X-ray Interferometry:
Ultra High Resolution Astronomy

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ABSTRACT

X-rays have tremendous potential for imaging at the highest angular resolution. The high surface brightness of many x-ray sources will reveal angular scales heretofore thought unreachable. The short wavelengths make instrumentation compact and baselines short. We discuss how practical x-ray interferometers can be built for astronomy using existing technology. We describe the Maxim Pathfinder and Maxim missions which will achieve 100 and 0.1 micro-arcsecond imaging respectively. The science to be tackled with resolution of up to one million times that of HST will be outlined, with emphasis on eventually imaging the event horizon of a black hole.

Keywords: X-rays, Interferometry, X-ray Astronomy, X-ray Optics, Grazing Incidence Optics

1. INTRODUCTION

X-ray interferometry is now a practical reality[1,2] and it represents an unprecedented opportunity for the astronomer. The extremely short wavelengths and the high brightness of the sources combine to allow celestial observations with thousands and even millions of times the resolution of the Hubble Space Telescope[3]. The scientific return should be truly revolutionary. One can plan to take images of the coronae of other stars, accretion disks in quasars and eventually image the event horizon of a black hole.

In 1998 and 1999 NASA funded a study of the feasibility and importance of x-ray interferometry. Named MAXIM, for Micro Arcsecond X-ray Imaging Mission, this group investigated the potential range of scientific return and the approaches to solving the technical problems. The results are available at the Maxim website[4].

The Maxim group recommended a three phase approach to the problem.

- A technology development phase in which to learn the practicalities of x-ray interferometry as applied to astronomy.
- A Pathfinder Mission with a meter-class interferometer. With 100μas resolution and modest collecting area, this mission will take detailed images of the stellar coronae and probe deep into the accretion disks of quasars.
- Development toward the full Maxim, with the goal of acquiring a black hole image before the year 2020.

Maxim now appears in the advance planning for the Structure and Evolution of the Universe Space Science theme at NASA. A full capability Maxim, with resolution better than one micro-arcsecond and ability to image event horizons in AGN's is described as a “Vision Mission” for the time period beyond 2015. A more modest mission, called Maxim Pathfinder is planned for a new start as early as 2008.

The Maxim Pathfinder Mission is expected to operate in the 0.5 to 1.5keV band and collect images of x-ray sources with resolution of 100 micro-arcseconds or better[5]. With such a huge leap in capability (representing a thousand-fold improvement over HST) there exist many technical problems to be solved.

2. SCIENCE GOALS AND REQUIREMENTS

The x-ray band, contrary to popular opinion, is actually a natural place to perform interferometry and observe targets at the highest angular resolution. There are two major advantages that x-rays hold over imaging at longer wavelengths.

First, because the wavelengths are a thousand times shorter than the visible, the baselines required are similarly short. For example, in order to achieve resolution of 100 micro-arcseconds at 1keV, we need an interferometer with a baseline of about 1.4 meters, achievable in a single spacecraft. For comparison, to achieve the same resolution in the radio at 6cm wavelength would require 120,000 kilometers. At 5000A, the required baseline is already a kilometer.

The second advantage of x-rays is the intrinsic brightness of many of the sources. X-ray sources are considered faint, but that is largely because of the small region from which the x-rays emanate. For example, a mass transfer binary can emit 10,000 solar luminosities of x-rays from a region that is only .0001 solar areas in extent. It is emitting 100 million times more energy per unit surface area. Even allowing for the high energy content per photon, the x-ray source emits 100,000 times more photons per unit area. This means that when we look at tiny objects, the telescope collecting area required is much lower in the x-ray.

The major disadvantage of the x-ray so far has been our failure to build diffraction limited optics that can be used to construct a sensitive x-ray interferometer. But recent advances have demonstrated in the laboratory that such optics are feasible and have shown us a technical roadmap that leads to long baseline x-ray interferometry observatories[6].

The range of science addressable at resolution of 0.1milli-arcseconds is broad, and just a few of the goals are presented in Table 1.

Table 1: Science Goals

Target Class	*Goal*
Resolve the coronae of nearby stars	Are other coronal structures like the solar corona?
Resolve the winds of OB stars	What kind of shocks drive the x-ray emission?
Resolve pre-main sequence stars	How does coronal activity interact with disk?
Image center of Milky Way	Detect and resolve accretion disk
Detailed images of LMC, SMC, M31	Supernova morphology and star formation in other settings
Image jets, outflows and BLR from AGN	Follow jet structure, search for scattered emission from BLR
Detailed view of starbursts	Resolve supernovae and outflows
Map center of cooling flows in clusters	Resolve star formation regions
Image Event Horizon of Black Hole	Study Material in Extreme Gravitational Limit

The basic requirements for the Maxim Pathfinder mission are shown in Table 2. In order to achieve resolution of 100 micro-arcseconds at 1keV, we need an interferometer with a baseline of about 1.4 meters, obtainable in a single spacecraft. For comparison, to gain the same resolution in the radio at 6cm wavelength would require 120,000 kilometers.

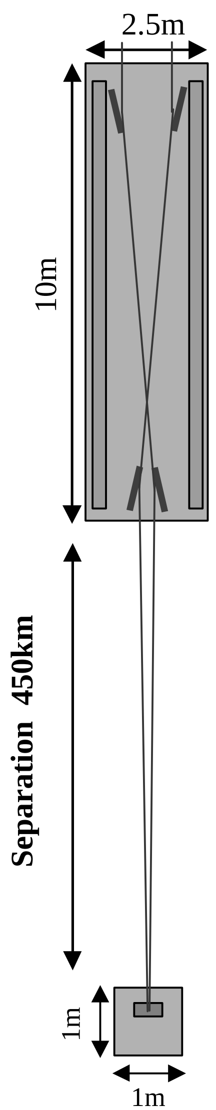
Table 2: Performance Requirements

Angular Resolution	100μas
Baseline	1.4 meters
Collecting Area	$100cm^2$
Field of View	10 mas
Bandpass	0.5-2keV + 6keV
Pointing	30μas
Spectral Resolution (E/δE)	20
Size	Single Launch
Orbit	High Earth or Drift Away

The science requires that we be able to observe at 1keV, since many of the most interesting targets are obscured below 0.5keV by absorption in the interstellar medium. Adding some capability at 6keV through the use of multilayers would be very exciting, giving the mission access to the astrophysically-important Fe K line. The collecting area should be in the vicinity of $100cm^2$. We know from previous missions like Einstein that $100cm^2$ supports excellent work on a large variety of objects. However, missions with just $10cm^2$ of collecting area have studied a limited range of bright targets.

We do not expect or need to move to new targets hourly. A new target every few days would allow the mission to return a spectacular set of about one hundred unique images per year. Thus modest collecting area and leisurely target acquisition are acceptable.

The stability requirements on the spacecraft are quite challenging. There is little hope of suppressing all the extraneous mechanical influences of low Earth orbit, so it appears that either a high orbit or a drift-away orbit will be required. These high orbits naturally allow lengthy observations of targets, which is valuable for high quality image reconstruction.



Optics Spacecraft

Carries: **X-ray Interferometers**
Finder X-ray Telescopes
2 Visible Light Interferometers
Laser Ranging System

Size:	**2.5x2.5x10m**
Pitch&Yaw Stability:	**3×10^{-4} arcsec**
Pitch&Yaw Knowledge:	**3×10^{-5} arcsec**
Roll Stability:	**20 arcsec**
Position Stability:	**-----**

Detector Spacecraft

Carries: **X-ray Detector Array**
Laser Retro Reflectors
Precision Thrusters

Size:	**1x1x1m**
Pitch&Yaw Stability:	**20 arcsec**
Roll Stability:	**20 arcsec**
Lateral Stability:	**5mm**
Lateral Knowledge:	**50 microns**
Focal Stability:	**10 meters**

Figure 1: Schematic of Maxim Pathfinder in the two spacecraft configuration.

3. MISSION CONCEPT

Pathfinder consists of an array of grazing incidence mirrors on a stabilized spacecraft, creating x-ray interference fringes on the detector, which is located on a second spacecraft 450km away.

The Optics: Mirrors that preserve the x-ray wavefront are very difficult to polish and figure, even at grazing incidence. While it is *possible* to build Wolter-type x-ray telescopes that are diffraction limited, these greatly complicate the fabrication of the observatory and depress the collecting area. For this reason we have chosen to use the flat mirror concept. The interferometer will consist of two rings of flat mirrors. Each ring will contain 32 flat mirrors, each fine adjustable to achieve zero null on axis. The interferometer will have about $100cm^2$ of effective collecting area, similar to that of Einstein and ROSAT.

Target Acquisition: Most of the science targets will boast celestial coordinates accurate to only slightly better than one arcsecond, but Pathfinder must have a way to allow the observer to center on the target of interest. As such, Pathfinder will have two x-ray optical systems, a Wolter telescope and an interferometer. The Wolter telescope will have approximately five arcseconds resolution while the interferometer will have a 1.4 meter baseline and produce the full 100 micro-arcsecond resolution. The detector spacecraft will have a 30x30cm array of CCDs. The size of the 3cm beam cast by the mirrors at a distance of 450km is only about 15 milli-arcseconds. The array of detectors increases this coverage to about 150 milli-arcseconds. If the Wolter telescope has resolution of about five arcseconds, then it should be possible to centroid the target to about 0.15 arcseconds. The first image with the interferometer can then be used to center exactly on the target.

Optics Spacecraft: The spacecraft that carries the interferometers should be about 2.5 meters in diameter and ten meters long. In most respects, such as power and mass, it will be conventional. In the area of pointing stability it must be exceptional. We need to hold the pointing stable to about 300 micro-arcseconds and provide pointing information down to about 30 micro-arcseconds. Drifts greater than 30 micro-arcseconds must not occur during the readout time of the CCD. The pointing information will be generated by two visible light interferometers that will view stars that lie in the heavens approximately perpendicular to the target line of sight and to each other.

Detector: We have chosen to use an imaging quantum calorimeter for the detector. It needs to be about 30mm square with 200 micron or smaller pixels. Energy resolution of 10eV at 1keV would nicely support the science. The optics have a very wide field of view, so an array of these 3cm CCD's will be used to increase the field for centroiding on poorly known target positions.

Formation Flying: The detector spacecraft needs to hold its position in space relative to the main spacecraft, to about a tenth of a fringe spacing. This can be accomplished using a laser ranging system between spacecraft and microthrusters to offset drifts. This capability is comparable to that needed in the LISA mission, but is in some ways easier as they need to measure acceleration while we care only about position.

Orbit: Because the two spacecraft need to be stable relative to each other and to the celestial sphere, we must move the mission away from the turbulence of low Earth orbit. We expect that either a flyaway orbit or a Lunar Lagrangian point would be appropriate.

Table 3: Interferometer Characteristics

Primary Ring Diameter	140cm
Secondary Ring Diameter	30cm
Distance: Primary to Secondary	1000cm
Distance: Secondary to Detector	450km
Mirror Size	3x90cm
Graze Angle	2 degrees
Number of Primary Mirrors	32
Number of Secondary Mirrors	32
Mirror Quality @ 6328Å	λ/400
Mirror Coating	Ir + Multilayer
Resolution @ 0.25keV	360 μas
Resolution @ 1keV	90 μas
Resolution @ 6keV	15 μas
Fringe Width @ 1keV	2mm
Fringe Width @ 6keV	0.3mm
Field of View	10 mas
Bandpass	0.1-2keV+6keV

4. OPTICAL DESIGN

1. Layout

To avoid the potential difficulties of building diffraction limited Wolter x-ray optics, we have baselined the flat mirror interferometer in the "x" configuration as demonstrated in the laboratory[2,7,8]. Table 3 summarizes the characteristics of the interferometer design, while Figure 2 shows the layout of such a system schematically in two dimensions, while Figure 3 shows a 3D perspective.

This reduces the optics problem to its absolute minimum. Flats are the easiest mirrors to fabricate and to align. The problem is that to achieve adequate fringe magnification the beams must

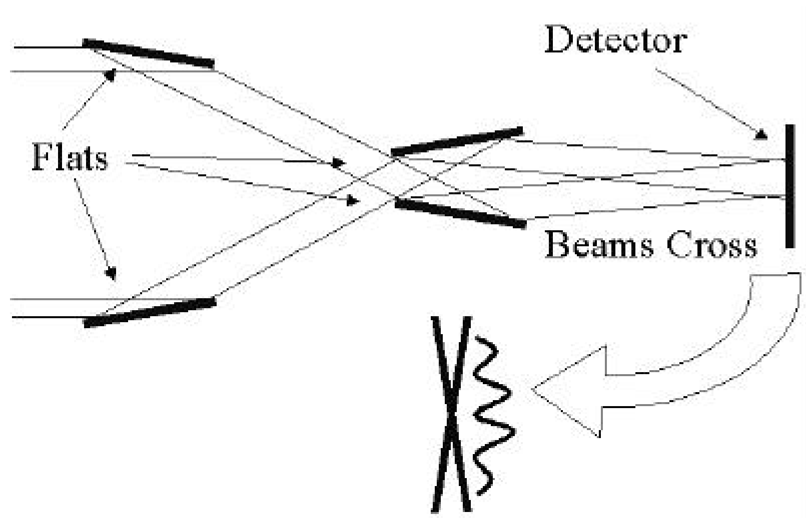


Figure 2: The basic arrangement of the interferometer involves four flat mirrors in an “x” shaped configuration.

cross at a very low angle. To magnify 1nm waves to 100 micron fringes requires a cross angle of about 2 arcseconds, which implies that L will be large.

The size of L is in turn driven by the size of d, the spacing between the flats in the beam converger. Our design requirement of $100cm^2$ enters here. We will need 32 flat mirrors in a ring to achieve a nice field of view, so each mirror channel should have about $3cm^2$ of effective area. Allowing for losses due to the two reflections and the detector, we find the aperture should be 3cm square. Fitting 32 such mirrors in a ring requires a 30cm diameter, which we use as the baseline separation in the beam converger.

The effect of bringing 32 flats in a ring into phase coherence is dramatic as shown in Figure 4. The figure is a simulation of the pattern resulting from a monochromatic point source. With two mirrors the detector records the expected sine wave. With four mirrors we find a checkerboard. As the number of mirrors rises, the pattern first becomes complex, and then starts to clear out the region around the central point of constructive interference. We are, effectively, building a diffraction limited telescope out of flat subapertures. As the pointing changes, the bright spot moves around the field of view just as in a telescope. For the 32 mirror case, an excellent image 64x64 pixels in extent is achieved without inversion of fringes. For wider fields of view, there is a substantial power to be found in the surrounding rings, that must be removed through image processing.

Thus, an interferometer consists of two rings of flat mirrors. In Figure 3 we show a 3-D rendering of the arrays. We show only 8 mirrors per ring for clarity, when the interferometer will have 32 per ring. Each mirror will be mounted on precision actuators that will allow in-flight alignment. The mirrors themselves will be 3cm wide and 90cm long. They can be as thick as desired because there is no nesting envisioned. The total amount of glass in each interferometer is about the equivalent of a 1m square mirror.

Figure 3: Rendering of the two rings of mirrors shown with 8 mirrors per ring.

The primary ring of the interferometer will consist of 32 mirrors with actuators in a ring 1.4 meters in diameter. The resolution of such a ring is given by $\lambda/2D$, where D is the diameter of the ring. This supports resolution of 70μas at 1nm, and 100μas at 0.9keV. At 6keV, using the multilayer reflection, the resolution reaches 14μas.

Note that the resolution is given as $\lambda/2D$, not the usual λ/D. The usual formula is appropriate for a filled aperture telescope, where, when the outer edges of the mirror are 180 degrees out of phase, most of the center is still in phase. Also, consider that in an interferometer, an angle change of λ/D will cause a the a full fringe shift, but we can resolve two stars when they are half a fringe out of phase, indicating the resolution is $\lambda/2D$. Our use of a single ring creates large diffraction rings, but it also doubles the resolution.

2. Mirror Requirements

An x-ray interferometer is a sensitive device. The lengths of the paths that the x-rays travel are sensitive to errors in position and angle in the mirrors. They have to be held to a fraction of an x-ray wavelength, which means 100 picometers. This would be extremely challenging except that we are once again rescued by the geometry of grazing incidence.

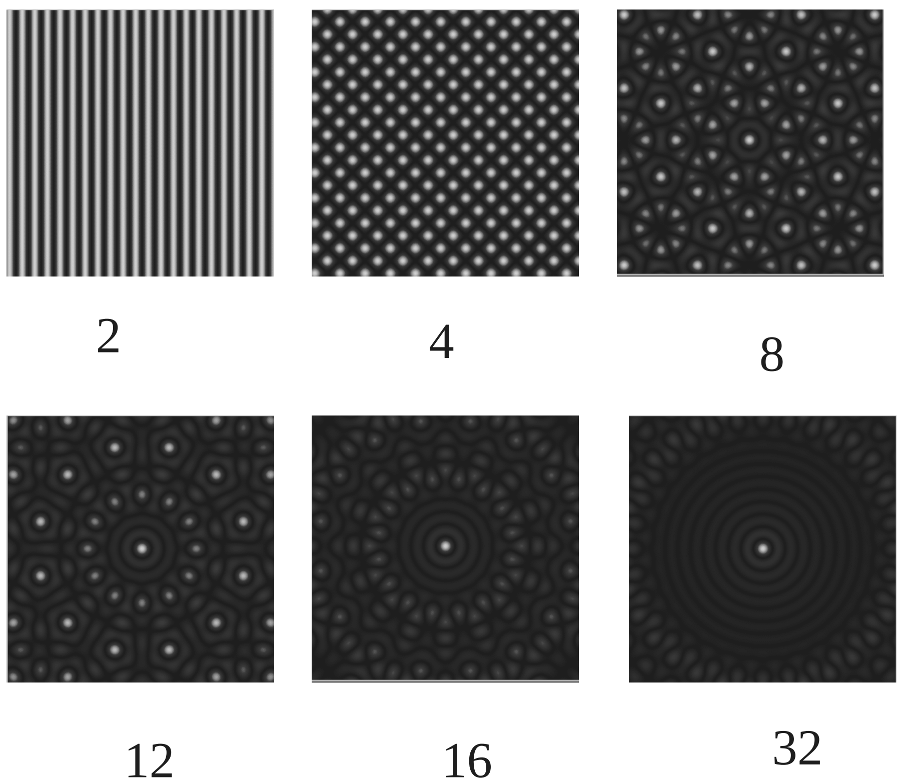


Figure 4: Interferometric patterns created by flat mirror pairs in a ring. Two mirrors create lines (fringes), while additional mirrors create more complexity and greater image clarity.

In the direction of the mirror normal we find that the position tolerance is relaxed by a factor of $1/\sin\theta$ relative to a normal incidence reflection. For 1nm radiation, we typically use a 2 degree graze angle, which, when inserted into the formula implies that the mirror must be held to about 1.5nm relative to the mirror on the other side of the interferometer if the fringe is to be held to one tenth of a wavelength. This is the tightest metrological tolerance.

In an accompanying paper at this meeting[9] we present an analysis of the angular tolerance for each mirror in the interferometer. Its tightest tolerance is for an angular deviation in the in-plane direction. The figure proves that each mirror should be held to one tenth of its own diffraction limit. This makes sense, as there is no optical information below the diffraction limit except at the fraction of a fringe level. For Pathfinder we find that each mirror must be aligned and held to about one milli-arcsecond if it is to hold the tenth fringe requirement.

This is an area that needs substantial development before flight. The tolerances are stringent and at the state of the art. We need to develop both the mirrors and their holders for flight.

5. DATA SIMULATIONS:

An important question that needs to be answered for MAXIM is what science it will be able to achieve. Simulating the types of objects that the interferometer is likely to see while also taking into account instrument specifications can provide a solution.

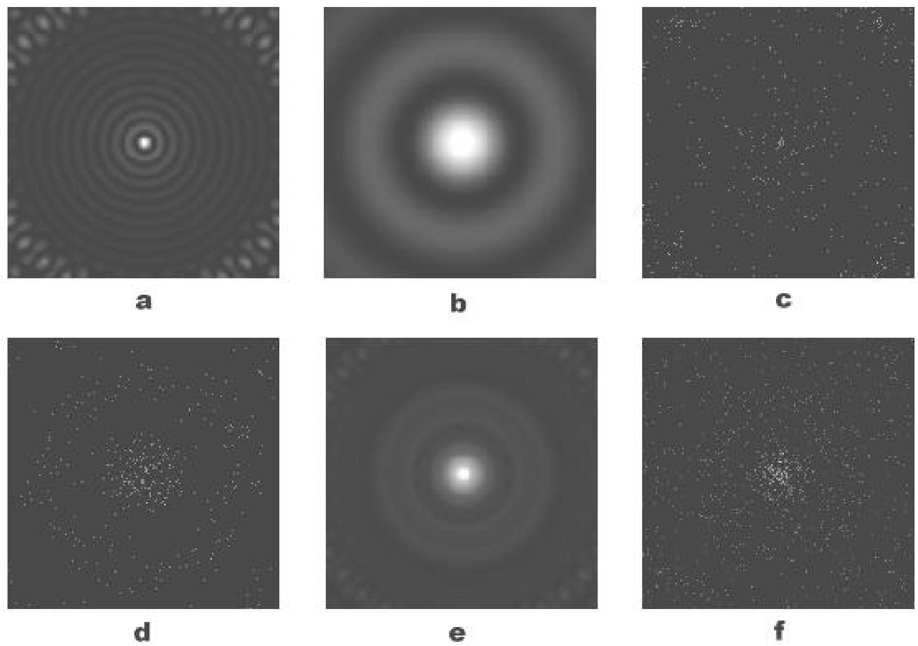
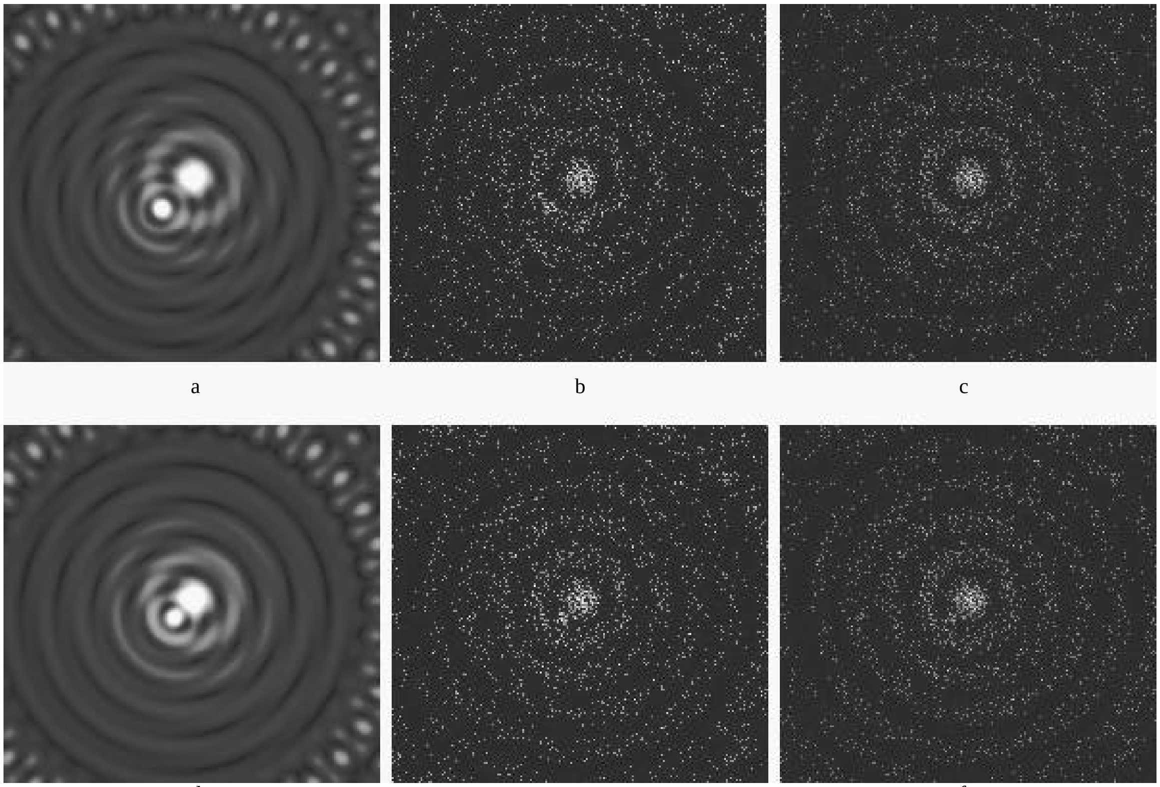


Figure 5: Simulations of point sources viewed by a 32 mirror interferometer. a) beam pattern at 6keV b) beam pattern at 1keV c) poisson data simulated at 6keV d) data at 1keV e) beam pattern of 0.5 to 6keV continuum f) data simulation of continuum

Figure 5 displays point sources with a variety of characteristics as seen through an array of 32 flat mirrors arranged in a ring. Figures 5a and b show the probability distribution function (PDF) for 6keV and 1keV point sources, respectively. The next two images show Poisson data generated using the corresponding PDFs. Finally, in Figures 5e and f, a continuum was generated with 0.01keV resolution along with Poisson data for this continuum.

Other interesting simulations using point sources include those depicted in Figure 6. These are a series of binary systems with differing intensities and separations in the same field of view. In Figure 6 a the central source has flux half that of the source that is displaced to the lower left. The next image shows 9000 total events for this system with the lower flux source having twice the intensity of the higher flux source. Even though the higher flux source is in the first maximum of the other, the two can be easily distinguished. Following this is another image with 9000 events. However, this time the central source has five times the intensity of the higher flux source and now the presence of a second source is not obvious. Figure 6d shows the same system with a smaller separation so that the higher flux source is in the first null of the lower flux source. Now, the higher flux source is noticeable not only at half the intensity but also at a fifth of the intensity of the lower flux source.

A series of simulations more indicative of MAXIM's capabilities is shown in Figure 7. These images depict how stellar coronae would appear to MAXIM. The first image is a SOHO image of the Sun in the extreme ultraviolet. This is probably analogous to the high altitude regions of many solar type stars in our vicinity. The image was sensitivity limited to the pixels with the highest count values.

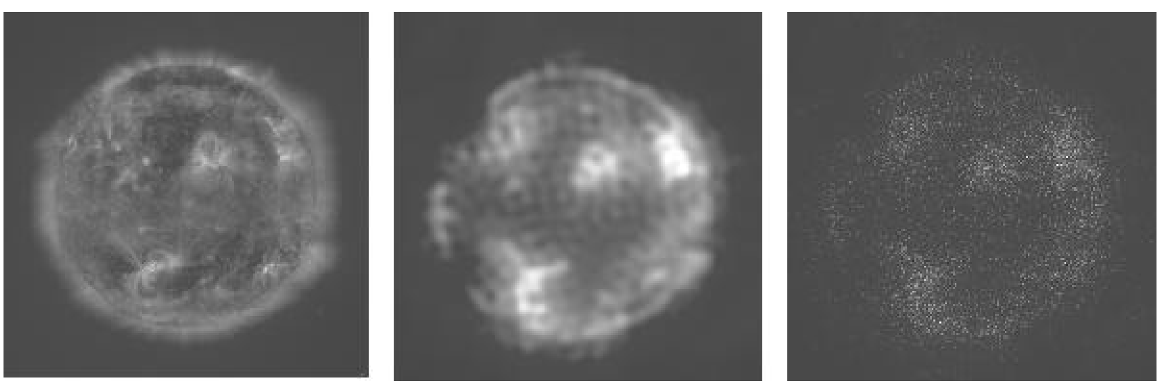


a b c

d e f

Figure 6: Binary point source distributions at differing intensities and separations. These simulations demonstrate that the interferometer acts like a telescope with major diffraction rings.

A new image was made by mapping a point source to the position of each pixel that contained a value. The intensity of each point source was scaled according to the pixel's count value. The result is shown in Figure 7b. This probability distribution function was then used to define the mapping of Poisson data as shown in the final image.



a b c

Figure 7: Simulations of the observation of a stellar corona with 32 element flat interferometer. a) is the original image b) is the image convolved with the interferometer beam c) poisson data applied to image response.

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