The future of high angular resolution X-ray astronomy

Paul Gorenstein[*a], Webster Cash[d], Neil Gehrels[b], Keith Gendreau[b], John Krizmanic[b], M.Coleman Miller[c], Christopher S. Reynolds[c], Rita M. Sambruna[b], Gerald Skinner[b,c], Robert E. Streitmatter[b], David L. Windt[e]

[a]Harvard-Smithsonian Center for Astrophysics, 60 Garden St. Cambridge, MA, USA 02138-1516

[b]Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD USA 20771-0003

[c]University of Maryland, College Park, MD USA 20742-2421

[d]University of Colorado, CASA Campus Box 389, Boulder, CO USA 80309-0389

[e]Reflective X-ray Optics LLC, 1361 Amsterdam Ave. Suite 3B, New York, NY USA 10027-2589

ABSTRACT

The angular resolution of Chandra is close to the practical limit of grazing incidence telescopes due to the difficulty of imparting an accurate figure and smooth surface to mirror substrates whose physical area is over two orders of magnitude larger than their effective area. However, important scientific objectives lie beyond the reach of Chandra and all future missions being planned by the space agencies. By transmitting X-rays diffractive and refractive optics are not subject to the same limitations and have a superior diffraction limit. A Fresnel zone plate can be paired with a refractive lens such that their intrinsic chromatic aberrations cancel to 1st order at a specific energy. The result is a limited but significant energy band where the resolution is a milli arc second or better, for example, at 6 keV. Chromatic aberration can be corrected to 2nd order by separating the diffractive and refractive elements. This configuration allows a resolution of a few micro arc seconds. The optics are very light weight but have extremely long focal lengths resulting in a requirement for very long distance formation flying between optics and detector spacecraft, and small fields of view. Opacity of the refractive element imposes a lower limit upon the X-ray energy of about a few keV.

Keywords: X-ray telescopes, X-ray diffraction, high angular resolution

1. INTRODUCTION

The goal of the next generation major X-ray astronomy observatories, namely XEUS and Constellation-X is developing high throughput, moderate angular resolution telescopes that are used primarily for high resolution spectroscopy. Their throughput will exceed Chandra's and XMM-Newton's by two orders of magnitude. The subsequent Generation-X mission should provide another order of magnitude or higher throughput. While 2, 3 orders of magnitude higher collecting area is attainable with grazing incidence optics, a comparable improvement in angular resolution is not. Grazing incidence technology, which had three generations of significant progress from the Einstein Observatory to ROSAT to the Chandra X-Ray Observatory, has arrived at or is near the technology's limit. Any improvement upon Chandra's resolution obtained with a large grazing incidence telescope is likely to be minimal. The resolution of grazing incidence telescopes is very sensitive to figure errors and surface roughness. Increasing the focal length can ease some problems. However, longer focal length diminishes the effective area and/or results in more substrate area requiring accurate figure control, super-fine polishing and mass.

Obtaining significantly better angular resolution than Chandra requires a new technology. Normal incidence reflection is not the solution because it is effective only below 1 keV at most and within a very small bandwidth. The only type of X-ray telescope that offers several orders of magnitude improvement upon Chandra's resolution over a significant bandwidth is a diffractive-refractive doublet that transmits, rather than reflects, X-rays.[1,2,3,4,5]. The intrinsic chromatic aberration of both members of the doublet can be made to offset each other over a bandwidth of about 15%. Broader energy coverage can be obtained with several systems operating in parallel either as a cluster of separate telescopes + detectors with the same focal length but covering a different wavelength band or co-axially and sharing the same detector. Even with several systems operating in parallel a <u>**di**</u>ffractive-<u>**re**</u>fractive <u>**X**</u>-ray (DIREX) telescope system is

[*] goren@cfa.harvard.edu; phone 1 617 495-7250; fax 1 617 495-7356

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light weight compared to a grazing incidence telescope. However, extremely long focal lengths, from about 10^3 km to more than 10^4 km are needed. The problems associated with very long focal length are small field of view, larger cosmic ray background, and more demanding mission operations. Depending upon the telescope's geometry the angular resolution at 6 keV is expected to be within the range of a milli arc second to several micro arc seconds. That is comparable to or superior to the best angular resolution that has been achieved in any branch of astronomy.

The resolution of a DIREX telescope is limited by either diffraction or chromatic aberration. Increasing the optic's diameter improves the diffraction limit but increases the chromatic aberration with the focal length constant. Increasing the focal length while the diameter is constant ameliorates chromatic aberration, and eases the optics fabrication process. It is likely to improve the resolution but decreases the field of view and reduces sensitivity because of more background in pixels that are physically larger. Longer focal length also makes aligning the optics with the detector more difficult and increases the amount of time and rocket propellant needed to change targets. The size of the useful field of view is limited by the size of the detector. The MASSIM mission concept, described in another paper presented at this symposium[6], is a prime example of a DIREX system.

The theme of this symposium is "Synergies Between Ground and Space". In all the other branches of astronomy the space based telescopes and their ground based analogues are qualitatively similar in size and application. However, the nearest ground based counterparts of components of the meter size DIREX telescopes are sub millimeter size X-ray microscopes operating at synchrotron radiation laboratories.

2. SCIENTIFIC OBJECTIVES

We list some scientific objectives for a very high angular resolution X-ray telescope followed by a brief discussion.

- The environment surrounding super massive black holes (SMBH),
- The merging of two SMBH's up to the final stages,
- Origination points and bright spots in jets from SMBH's and black hole binaries,
- Coronas of active nearby stars,
- Structure of protoplanetary disks surrounding very young stars by imaging fluorescent Fe lines.

There exists competing models for the environment surrounding a SMBH. Two are shown in Fig. 1.

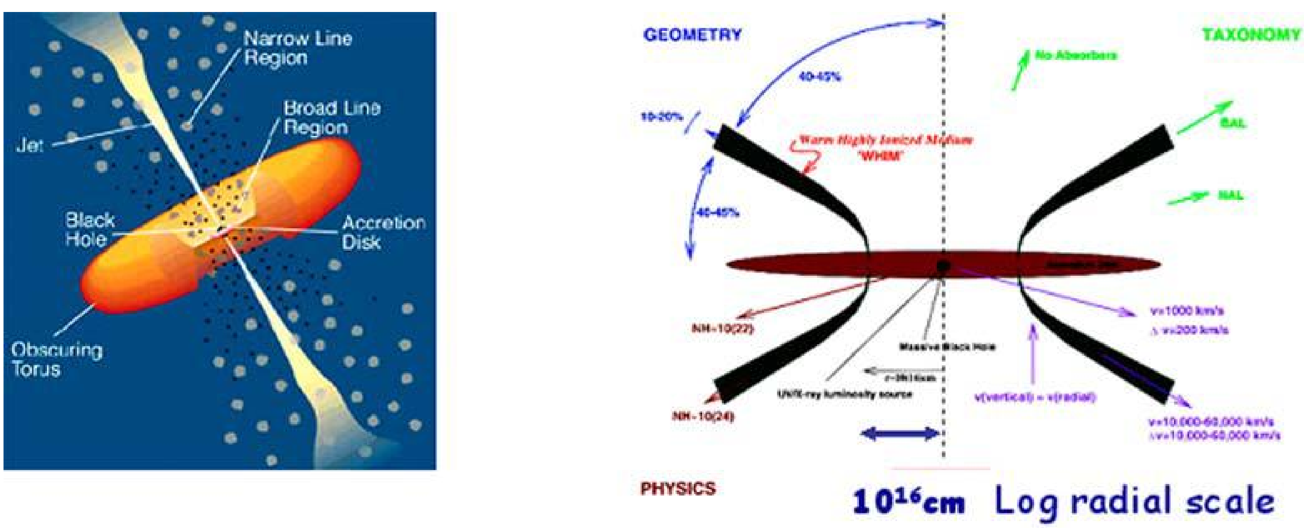

Fig. 1. Models of the environment surrounding a super massive black hole. The left panel shows the best known model, a large torus with opposing jets emanating perpendicular to the central plane[7]. The model shown in the right panel consists of broad conical outflows from a much smaller structure [8].

The physical structure of the SMBH will be reflected in the structure of its X-ray emission. Very high resolution X-ray images may be able to elucidate it. At a distance of 10 Mpc the linear size of "10^{16} cm" shown in Fig. 1 corresponds to an angular size of 66 micro arc seconds. This is obtainable with a long focal length separated diffractive-refractive doublet.

Following an indication of extent by a radio measurement the Chandra X-Ray Observatory showed that X-ray emission from the center of the starburst galaxy NGC 6240 came actually from two nuclei, about 2 arc seconds apart [9]. They will merge eventually to form a single SMBH. Higher resolution images of many AGN's especially those exhibiting suggestive radio signals like NGC 6240, are likely to reveal SMBH mergers in process that are much further advanced. Obtaining images of black holes is one of the few ways that the behavior of matter in very strong gravitational fields can be studied. Also there is increasing evidence that the evolution of a galaxy in linked to the growth and evolution of its central SMBH. Very high resolution X-ray images of the SMBH's of external galaxies in various stages of evolution will be crucial to examining this issue.

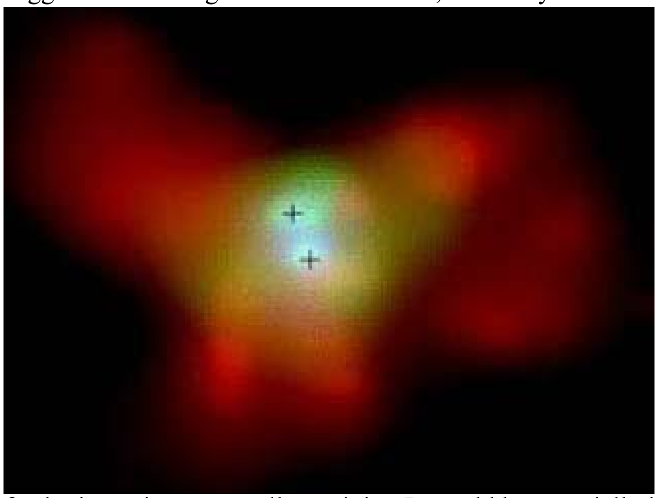

Fig.2. Chandra X-ray image of NGC 6240. The two nuclei are about 2 arc seconds apart

There are about fifty stars within 5 pc of the Sun. Many of them are more active and emit more X-rays, especially above 4 keV. At 5 pc the angular size of the solar disk is about 1 milli arc second. A DIREX telescope with a resolution of one-tenth milli arc seconds will be able to image the active regions of stellar disks and provide a fresh viewpoint upon stellar activity. It would be especially interesting to compare the stellar X-ray images with the very many of the Sun obtained from a succession of solar X-ray telescopes in space over two decades.

The Chandra X-Ray Observatory has observed the 6.4 keV Fe fluorescence line from pre-main sequence (PMS) stars [10]. The source must be the fluorescence of circumstellar cold material. The PMS phase coincides with the era of high stellar activity and planet formation where the stars are surrounded by a disk of gaseous and terrestrial proto planetary material. The source of the Fe lines must be the terrestrial material. Current studies of exoplanets have been very successful at finding Jupiter size and larger gaseous giant planets but relatively poor at imaging terrestrial material. Very high resolution X-ray studies of Fe K lines will be sensitive to the relatively cold terrestrial material, making them an important means of studying exoplanets. A modest, light-weight DIREX telescope can have an order of magnitude more effective area than Chandra at 6.4 keV. By concentrating upon a narrow energy range with a high resolution detector the influence of background is minimized. At a distance of 500 pc the angular size of a 5 AU proto planetary disk is 10 milli arc seconds, well within the telescope's capability.

3. DIFFACTIVE-REFRACTIVE X-RAY TELESCOPES

3.1 Introduction

The status of DIREX telescopes is still in the conceptual development phase. However very small size versions of the diffractive and refractive components are operating successfully at synchrotron laboratories as microscopes and beam shaping devices but not in the chromatic aberration correction configuration we desire. Also, achromatic optical devices using similar principles are the basis of some professional camera lenses. Although there are laboratories attempting it, it is difficult to test even small telescope prototypes at the milli arc second level on the ground. A very long vacuum chamber with a stable platform between the object, the optics, and the image is needed. There is also a need for a detector with both very high spatial resolution and good energy resolution. Nevertheless, there is little reason to doubt that a DIREX telescope will function as described in the papers cited. Fabrication of the components should be non-problematic compared to grazing incidence telescopes. The absolute mechanical tolerances on the macroscopic astronomy components are actually much less stringent than they are on the microscope components. However, a monolithic meter size telescope as thin as required for transparency would be too fragile. Therefore the telescope will have to be segmented and supported with a rib structure plus an underlying (and perhaps an overlaying) taut mesh, similar to the thin window of a gas proportional counter. Aligning and maintaining the alignment of the segments is likely to be more demanding than their fabrication. The mass of the telescope will probably be dominated by the mass of the support structure.

With focal lengths of ~10^3 km and higher, mission operations far more than constructing the optics will determine the cost of the program. The issues are deployment and separation of two (or three) spacecraft, maintaining the alignment of the optics and detector spacecraft with a tolerance of about a centimeter, and changing targets.

3.2 Configuration of DIREX telescopes

Fig. 3. shows two types of DIREX telescopes. One is the contact doublet, a zone plate and a refractive lens acting as a single device aboard one spacecraft with the detector a focal length's distance away aboard another spacecraft.

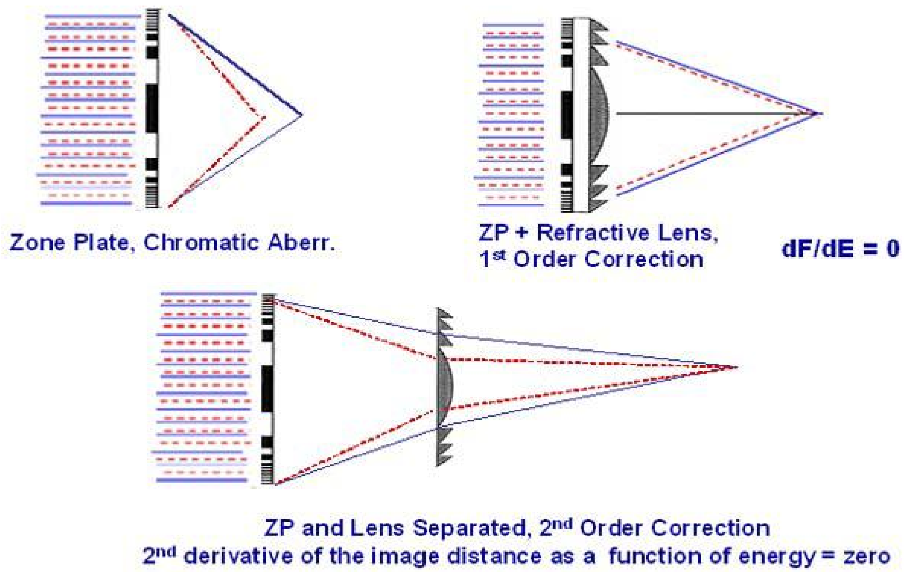

Fig. 3. Two types of DIREX optics are shown. The upper left panel illustrates the chromatic aberration characteristic of a Fresnel zone plate, which applies to the refractive lens as well to an even greater degree. The upper right panel is a contact doublet that is corrected for chromatic aberration to 1st order at a specified energy. The lower panel is a separated doublet where chromatic aberration is corrected to both 1st and 2nd order. Note that the convex lens is diverging, because the index of refraction of any solid material is less than 1 at X-ray energies.

As explained in references [1] to [5] given the linear dependence upon X-ray energy of the focal length of the zone plate and the quadratic dependence of the refractive lens the net focal length of the contact pair as a function of energy will be stationary at an energy where the focal length of the lens is minus twice the focal length of the zone plate. This condition can be satisfied at any energy by selecting the dimensions of the devices appropriately. There is a band centered upon that energy where the chromatic aberration is greatly reduced. The energy band is selected by the energy resolution of the detector. For example as shown in Fig. 4 correcting the chromatic aberration of a 1 m diameter optic with a focal length of 2000 km at 6 keV would result in the angular resolution being better than 1 milli arc second within

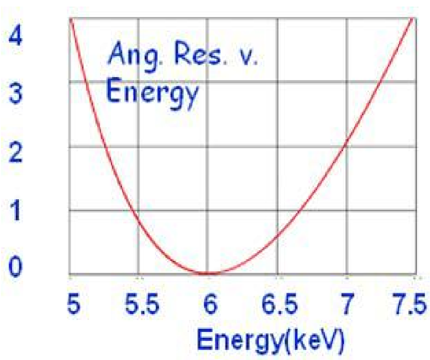

Fig. 4. The variation of angular resolution (in milli arc seconds) due to chromatic aberration of a 1 m diameter telescope with a focal length of 2000 km that is corrected to 1st order at 6 keV is shown. The effect of diffraction is assumed to be negligible in comparison. An explanation of how the resolution is defined appears in sect. 4.1.

an energy band of about 1 keV. The central energy can be varied by changing the configuration. The energy range is extended by operating several systems in parallel. The MASSIM mission concept (Skinner et al, this meeting) contains a six telescope array that, collectively, covers the 5 to 11 keV band.

The angular resolution can be corrected to 2nd order by separating the diffractive and refractive components. The distance of the focus from the first element as a function of energy is stabilized by setting its 1st and 2nd derivatives as function of energy equal to zero. The result is a relation between the focal lengths of the two elements and their separation. The angular resolution can be much better than the 1st order's. However, diffraction may be the limitation. For a 1 m diameter optic that is coherent the diffraction limit is 50 micro arc seconds at 6 keV. Note that the 2nd order configuration requires three spacecraft to be aligned.

3.3 The optics components

The need for transparency requires that the refractive lens be a "Fresnel" lens rather than a thick spherical (paraboloidal) lens. When the surface of the underlying spherical lens would be forward of the reference plane by, for example, one mean free path of absorption it is instead brought back to near zero thickness at the plane. (For Be the mean free path at 6 keV, is 2.2 mm). The result is the lens structure shown in Fig. 3 but probably with a larger number of radials zones like the MASSIM telescopes. The distance the surface is from the underlying sphere is likely to be small with respect to the depth of focus; therefore the displacement will have little effect upon the resolution. Depending upon how the lens is tailored the radial zones may or may not be in phase. If the phases of the zones are random with respect to each other then the zones are effectively independent lenses whose intensities add. The diffraction limit is then determined by the geometry of the zones rather than the superior diffraction limit of the entire lens. One wavelength of phase advance (with respect to vacuum) for 6 keV X-rays requires 22 microns of Be. Dimensions can be controlled with much greater accuracy than that. Therefore it is possible in practice to keep the Fresnel lens in phase at a specific X-ray energy by designing it such its surface is positioned a distance from the surface of the underlying spherical lens by an amount that equals an integral number of waves of phase advance at a specific energy. Those X-rays arrive at the focus with the same phase it would have had with the spherical lens. However, at other wavelengths the extent to which the radial zones interfere constructively or destructively at the focus will vary. At the focus the intensity at the center of the point spread function will vary quasi periodically with energy and there will be energies where constructive interference occurs too far from the focus to contribute to the useful number of photons. Constructing a coherent Fresnel lens is probably the most difficult aspect of constructing the optics.

Be, free of contamination by heavier metals, seems to be the best material overall for X-rays below 10 keV because of its stiffness, low thermal expansion, and relatively low opacity. More transparent small lithium lenses are used in synchrotron X-ray experiments at low energies but Li's high chemical reactivity makes it unsuitable for large area telescopes.

3.4 Fresnel zone plates

Several types of Fresnel zone plates are listed in Table 1. There is almost an inverse relation between their efficiency at the prime energy and their manufacturing costs. The low efficiency devices can be made very large and the same device

Table 1. Several Types of Fresnel Zone Plates

Fresnel ZP Type	Description	Efficiency*	Comment
Basic (textbook)	Alternating open and opaque radial zones of decreasing width with distance from the center	10%	Easy fabrication Very large area Wide energy range
Phase	Uniform thickness closed zones that advance phase at prime energy by half wavelength	40%	Less easy fabrication Large area Limited energy range
Multilevel And fully blazed	No open zones. Thickness tailored on fine scale to keep prime energy photon in phase	70% and higher	More difficult fabrication Limited energy range
Photon Sieve [11]	Similar to basic ZP but the open zones are composed of a random distribution of small holes	~ 5%	Very easy fabrication Can be membrane Very large areas Wide energy range

*The efficiency does not include losses due to support structure, which should be significant

can be used over a wide energy range when paired with the appropriate lens, which may be different for each energy band. The multi-level and fully blazed will usually be the most desirable version of the zone plate because of their high efficiency. However, the basic zone plate or the photon sieve could be best in situations where mass and cost are the major issues, the photons are abundant and a very larger diameter optic is needed to limit diffraction. They could be membranes with thin metal layers for the opaque regions. However, there remains the more difficult task of fabricating its companion coherent refractive lens.

4. HIGHER RESOLUTION DIREX TELESCOPES, IMAGING SGR A*

4.1 Correcting chromatic aberration to second order

Chromatic aberration can be corrected to second order by separating the diffractive and refractive components of the optics. Either the zone plate or lens can be further downstream. The image formed by the first optic becomes the object for the second. An expression is obtained for the location of the final on-axis image as a function of energy. The 1st and 2nd derivatives of the image position as a function of energy are set equal to zero. Solving the equations provides the ratios of the focal lengths of the two components to their separation. Details appear in a paper by Skinner[3]. The correction for chromatic aberration is perfect only on-axis. However, over the very small field of view the off-axis degradation will be very small.

We consider a telescope with an angular resolution of 2 micro arc seconds at 6 keV. Overcoming the diffractive limit requires that the diameter of the first component be 25 m or larger. The telescope would have to be folded for launch and opened in orbit. It should be relatively easy to execute these tasks with at least two of the zone plate types. Past the zone plate the beam converges down to 19 m when it encounters the Fresnel lens. Preserving coherence in the refractive lens will require that considerable attention be given to the stowing and deployment procedures.

Neglecting the support structure the mass of a simple zone plate or photon sieve made of 120 micron aluminum sheet would be below 320 kg. The unsupported mass of a 19 m diameter beryllium lens whose average thickness is 1 mm is about half a ton. Support structure will increase the mass. The mass of the optics is compatible with the lift capability of current moderate launch vehicles.

Omitting the details we calculate the variation of angular resolution with energy due to chromatic aberration for a 25 m diameter DIREX optic with the assumption of 27,000 km for the focal length. Both the first and second order corrections are considered. The angular resolution for both is shown in Fig. 5.

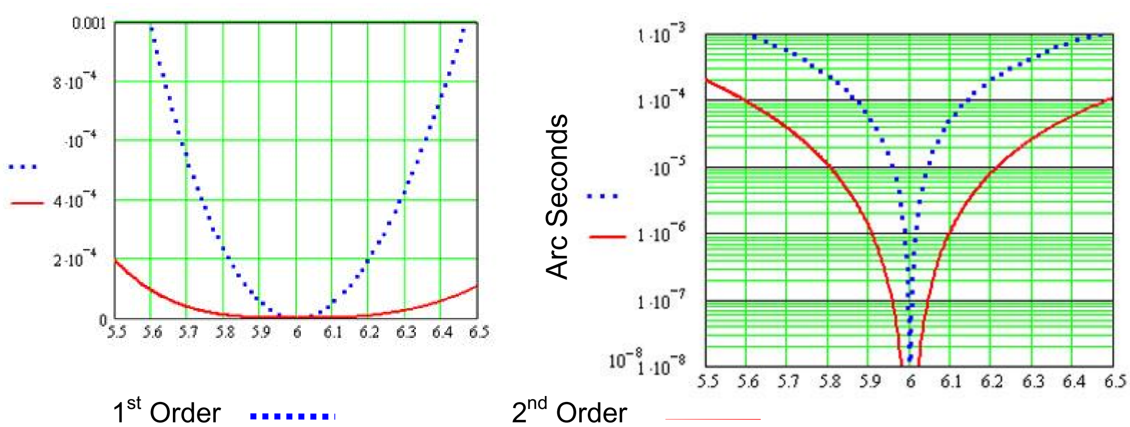

Fig. 5. Chromatic aberration in arc seconds of DIREX telescopes with 25 m diameter and 27,000 km focal length. Chromatic aberration is corrected to 1st order (blue dotted line) and 2nd order (red solid line). The left panel is a linear plot; the right, logarithmic.

The chromatic aberration for a given energy is determined by first calculating the difference in axial position of the image relative to the image at 6 keV. The diameter and focal length of the optic determine the angular divergence of the beam. The axial position of the image determines its lateral spread at the 6 keV focus where the detector is situated. We define the lateral spread divided by the focal length at 6 keV as the chromatic aberration. When corrected to 1^{st} order the chromatic aberration is one milli arc second or better from 5.60 to 6.45 keV for a bandwidth of 0.85 keV. Corrected to 2^{nd} order the chromatic aberration is one micro arc second or better from 5.9 to 6.1 keV for a bandwidth of 0.2 keV. (For comparison the 6 keV diffraction limit of the 25 m telescope is 2 micro arc seconds.) The spatial resolutions of a CCD and the newer CMOS position sensitive X-ray detectors are good enough to select only photons in those bands. While the bandwidths are small, the telescope area is very large. The gross geometric area of a 25 m diameter optic is 490 m^2. With a 10% efficient zone plate, a Fresnel lens that is assumed to be 30% efficient (to allow for not including portions of the band where there is no constructive interference at the focus) and assuming the loss from support structure is 20% the effective area of the system is still over 50 thousand cm^2. The area bandwidth product from 3 to 7 keV is several times larger than Chandra's. The focal plane scale is 1 cm equals 74 micro arc seconds. With a 1 m array of CCD, CMOS, or cryogencic type detectors in the focal plane and a focal length of 27,000 km the field of view of the telescope is 7.5 milli arc seconds, small by current standards but large enough to encompass many potential targets.

4.2 Imaging Sagittarius A*

With an angular resolution of 2 micro arc seconds it may be possible to image Sgr A*, the 3 x 10^6 solar mass super massive black hole (SMBH) at the center of our galaxy. For a Schwarzschild black hole (zero spin) at a distance of 8 kpc the radius of the innermost stable circular orbit (ISCO) should have an angular size of about 20 micro arc seconds. For an extreme Kerr (maximally spinning) black hole the angular size is a factor of 6 smaller. The X-rays must be coming from a region that is outside of the ISCO and if so would have a larger angular size. If the telescope is pointed directly at Sgr A* its field of view would be quite sufficient for observing the region of its X-ray emissions.

Baganoff et al.[12] observed Sgr A* with Chandra and report a flux and spectrum for photons within one arc second of Sgr A*. It is faint and soft compared to the spectra of SMBHs in many external galaxies. Fitting a power law they find:

$$N(E) = 3.5 \times 10^{-4} \times E^{-2.7} \text{ photons/sec-cm}^2\text{-keV} \qquad Nh = 10^{23} \text{ atoms/cm}^2$$

With the effective area and bandwidth (5.9 to 6.1 keV) obtained above and an exposure of 3 x 10^5 seconds we expect a total of 14,000 counts. Scaling the background rate for the ACIS of Chandra to our bandwidth and exposure time the expected background is 1500 counts/cm^2. If the source size were as large as 200 micro arc seconds or about 10 cm^2 on the detector, the signal to noise (square root of background) would be equal to 35 overall. This is large enough to allow the image to be divided into a significant number of pixels for analysis.

However, the above applies only to a very narrow energy 200 eV band at 6 keV. Images are needed in more spectral bands to fully understand the regions that are nearest to the galaxy's SMBH. The large diameter of the system precludes having more DIREX telescopes that observe other energy bands in parallel in the style of MASSIM. It should be possible to divide the 25 m diameter area into multiple azimuthal zones (like servings of a pie), with each group of say 4, tuned to a different energy band but with the same focal length. Each group would of course have less throughput than the undivided lens. The effect of partially filled apertures would be that the image in each energy band from the appropriate azimuthal sections would be accompanied by side lobes plus out of focus halos from other azimuthal sections that focus a different energy band. More study is required to determine if this type of multiplexing is feasible or results in too many of these artifacts.

4.3 SMBH in an external galaxy

Arriving at conclusions about the X-ray emission and the nature of SMBH's overall require that more objects be observed. There exist SMBH's in external galaxies with a mass and linear size that are 10^2 times larger than Sgr A*'s and are considerably more intense. However, they are a factor of 10^3 more distant so that their angular size is a factor of 10 smaller or about 2 micro arc seconds. In order to obtain an image, the resolution of the telescope should be at least ten times finer. Models of SMBH's suggest that the energy band containing the gravitationally redshifted Fe 6.4 keV fluorescence line is the most important regime to observe. Overcoming the diffraction limit below 6.4 keV at the level of tenth micro arc seconds requires that the X-ray optics cover a region whose size is of the order of a kilometer. This is obviously beyond the capability of any type of monolithic telescope. An alternative is to observe at much higher energy, for example at 100 keV, where the tenth micro arc second diffraction limit is satisfied with much smaller diameter optics. However, with the AGN photon number spectrum declining with energy the signal in the hard X-ray band would be much smaller and the gravitationally redshifted Fe line would be out of range. X-ray interferometry, for example the version described by Gendreau et al [13] and Cash[14], is a possible technique for imaging a SMBH at 6 keV and below. Determining whether or not DIREX optics could have a useful role in X-ray interferometry as collectors may merit some study. However, at the tenth micro arc second level overcoming the chromatic aberration of DIREX collectors spread over a kilometer may prove to be too formidable an obstacle.

5. SUMMARY AND CONCLUSIONS

There remain important scientific issues that can be resolved only with very high angular resolution X-rays telescopes. They include studies of the environment surrounding super massive black holes, pulsar wind nebulae, stars in various stages of stellar evolution, and more. Because there are too many technical difficulties it is not likely that a large area grazing incidence telescope with angular resolution much superior to the Chandra X-Ray Observatory will ever exist.

A diffractive-refractive X-ray (DIREX) telescope that transmits rather than reflects X-rays is an instrument with the ability to improve significantly upon Chandra's resolution. The telescope consists of a Fresnel zone plate plus a refractive lens. It is much less affected by figure errors and surface roughness. Also, while it is virtually impossible to make the multiple concentric mirror shells of a grazing incidence telescope coherent over the entire aperture it should be possible to do so for the planar DIREX telescope. Therefore, the achievable diffraction limit of the DIREX device is much superior. Furthermore, the optics are very low mass per unit area. Because at least one of the two optics has no open areas, with Be as the material there will be a lower limit to the energy range of a few keV.

To overcome chromatic aberration in both the zone plate and the Fresnel lens the focal length of DIREX telescopes range from the order of a thousand to tens of thousands of kilometers depending on the energy and the diameter of the optics. When the two components are in direct contact, essentially acting as a single device chromatic aberration vanishes to first order at the energy where the focal length of the lens is minus twice that of the zone plate. There is a ~15% wide energy band centered at the prime energy keV where the angular resolution is a milli arc second or better. Separating the two components and making their two focal lengths with the correct ratios with respect to their separation distance can provide an energy band where the resolution can be much finer than a milli arc second. The diameter of the coherent region has to be large enough for diffraction to not be the limitation.

The ability to accommodate very long focal lengths and perform high precision formation flying between optics and detector spacecraft is essential for this technique to be viable. The ability is not available currently but there seems to be no fundamental obstacle in the way of its development. It requires merely advances in guidance and greater attention to mission operations rather than the need for heavy lift launchers, which are the main cost driver of space missions. There is demand for precision formation flying between multiple spacecraft by other future missions, for example several optical interferometer concepts and the New Worlds Observer[15] search for exoplanets. With multiple future missions requiring precision formation flying the space agencies will be highly motivated to provide it. In fact, the development of precision formation flying is already underway, albeit with a short separation distance, with the Simbol-X mission. XEUS may follow.

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