MAXIM
MicroArcsecond X-ray Imaging Mission

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1 Introduction

X-rays have been studied in detail for over a century, yet until relatively recently, x-rays were a region of the electromagnetic spectrum inaccessible to astronomers. The Earth's atmosphere is completely opaque to x-ray radiation, so measuring x-rays from an astronomical source necessarily means that the instrument be in space, either on an orbiting platform or aboard a sub-orbital experiment such as a sounding rocket or balloon. This alone has only been technically possible for the last 50 years. The problem is compounded by the fact that x-ray detectors capable of astronomical measurement have been hindered by large measurement errors and to obtain a true focus with an x-ray system, the beam must reflect twice off of nested, hyperbolic and parabolic grazing incidence optics. The most common configurations for x-ray telescopes are the Wolter types, which are optical systems that use parabolic surfaces to direct incident light onto a hyperbolic surface that focuses it [8]. For example, The Chandra X-ray Observatory employs a Wolter Type I telescope. These optical systems are not only technically challenging, but also very expensive to manufacture, thus preventing the production of large apetures.

A collaboration of astronomers from University of Colorado at Boulder and NASA's Goddard Space Flight Center have proposed a solution to the traditional limitations of x-ray astronomy with MAXIM, the MicroArcsecond X-ray Imaging Mission. The MAXIM mission proposes to fly an array of telescopes in formation that will synthesize the collecting area of a larger telescope. The basic concept is not very different from the stellar interferometer designed by Michelson in the early 20th century, with modifications to allow for operation in the x-ray band. MAXIM proposes to fly it's collector spacecraft at a separation (or baseline) of up to several hundred meters, which would provide an angular resolution given by:

$$\theta = \frac{\lambda}{2B} \tag{1}$$

where θ is the angular resolution (in radians), λ is the wavelength and B is the baseline. For example, at a baseline of 100 meters and a wavelength of 2 Å (roughly corresponding to well studied Fe emission lines), a resolution of 0.2 microarcseconds (μas) can be achieved.

The primary science goal for the MAXIM mission is to image the event horizon of a black hole. The black hole would be seen in silhouette against bright emission from the hot accretion disk surrounding its event horizon. General relativity leads us to expect to see the light from the disk bent and distorted around the shadow of the black hole by the strong gravitational field near the event horizon. Nearby active galactic nuclei are the best candidates for imaging with MAXIM, with diameters of a few μas. Angular resolution of tenths of microarcseconds would allow astronomers to resolve the inner regions of accretion disks and event horizons of black holes. MAXIM has several other major science goals, including imaging the accretion disk surrounding the black hole at the center of our Galaxy and imaging flares and coronas of nearby stars at a spatial resolution of a few hundred kilometers [2].

2 Instrument Design

X-ray telescopes are very challenging to build because the mirrors needed are subject to very tight constraints, not only in their curvature, but also in their surface smoothness. MAXIM avoids the complication of attempting to obtain a precise focus by using flat mirrors to mix the wavefronts from adjacent arms of the interferometer. The x-ray interferometer proposed differs from the Michelson stellar interferometer in that it requires grazing incidences on all of its bounces to retain an appreciable reflectivity. Additionally, x-rays do not have the option of a focusing optic to ensure that the Fraunhofer zone is near the collecting mirrors. In order to observe x-ray fringes, the detector must be placed considerably behind the collecting and converging optics. However, because the system uses flat mirrors instead of focusing mirrors, there is no focal constraint on the separation of the collecting and converging surfaces. This means that the collecting optics can be placed at a larger baseline, further in front of the converging mirrors without any other change to the system configuration and, the resolution will increase [2, 3].

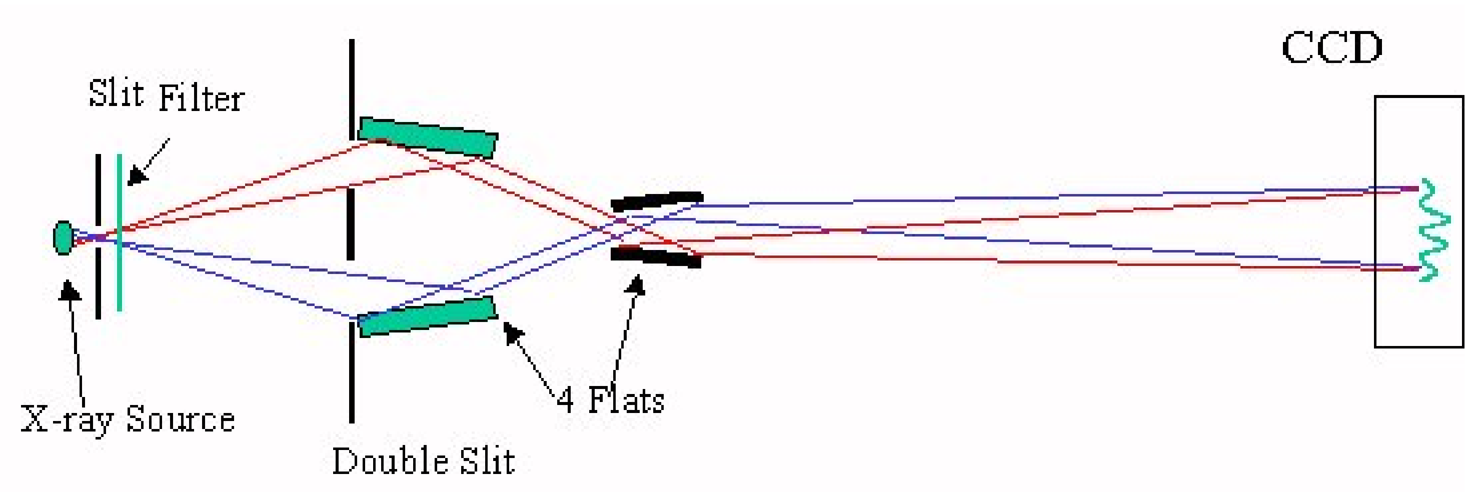

Figure 1: Two-dimensional, prototype x-ray interferometer layout.

3 Spacecraft Design

The entire MAXIM instrument will consist of a total of 36 individual, free-flying spacecraft (S/C). These will consist of 32 collector S/C, one hub, a converger, a detector, and a delay line S/C to assist in pointing stability (see below). The 32 identical collector S/C will contain three meter flat mirrors, and fly with an overall separation of several hundred meters. They will be kept in formation by reference to the hub S/C. The hub craft also helps maintain stability in the pointing by forming a visible wavelength interferometer with the converger craft. A star perpendicular to the optical axis of the MAXIM system is incident upon both the hub and the converger S/C. The light at the hub is sent through a 90 degree bounce and directed at the converger. The converger sends it's beam to a delay line craft that reflects the light back to the converger and the beams combine to form a nulling interferometer. The delay line craft will reference it's position relative to the converger via laser, and the overall setup allows pointing errors to be detected as a shift in the null [1].

The detector S/C will fly in formation about 5000 km behind all of the other S/C, and will most likely employ a CCD. The detector S/C needs to be several thousand kilometers behind the converger for the fringe spacing to be large enough to measure with CCDs currently available. The fringe spacing measured on the detector is given by $\lambda L/d$ where L is the distance from the converger to the detector and d is the separation of the converging optics. For example, at 2 Å a converger separation of 5 meters, and a detector distance of 5000 km, one would expect a fringe spacing of 0.2 mm on the detector, easily resolvable by CCDs available today. Another important issue at the detector is having enough photons per pixel to take high quality data. The brightest x-ray sources will be needed, the number of photons detected by MAXIM is given by:

$$N = (4.5 \times 10^{18})\theta^2 T^3 \quad (2)$$

where T is the effective temperature of the target and θ is the angular resolution; for an integration time of 100 kiloseconds and an effective area of 1000 cm^2, a reasonable estimate of the effective area MAXIM can hope to achieve, and a long exposure time for premier targets [2]. Data will also be energy-tagged, current x-ray band CCDs of flight quality are capable of an energy resolution of $E/\delta E \approx 50$ at 6 keV [3]. The energy

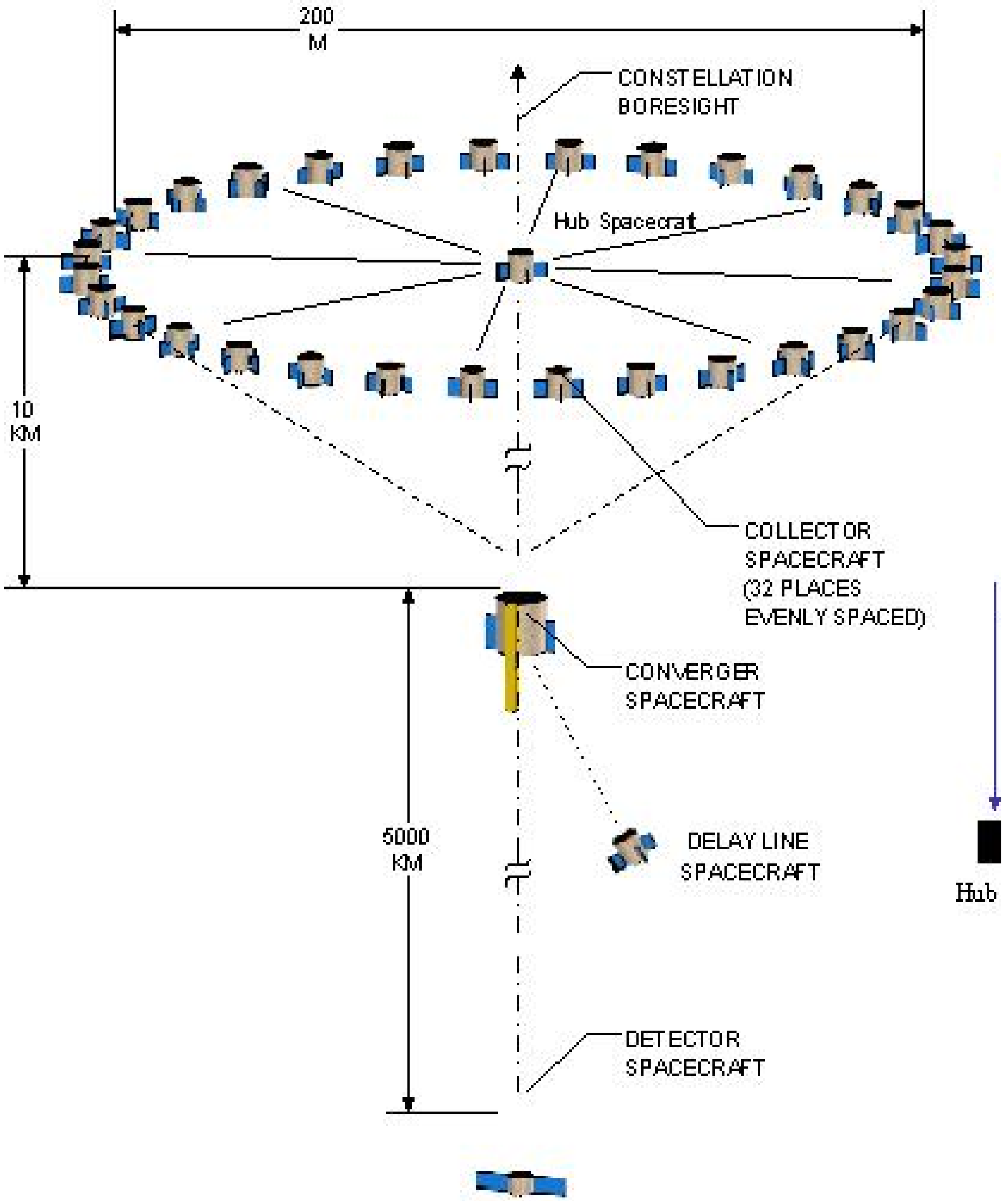

Figure 2: MAXIM constellation design.

resolution of the detector will provide the spectral resolution of the interferometer as data can be separated into individual sine waves of different frequencies.

The optimistic upper limit for the project is an effective area of 10,000 cm^2 [2]. Working through the equations at an x-ray energy of 2 keV, and combining this with the longest suggested integration time of one million seconds, a signal of 100 photons per pixel can be achieved at a resolution of:

$$\theta_{min} = 10^{-1} T^{-3/2} [arcseconds] \tag{3}$$

which would require a baseline of:

$$B = (6.7 \times 10^{-2}) T^{3/2} [cm] \tag{4}$$

These equations can be combined and evaluated at the target resolution of one-tenth microarcsecond to yield a baseline of 700 meters.

4 Technical Tolerances and Limitations

Interferometry at such short wavelengths requires tremendous instrument stability and high quality optics to assure coherence so that detectable fringes are created. MAXIM is proposed to fly in a heliocentric, 'driftaway orbit', at a distance of one astronomical unit (AU). The most highly constrained instrument dimension is the baseline separation, where the tolerance is given by:

$$\delta B = \frac{\lambda}{20 sin\phi} \tag{5}$$

for one-tenth fringe stability, where ϕ is the graze angle, which requires the collector S/C to deviate from their position by less than a few nanometers [1]. As mentioned above, the collector craft will maintain their position via laser reference to the hub S/C. Equally important is the constraint related to the surface figure of the flat mirrors. The surface deviation criteria is given by the same formula as the baseline tolerance, exchanging baseline deviation with surface figure deviation. At one nanometer and a 2 degree graze angle, this leads to a surface tolerance of 3.6 nm. This would be approximately a $\lambda/175$ off-the-shelf mirror. Such mirrors are available today, and as flats are all that is required, the cost is modest. The optics will also be required to have a front-back thermal gradient of less than one-hundreth of a degree Kelvin in order to maintain stability. All mirrors in the MAXIM system will need three-dimensional freedom of motion on orbit (tip, tilt, and piston) in order to make small corrections between observations, maintain equal pathlengths during an observation, and to correct any misalignments that may occur on launch. Maintaining equal pathlengths in each channel will require tilt and piston resolution and knowledge of 10 nm or better. This tight constraint, coupled with the thermal constraint mentioned above put the mounts needed for the MAXIM optics beyond the scope of current technology, and progress will need to be made to that end. The collector-to-converger distance and the converger-to-detector distance must also be constrained, but these can be easily satisfied by today's formation flying capabilities [1].

Pointing and orbital stability are also concerns for a fleet of 36 separate spacecraft, particularly when they are spaced over large distances and have different mass and ballistic properties. Solar gravity and radiation pressure play the largest role in exerting external forces on the formation elements. The formation is flown at an ecliptic inclination of zero, with the converger S/C, as it is by far the most massive craft, in a true Keplerian orbit. Solar gravity acts on the collector, hub, delay-line, and detector S/C, and is at a maximum when the MAXIM formation is normal to the ecliptic. The detector S/C, being roughly 5000 km from the ecliptic plane in these cases, would be shifted by as much as 750 m/day. In addition, there are second order effects due to gravitational forces from both the Earth and Jupiter that must be taken into account. It is clear then that the formation must be continuously corrected to make precise pointing and long integration times possible.

MAXIM will slew at a rate of no greater than five degrees per day, as even small changes in the collector-hub S/C plane correspond to large movements of the detector S/C. Additionally, to minimize thermal fluctuations, the instrument will always point perpendicular to the sun line. No observations are planned during maneuvers and a six-hour 'fine-tuning' is required after each maneuver. Orientation changes and stability against the perturbations listed above will require each S/C to carry a three-dimensional propulsion system. Currently, the proposed system is composed of pulse plasma thrusters (PPT), several types of which are being/have been tested on Department of Defense LES missions. Six to eight PPTs mounted on each collector S/C would allow for a 10 year mission life. As the converger and delay-line S/C experience the least disruptive force and move the least during maneuvers, controlling them is a manageable task with existing technology. The most challenging aspect of maneuvering MAXIM is the detector S/C. Being located at a large distance behind the rest of the formation, it requires large movements to stay in alignment with the optical axis. At this time, there does not appear to be a self-contained propulsion system that can sustain these large movements over the life of the mission. Two possible solutions that are being considered are: a) a second detector spacecraft that would cover a certain range of orientations (and offer redundancy) and b) the use of hydrazine arcjets that are currently being developed on other space missions [1].

5 MAXIM Science Goals

The primary science goal of the MAXIM mission is to image the event horizon around a black hole. Matter in the inner regions of accretion disks in active galactic nuclei is under the influence of the extreme gravitational field of a black hole of several million to several hundreds of million solar masses. Such extreme environments are known to produce bright x-ray sources, which is why the x-ray band is desirable for imaging the region surrounding a black hole. Besides the obvious interest in indisputable verification of black holes, detailed imaging would allow astronomers to study material falling into the black hole and provide a 'laboratory' where general relativity should have macroscopic effects. The best candidate for observation at present is the black hole at the center of M87. The center of M87 is believed to harbor a 100 million solar mass black hole which powers x-ray emission and high speed jets. At a distance of roughly one megaparsec, the angular size of the accretion disk should be a few microarcseconds in diameter, resolvable if MAXIM can achieve the goal of one-tenth μas resolution [2, 9].

X-ray bright black hole accretion disks are the primary targets due to the large flux from such objects, but with sufficient observing time, a host of other science goals may be attainable. One such project would be a high resolution map of the inner most regions around the black hole at the center of the Milky Way. X-rays can penetrate the galactic dust obscuration and could tell astronomers about the nature of an accretion disk and the motion of the material in the region. Another goal of MAXIM is to image the accretion disks of x-ray binaries both in our galaxy and in the Magellanic Clouds. The distribution of x-ray emitting gas in the binaries would also be a topic of study. Finally, given sufficient flux and the resolution of the instrument, the atmospheres of nearby stars could be measured to a resolution of a few hundred kilometers and trigonometric parallax could be measured for stars as distant as the Virgo cluster [2, 9].

6 Current Status

High resolution x-ray imaging of astrophysical objects is a relatively new observational possibility, however, physicists have been creating interference patterns with x-rays for almost 70 years using a combination of the Lloyd's mirror geometry and the Fresnel double mirror [6, 5]. Clearly, before any large scale space mission can be reasonably proposed, the technology required must be demonstrated in a laboratory setting.

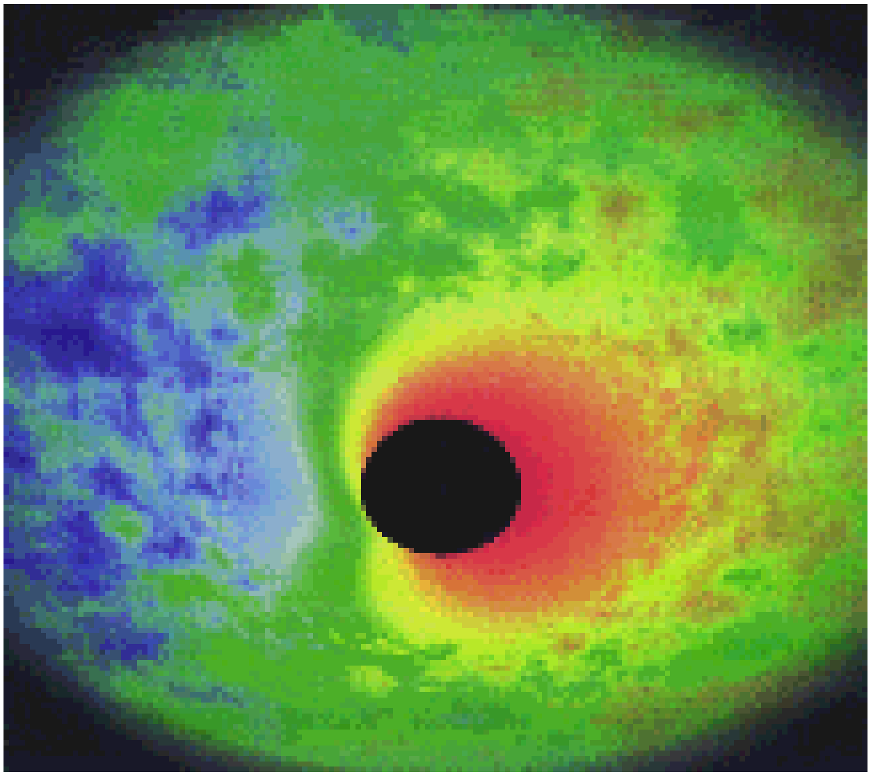

Figure 3: Simulation of event horizon image.

Recently, a prototype x-ray interferometer was built by the University of Colorado and successfully tested at Marshall Space Flight Center (MSFC). Using the 120-m vacuum facility at MSFC, an x-ray interferometer using the same flat mirror, grazing incidence design as described for the MAXIM mission, produced fringes. The model instrument used a baseline of about 1-mm and a CCD mounted 100-m behind the converging mirrors. The 50-mm circular flat mirrors, at graze angles of 0.2 degrees, were mounted on manipulators that allowed for rotational and translational motion during the tests. The incident beam was created using an electron impact source with a magnesium target and an aluminum filter that created a beam predominantly composed of the 1.25 keV Mg K line. The beam was cut down at the front of the interferometer by a double slit mask that allowed only the light striking the collector mirrors to enter the system. Fringes with a spacing of about 0.2-mm were recorded, which correspond to an angular resolution of roughly 100 mas [3].

A successful laboratory model is only the first step towards the full MAXIM observatory. Demonstrating a scaled down model of the instrument in a sounding rocket mission using formation flying of a mirror and detector payload has been discussed, but the most likely prototype for the MAXIM mission is the MAXIM Pathfinder [4]. The Pathfinder is designed to be a proving ground for the x-ray interferometer concept without the complication of formation flying all the collector mirrors. The Pathfinder has an array of 32 collector and converger mirrors, but at a baseline of only 1-m, which will provide an effective area of about 100 cm^2 and allow everything but the detector to be housed on one spacecraft. The detector would fly on a separate spacecraft (at a distance of $\approx$ 450-km), which would provide a test for the long distance, formation flying that would be necessary for the final MAXIM mission. The Pathfinder mission would achieve an angular resolution of 100 μas.

The Pathfinder will also help in creating the final target list for MAXIM, providing detailed celestial coordinates. Only a few targets will have detailed coordinates prior to the Pathfinder mission however, and since targets may not be visible in the optical or may be in confused fields, an x-ray 'finder scope' will

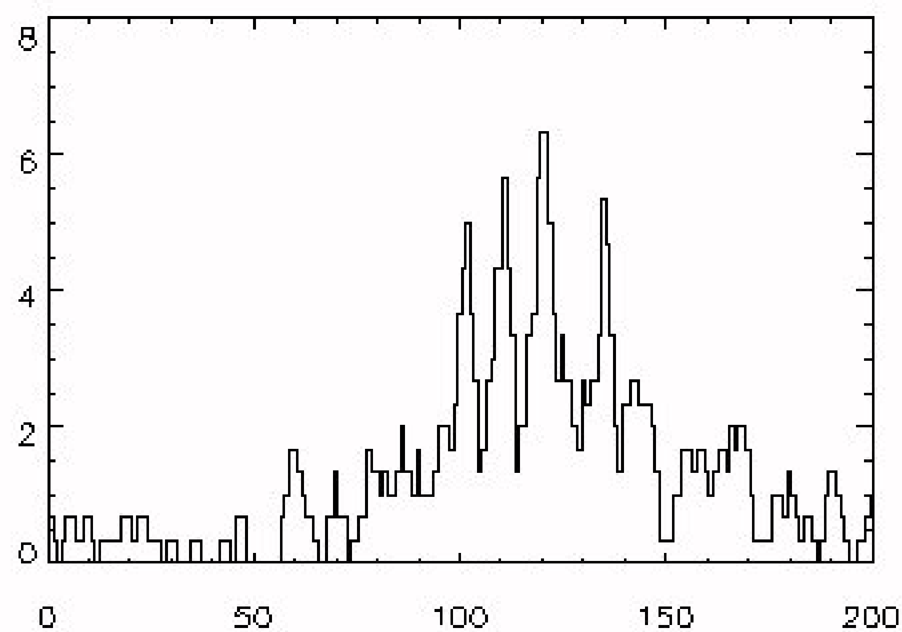

Figure 4: X-ray fringes created by x-ray interferometer prototype.

be required. A Wolter telescope with arcsecond resolution is proposed, and once the target is acquired on the detector, the interferometer can be used to correct the pointing. The detector S/C maintains its position through the use of laser ranging devices [4].

The MAXIM Pathfinder will not be solely a technology demonstration though, with 100 μas resolution, it represents an increase of 1000 over what is currently possible with Hubble and Chandra (100 and 500 mas, respectively). This means that Pathfinder will have a set of science goals all its own [4, 7]. For example, the disk of Alpha Centauri has a diameter of 7 mas, so the Pathfinder would allow astronomers to image the disk of a solar-type star in detail. The signal-to-noise ratio for the image of a stellar disk with MAXIM Pathfinder (using an effective area of 100 cm^2 and a 10 kilosecond integration time) is given by:

$$(S/N)^2 \;=\; 10^7\, f_X^{tot} (\frac{\theta_{min}}{\theta_D})^2 \tag{6}$$

where f_X^{tot} is the x-ray flux in $photons/cm^2/s$, θ_{min} is the instrumental resolution, and θ_D is the angular diameter of the stellar disk. α Centauri, for example, has an x-ray flux of 0.0067, which yields a signal-to-noise of 3.7. Higher signal-to-noise can be attained on stars with a larger x-ray flux such as Capella, a binary system whose brighter component has an angular diameter of 9 mas and an x-ray flux of 0.12. Capella would have a signal-to-noise ratio of 12.2 for the observation described above. Imaging hot gas in x-ray binaries, at smaller distances than suggested for MAXIM, would also be possible. Colliding stellar winds and other x-ray emitting shock fronts could also be imaged, provided the flux was sufficient. It seems clear that Pathfinder, and it's parent instrument, MAXIM, provide an opportunity to push the edge of our current technological and scientific boundaries.

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