to one another that hard X-ray spectral determinations without P/OF are impossible. Point sources in M31 that were imaged with the HRI on Einstein (van Speybroeck et al., 1979) should be accessible to P/OF in long integrations. The spectral characteristics of an ensemble of binary sources could be determined in this way.

The number-flux relationships for source populations were used earlier to characterize source accessibility, but they have a deeper significance in that the departures from $N(S) \sim S^{-3/2}$ (the Euclidean, isotropic case) reflect population evolution and cosmological corrections to the Euclidean volume element. A main ambition of high-energy astrophysics has been to determine whether and how the diffuse background resolves into discrete sources. The $S^{-3/2}$ relation cannot continue to arbitrarily low fluxes without truncation because it will diverge; hence, a turnover is expected. At the lower end of the P/OF's energy range it should be possible to observe this turnover in very long integrations, perhaps one or two weeks. This might be accomplished by summing images from several shorter integrations. Faint sources seen in these long integrations would be positioned to very high accuracy, so that their counterparts could be identified in optical and radio wavelengths. While the turnover flux level could be reached at energies >10 keV only with unacceptable long integration time, shorter integrations would greatly advance the statistical knowledge concerning source populations at those energies. The hard X-ray continuation of the diffuse background problem could be addressed by modeling and extrapolations but with unprecedented rigor, in much the same way as the same problem at energies <3 keV is now treated using source counts from the Einstein Observatory.

IV. TIMING AND SPECTROSCOPY

Let us now consider cases where timing and low-resolution spectroscopy are vital to advancing physical understanding. These come chiefly from the accreting binary sources and active galactic nuclei (AGN). It is natural to regard P/OF as primarily an imaging instrument, but its design is also ideal for point-source spectroscopy and photometry, being superior for these purposes to mirror instruments (for the bright sources where most work is done) by reason of greater area and energy bandwidth, and superior to non-imaging detector arrays of comparable area because its imaging permits clean target isolation from other sources and background variations. These assets give P/OF a data quality advantage in many practical situations.

Accreting Binary Sources

The brightest objects in the X-ray sky are compact objects accreting in binary systems. These divide into three subclasses, according to whether the accreting component is a black hole, neutron star, or white dwarf. Further subdivision may be made: e.g., when an accreting neutron star has a strong magnetic field it will be a pulsar, but a weak field will give either an X-ray burst source or one of the so-called "bulge sources," found mainly but not exclusively in the region of the galactic bulge and which neither pulse nor burst.

Black holes are predicted by General Relativity and other gravitation theories as well. They become luminous X-ray sources if they accrete matter from their surroundings. Several candidates are known in our galaxy and the LMC, the best studied being Cygnus X-1. In these objects, accreted material is provided by a binary companion. Determination of binary orbit parameters has provided mass estimates, one type of evidence for the black hole interpretation. (Stable neutron star configurations do not exist above $\sim 3\ M_\odot$.)

Much literature has been devoted to rapid intensity variations in black hole candidates. These bursts have a noisy, aperiodic character, with timescales as short as a few milliseconds now established. (See Meekins et al., 1984, which describes techniques for analyzing rapid aperiodic variability that occurs over a wide range of timescales.) Study of these fluctuations is a good task for P/OF in virtue of its collecting aperture and timing resolution. P/OF's broad energy range will allow spectra of the rapid outbursts to be established for the first time.

There can be few problems in astrophysics more important than understanding black holes and the plasma processes taking place in their vicinity; quasars and other active galactic nuclei may represent the same phenomenon on large scales (see Rees, 1984, for a recent review of models). It can be argued on general grounds that the rapid fluctuations must originate near the innermost part of the accretion disk around the black hole; hence, they are the best probe of the most extreme non-Euclidean space accessible to astronomical observation.

Generally speaking, the millisecond domain is accessible only to collecting areas > 1000 cm^2, and calls for telemetry rates of at least a few kbps and preferably more. These considerations have to date limited the information gathered on fast processes, but new results from HEAO-1 and EXOSAT plus anticipated results from ASTRO-C and XTE will make millisecond X-ray astronomy a rich field by the time P/OF flies.

Fast processes have been in neutron stars as well as in black hole candidates. Figure 3 shows X-ray bursts from the source MXB 1728-34, with risetimes resolved using HEAO A-1. The total collecting area, 2000 cm^2, was far smaller than the P/OF collecting area. P/OF should obtain much better statistics and be able to determine how the spectrum evolves during the rise of the burst. This should test hydrodynamic calculations of burst evolution. Using EXOSAT data, van der Klis et al. (1985) have recently reported detection of quasiperiodic oscillations at high frequencies (several to a few tens of Hz) in GX 5-1. This new phenomenon presents observational goals again well matched to P/OF's capabilities, for essentially the same reasons as in the black hole fluctuations and X-ray bursts.

Magnetized accreting neutron stars (binary pulsars) have had a large role in X-ray astronomy beginning with UHURU. About 20 systems are now known, with spin periods ranging over 4 orders of magnitude, 69 ms to 13 minutes. In most systems the spin period decreases over time, but this spin-up is irregular, being driven by accretion torques and possibly other processes. Variations in period and luminosity can be used to determine neutron star parameters such as the moment of inertia or the magnetic moment. A detailed model of the accretion flow and of the dynamic response of the neutron star to the associated torque is one goal of current work.

The source A0538-66, located in the Large Magellanic Cloud, exemplifies several points about the demanding nature of binary X-ray pulsar observations. This source is unusual because (1) it has the shortest spin period (69 ms) of any binary pulsar, (2) it is a "recurrent transient," sometimes unobservable but turning-on at periodic intervals, (3) it is not always pulsing when it is active, and (4) by straightforward arguments, it must have the weakest magnetic field of any binary pulsar. These facts show it has a most atypical accretion environment that will make it the target for many future observations, surely including hard X-ray pulse phase spectroscopy. Yet it is separated by only ~30 arc min from another bright LMC source, LMC X-4; hence, gathering the needed data will simultaneously exercise P/OF's imaging (to achieve isolation from LMC X-4), time resolution (to handle the short spin period), and hard X-ray sensitivity.

The effects of 10^{12} to 10^{13} G magnetic fields on radiation processes have been studied to date solely by means of hard X-ray spectral and timing measurements, i.e., by means of cyclotron features seen in binary pulsars and possibly in gamma-ray bursts as well. This is likely to remain a phenomenon uniquely accessible in hard X-rays, partly because the canonical magnetic fields of binary pulsars place the cyclotron resonance in hard X-rays. Furthermore, if the resonance were to occur below 10 keV in some sources, then it would be more difficult to isolate from other spectral features such as atomic lines and absorption edges that strongly affect spectra at lower energies. Cyclotron features have sometimes been isolated by subtracting the spectrum obtained at one phase of the pulse cycle from that obtained at another phase (e.g., Trümper et al., 1977). P/OF could employ imaging for background removal and provide high-quality source spectra in all pulse phases over 2 to 120 keV. It is difficult to overstress the importance to physics of systematics-free data on hard X-ray cyclotron resonances. These effects result from electron transitions between energy states that are not dominated by a nuclear Coulomb field but rather by a magnetic field 5 to 6 orders of magnitude beyond anything produced in terrestrial laboratories. Pulsar observations should remain the principal source of data.

Active Galactic Nuclei (AGN)

Active galactic nuclei have been discussed in connection with imaging extended jets. However, most of the X-ray flux from these objects comes from compact components having unresolved X-ray angular diameters. These cores will probably remain unresolved with P/OF, although this is not completely certain. The compact components undergo variations that can be as slow as months to years but which can also occur on timescales less than days (Snyder et al., 1980; Tennant et al., 1981). P/OF can make a unique contribution to the study of such variations. The AGN are comparatively faint sources, but spectrally they are comparatively hard.

It is important to ascertain the spectral character of these temporal variations, determining for example how spectral indices evolve during outbursts. Obtaining several hard X-ray spectra, at intervals of minutes to months, on relatively faint sources that sometimes must be isolated from other nearby sources and that always must be isolated by careful removal of background variations, is a straightforward task for P/OF but one that is difficult by other means.

Such spectral/temporal data can be used to determine radiation mechanisms and ultimately to study particle acceleration. A deep gravitational potential well, quite possibly containing a black hole, is required to power the process. As with stellar black hole candidates, the most rapid variations at high modulation will necessarily come from the central regions and therefore assist in probing the nature of the core and its energy release.

V. RELATION TO SOLAR PHYSICS AND SOLAR OBSERVATIONS

The examples from preceding sections show P/OF to be a facility of major significance for X-ray astronomy. Limiting fluxes will be at least a factor of ten below other hard X-ray instruments, and the imaging will be of unprecedented angular resolution (0.2 arc s) for high-energy astrophysics. Spectroscopic and photometric capabilities of P/OF will also provide major contributions.

P/OF's first role, however, is as a facility for solar physics. Its use for astronomical observations carries several benefits for the solar program that should be explicitly noted.

The clearest benefit is through the X-ray observations of other stellar coronae, the only major X-ray source class not discussed above. Such coronae are bright enough to show up among the bright X-ray sources (Figure 2, bottom) and become quite conspicuous during stellar flares, with peak fluxes exceeding 50 UFU in some instances (Heise et al., 1975). P/OF would be able to observe these stellar flares to higher energies than any other instrument now planned. Detection of flares can be accomplished by an independent X-ray sky monitor such as the one planned for XTE. P/OF will either need operational capability to respond promptly to such events or else must conduct prolonged monitoring of a flaring source while it is active. Data would be obtained on flares of greatly intrinsic different size scales from solar flares: emission measures for stellar flares reach 10^{55} cm^{-3}, and luminosities reach 10^{32-33} erg s^{-1}.

The brightest flares are seen from RS Canum Venaticorum binary systems and dMe flare stars (see Ambruster et al., 1983, for examples of each type). Fainter flares have been seen from associations of T Tauri stars. Quiescent fluxes from some of these objects will also be detectable, including W Ursae Majoris systems (Carroll et al., 1980). It may even be that the imaging capability will come into play, with detection of a measurable extent to the nearest of the RS CVn binaries. Models for the spectra of these systems require the hardest component to have dimensions comparable to those of the binary separation. Since the binary separation of Capella, the nearest RS CVn system, is 0.2 arc s, it is possible that a finite extent to its X-ray component will barely be measurable, establishing the size of the corona directly.

Another benefit is that astronomical observations provide checks and calibrations on the P/OF instrument itself. Point sources will test imaging systems, providing the best confirmation of theoretical point-source response functions. Point response functions obtained from stellar observations may prove important in fitting the shapes of flare emitting regions on the Sun. Because most point sources are variable, there will be a shortage of standard candles, but the time-average of the Crab pulsar will represent a reasonable calibration source. Many astronomical situations such as mapping supernova remnants or crowded source fields will exercise image reconstruction techniques to be used on solar flares, and will give high confidence in solar results obtained by those same methods.

Possibly the most significant benefit will be the transfer of scientific information and the exchange of ideas that the use of one facility for solar and cosmic observations will encourage. Certainly there is overlap between the physical problems studied in the two contexts. Particle acceleration is a case in point, with examples coming from stellar coronae, supernova remnants, and AGN, as well as the Sun.

Finally, one should realize that P/OF could be an intermediate engineering step toward yet more advanced 21st century facilities that would push angular resolution down to tens of milliarcseconds. Achievement of X-ray angular resolution in that range is not presently foreseen for focussing X-ray instruments; hence, transform telescopes should have an ever-growing role in X-ray imaging. The commonality of interest between astronomers and solar physicists that begins with P/OF will extend to these subsequent facilities.

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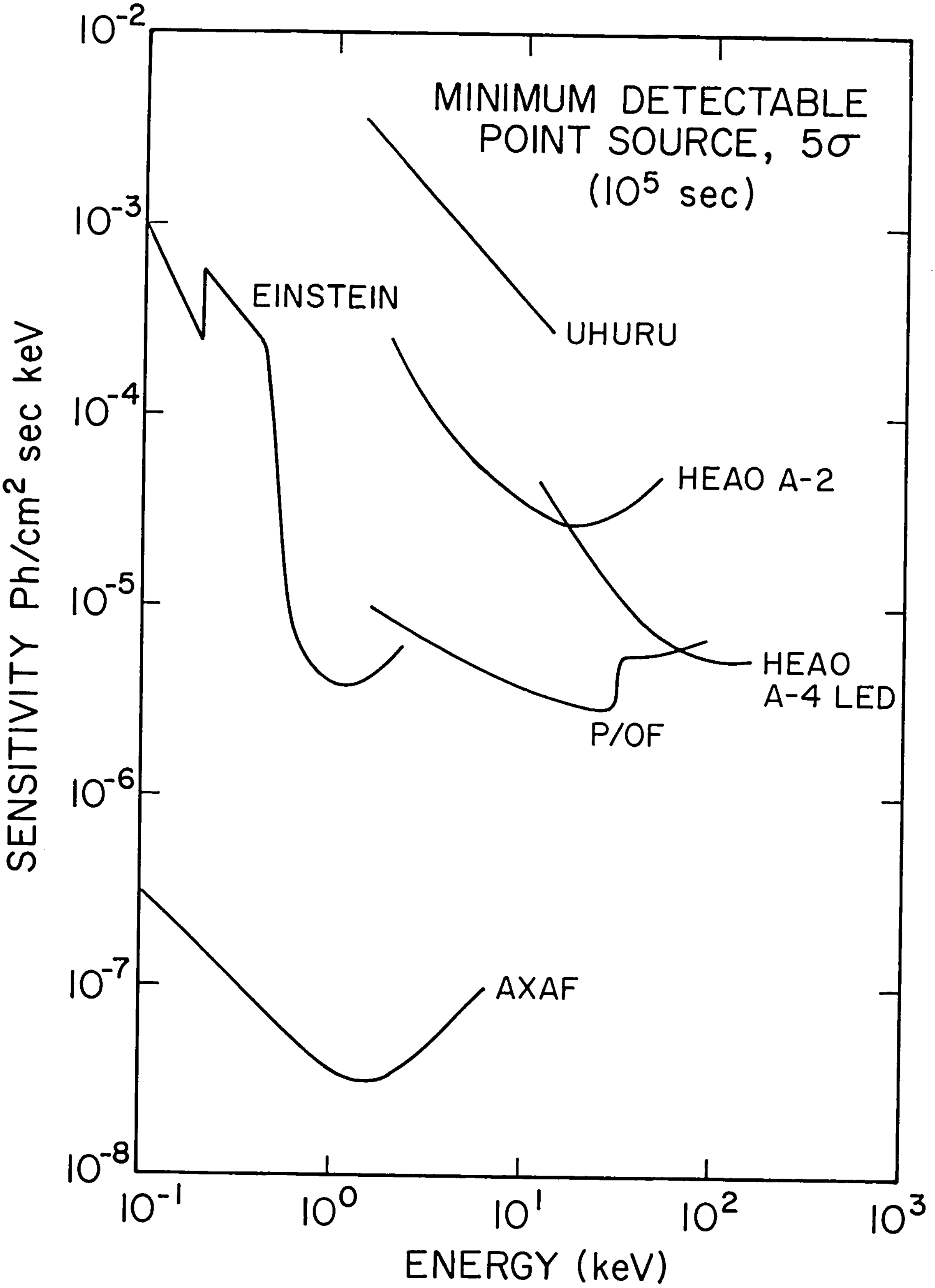
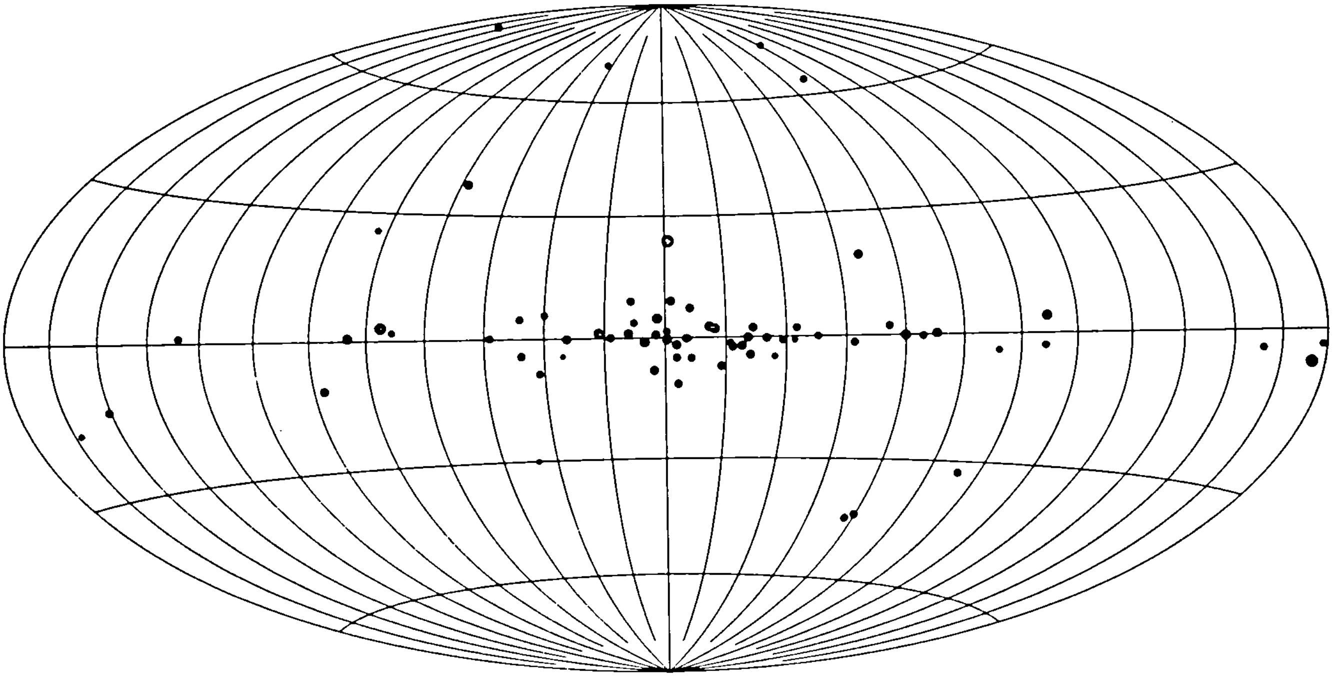


Figure 1. Spectral sensitivity of P/OF compared with other X-ray astronomy instruments.



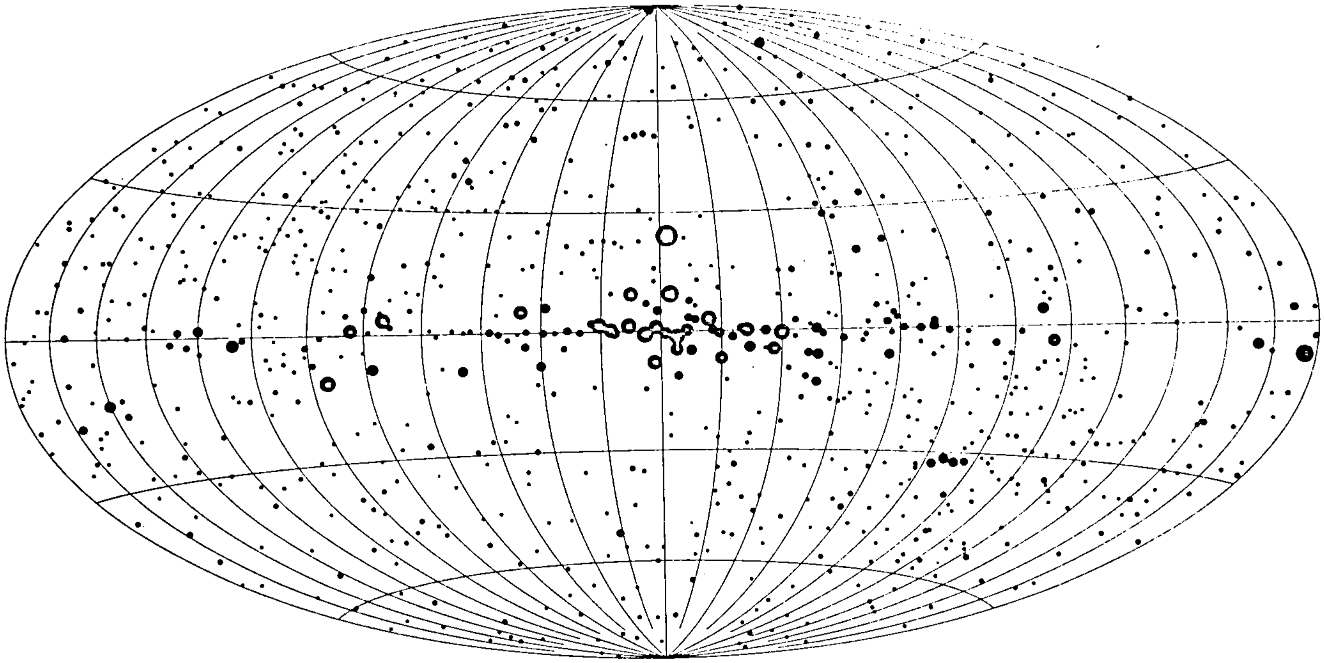


Figure 2. (Lower) HEAO A-1 catalog (0.5 to 25 keV), displayed in galactic coordinates. (Upper) HEAO A-4 catalog (13 to 120 keV) displayed in same mode.

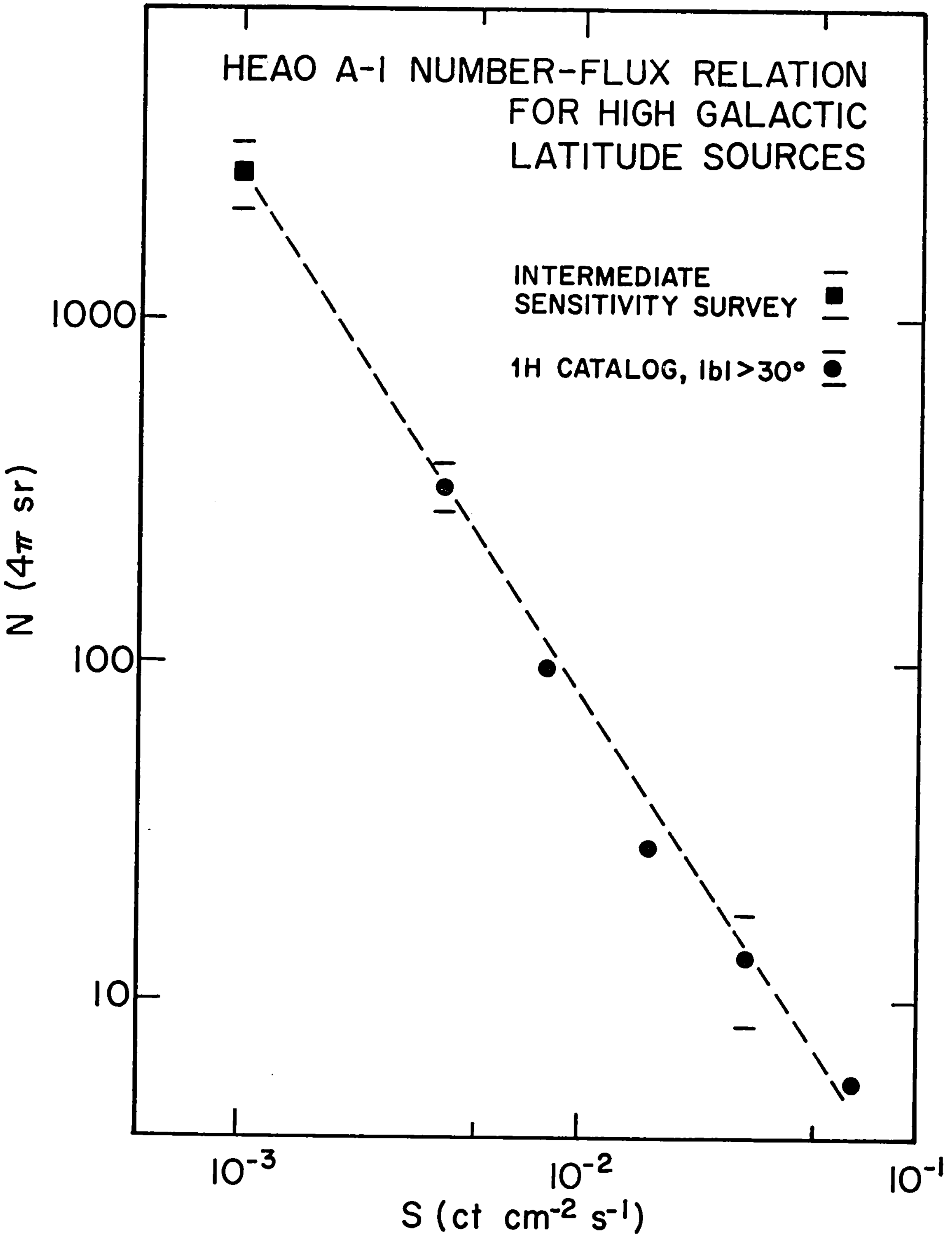


Figure 3. Source confusion, beam width, and flux limit: circles give source counts at several flux levels obtained with a 1 deg x 4 deg collimator. A finer collimator (1/2 deg x 1 deg) must be used below 3 x 10^{-3} ct cm^{-2} s^{-1}

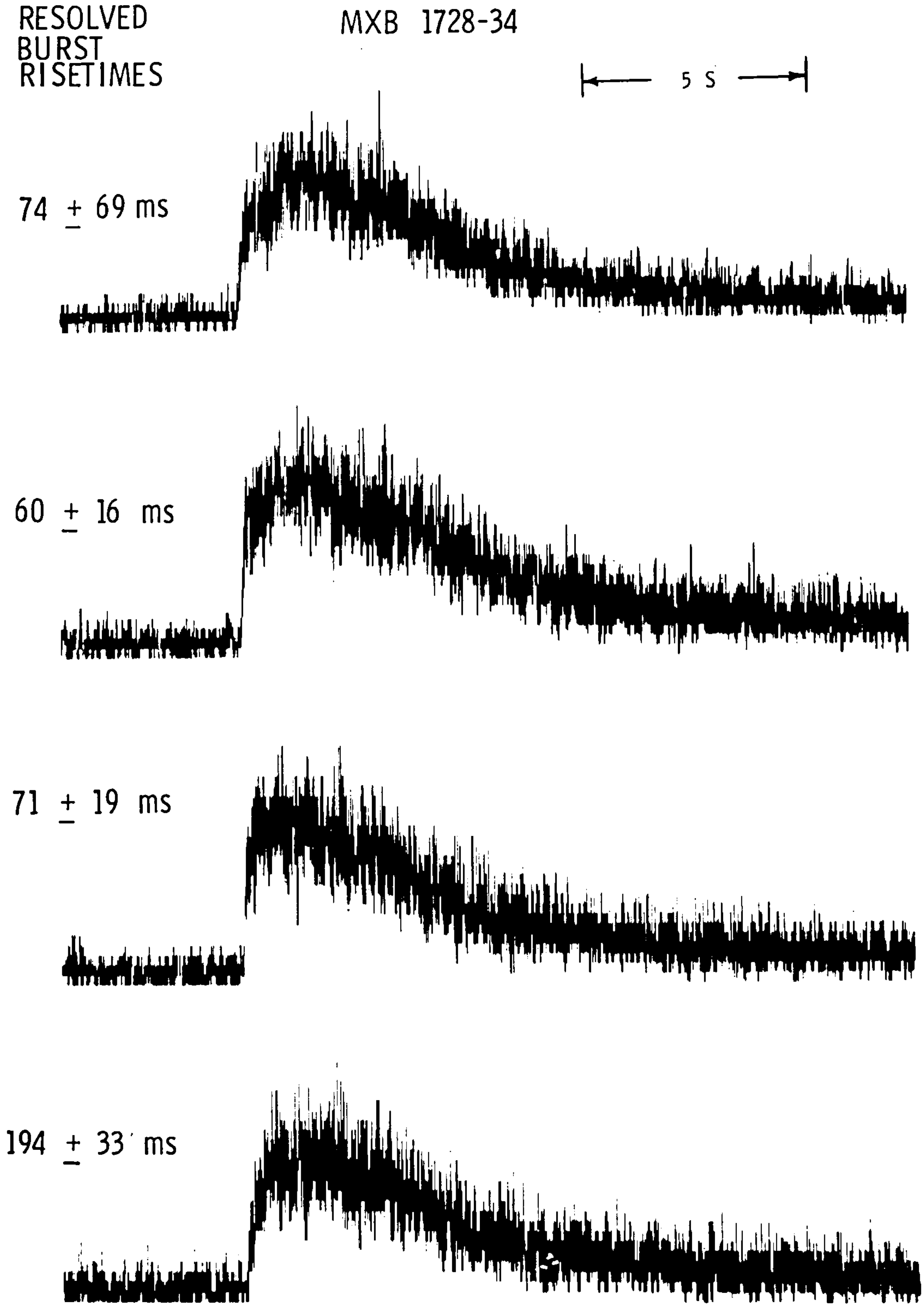


Figure 4. X-ray burst time profiles. Large collecting area and high-time resolution are needed to follow spectral evolution during the rapid rise of the burst.

TABLE 1. P/OF X-RAY INSTRUMENT PERFORMANCE SUMMARY (FOR ASTRONOMICAL OBSERVATIONS)

Angular resolution	0.2 arc s
Field of view	1 deg
Total area	15 000 cm^2
Time resolution	1 ms
Energy range	2 to 120 keV
Sensitivity at 20 keV	10^{-5} ct cm^{-2} s^{-1} keV^{-1}
Sensitivity at 5 keV	0.03 μJy
Telemetry allocation	250 kbps

TABLE 2

ASTRO-C

Proportional Counter and All-Sky Monitor to Study Time Variations

1987 Launch
Proportional Counter: 5000 cm^2; 1 deg x 3 deg FOV
All-Sky Monitor Sensitive to 100 UFU

XTE

Proportional Counter, Scintillator, and All-Sky Monitor

1991 Launch
Proportional Counter: 10 000 cm^2; 1 deg x 1 deg FOV; 2 to 60 keV
Hard X-ray: 2000 cm^2
Monitor: Sensitivity to 10 UFU in Long Integrations
Rapid Response to Transients

ROSAT

Moderate Resolution Telescope for Sky Survey

1988 Launch
X-Ray Telescope: Wolter I; E $<$ 3 keV; 500 cm^2 Limiting Area;
Angular Resolution: 3 arc s

AXAF

High-Resolution Telescope

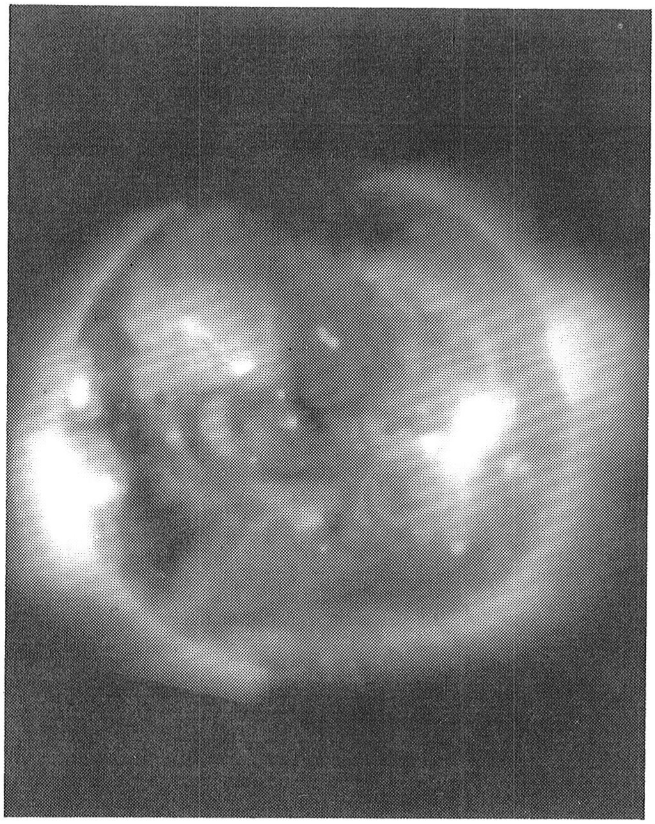
1991 Launch
X-Ray Telescope: Wolter I; E $<$ 8 keV; 3000 cm^2 Limiting Area; Angular
Resolution: 1/2 arc s within 3 arc min; 1 arc s within 1 deg

TABLE 3. NUMBER OF SOURCES IN FULL SKY ACCESSIBLE IN 10^4 s

E (keV)	Number (4π sr)
2	15000
4	12000
8	9000
16	2000
32	500
64	100

SUBPANEL SUMMARIES

● X-RAY PHYSICS



● CORONAL PHYSICS