Galaxies and Their Constituents at the Highest Angular Resolutions
IAU Symposium, Vol. 205, 2001
R.T. Schilizzi, S. Vogel, F. Paresce and M. Elvis

X-ray Interferometry

Webster Cash

University of Colorado, Boulder, CO, USA

Abstract. X-rays have tremendous potential for imaging at the highest angular resulution. 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.

1. Introduction

X-ray interferometry is now a practical reality (Cash, 1997; Cash et al. 2000), 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 (White, 2000). The scientific return should be truly revolutionary. One can plan to take images of the coronae of the 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 (http://maxim.gsfc.nasa.gov).

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 (Cash, White & Joy, 2000). 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 which is only .0001 solar areas in extent. It is emitting 10million 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 .

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.

As an example, consider Figure 1. To the left is a simulation of an x-ray image of the star Capella, captured with a resolution of 0.1milli-arcseconds. Not only is the star seen as a binary, but the details of the coronae of each star are also visible. To the right is a simulation of the x-rays from the accretion disk around the giant black hole at the center of an AGN. An image that shows the dark region requires resolution better than one micro-arcsecond for all but a couple of targets.

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 for studies of targets like stellar coronae that are relatively stable for a period of days. To properly study the material around a black hole requires more collecting area, several thousand square centimenters or more, in order to track individual bright points as they orbit.

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*

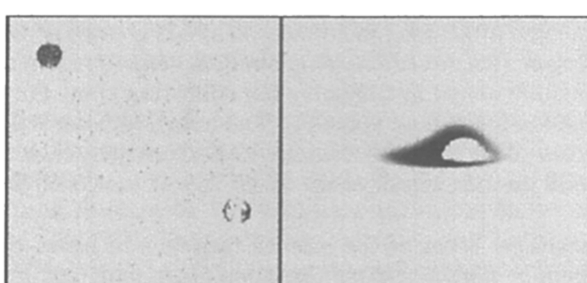

Figure 1. Left - Simulation of the x-ray bright star Capella. When observed at resolution of 100 micro-arcseconds, the individual coronae of the two stars can be mapped and studied. Right - Simulation of the x-rays from the accretion disk around a black hole. (Courtesy C. Reynolds)

https://doi.org/10.1017/S0074180900221761 Published online by Cambridge University Press

The observatories do not need to move to new targets hourly. A new target every few days would allow the mission to generate a spectacular set of unique images within a 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.

Table 2. Performance Requirements

Mission	**Pathfinder**	**Maxim**
Angular Resolution	100μas	100 nas
Baseline	1.4 meters	300 meters
Collecting Area	100cm^2	3000cm^2
Field of View	10 mas	10μas
Bandpass	0.5-2keV + 6keV	0.5-6keV
Pointing	30μas	30nas
Spectral Resolution (E/δE)	20	1000
Orbit	High Earth or Drift Away	Drift Away

3. Maxim Pathfinder

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. The ring will contain 32 flat mirrors, each fine adjustable to achieve zero null on axis (Cash et al. 2000; Joy et al. 2000; Shipley, Cash & Joy 2000).

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

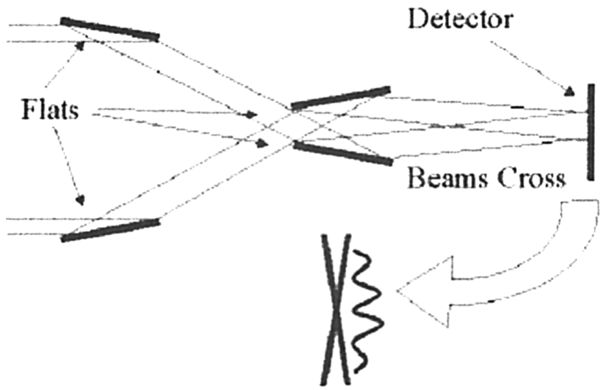

Figure 2. The basic arrangement of the interferometer involves four flat mirrors in an "x" shaped configuration.

0.15 arcseconds. The first image with the interferometer can then be used to center exactly on the target.

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.

Pointing: We need to hold the pointing stable to about 300 micro-arcseconds and provide pointing information down to about 30 micro-arcseconds (Marr et al. 1999). 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 (Stahle et al. 1999). 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.

https://doi.org/10.1017/S0074180900221761 Published online by Cambridge University Press

4. Maxim

The details of the full Maxim mission to image a black hole are less well defined. The mission is not planned for a new start before 2015. All of the concepts and tolerances of the Pathfinder are applicable to Maxim as well. The single biggest difference is in the baseline over which the apertures are placed. For the pathfinder it is 1.4meters. For Maxim we need something between 200meters and 2km. This will require mirrors to be deployed and monitored on nanometer scales across these much larger separations. Deployable structures or tethers might hold the mirrors. But, it might be possible to fly the apertures in separate spacecraft, held in precision formation. Such an array would be very versatile, allowing the craft to fly further apart, with the possibility of eventually achieving one nano-arcsecond resolution.

Acknowledgments. The authors wish to thank the members of the Maxim Committee and the NASA Institute for Advanced Concepts whose support and hard work have propelled the project toward reality. We would also like to thank A. Shipley, J. Grady and D. Gallagher for contributions to development of these concepts. This work was supported by a grant from the NASA Institute for Advanced Concepts.

References

Cash, W., "High Resolution X-ray Imaging", *The Next Generation of X-ray Observatories,* edited by MJL Turner and MG Watson, University of Leicester Report XRA97/02, pp 147-152, 1997

Cash, W., White N., Joy, M., "The Maxim Pathfinder Mission: X-ray Imaging at 100 Micro-Arcseconds", *Proc. Soc. Photo-Opt. Instr. Eng.*, **4012**, 258-269, 2000.

Cash, W., Shipley, A., Osterman, S., and Joy, M., "Laboratory Detection of X-ray Fringes with a Grazing-Incidence Interferometer", *Nature*, **407**, 160-162, 2000.

Joy, M., Shipley, A., Cash, W., Carter, J., "Results from a Grazing Incidence X-ray Interferometer", *Proc. Soc. Photo-Opt. Instr. Eng.* , **4012**, 270-277, 2000.

Marr, J. C., Dallas, S., Laskin, R., Unwin, S., Yu, J., "Space Interferometry Mission: Measuring the Universe", Proc. 16^{th} IEEE Instrumentation and Measurement Technology Conference, Piuri and Savino editors, 1117-1122, 1999.

Shipley, A., Cash, W., Joy, M., "Grazing Incidence Optics for X-ray Interferometry", *Proc. Soc. Photo-Opt. Instr. Eng.*, **4012**, 456-466, 2000.

Stahle, C. K., et al, "Toward a 2-eV Microcalorimeter X-ray Spectrometer for Constellation", *Proc. Soc. Photo-Opt. Instr. Eng.* , **3765**, 82-93, 1999.

White, N., "Imaging Black Holes", *Nature*, **407**, 146-147, 2000.