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High angular resolution X-ray astronomy in the next 50 years

Back to the future

P. Gorenstein

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA, e-mail: pgorenstein@head.cfa.harvard.edu

Abstract. The 0.5 arc second angular resolution of the Chandra X-Ray Observatory is likely to be the best that can be obtained with grazing incidence optics, especially when larger effective area is required. We describe a telescope concept based upon transmitting diffractive-refractive optics that appears to be capable of providing better than mili arc second angular resolution. However, focal lengths are of the order of 1000 km, which requires long distance formation-flying between two spacecraft. In order to counteract gravity gradient forces to maintain alignment of optics with the detector and change targets,one of the spacecraft must contain engines for propulsion.

Key words. X-ray telescopes,high angular resolution resolution, formation flying, diffractive optics

1. Introduction

High angular resolution X-ray telescopes have propelled X-ray astronomy to the frontiers of astrophysics. With the launch of NuSTAR in June 2012 eleven spacecraft have been or are currently in orbit with focusing X-ray telescopes and three more are scheduled for launch before 2015. They have all adopted the Wolter 1 technology with varying degrees of fidelity to the ideal figure. Defining high angular resolution as 5 arc seconds or better half power diameter three of these telescope missions whose launches were about a decade apart qualify as having or having had high angular resolution. Significant progress in astrophysics was achieved with the launch of each of them. They are listed in Table 1.

This author's opinion is that no future grazing incidence telescope with as large or larger effective area than the Chandra X-ray telescope will ever have significantly better angular resolution, i.e. factor of two or more, including telescopes with active figure adjustment systems. Although the 1 keV diffraction limit of the Chandra telescope is 14 mili arc seconds the angular resolution of grazing incidence telescopes is very near or already at its practical limit. The difficultly of achieving high angular resolution in future X-ray telescopes with large area is compounded by the necessity to segment the optics. Segmentation results in many more substrates to configure and align than the four integral mirror shells of ROSAT

Send offprint requests to: P. Gorenstein

Table 1. *half power diameter of telescope, detector not included

Mission	Period of Operation	Angular Resolution (arc seconds)*	Eff. Area at 1 keV on Axis (cm^2)
Einstein Observatory	Nov. 1978 - Apr. 1981	5	200
ROSAT	Jun. 1990 - Feb. 1999	< 5	400
Chandra X-Ray Obs.	July 1999 —	0.5	800

and Chandra. A totally different telescope technology is needed to improve upon Chandra's resolution.

Nevertheless a higher angular resolution X-ray telescope is required to fulfill many objectives. They include imaging the nuclear regions of galaxies especially those hosting single and multiple super giant black holes, finer detailed view of jets, imaging pulsar wind nebulas, the environments of stellar mass black holes, neutron stars, and the coronas of nearby stars. This paper describes a promising approach based upon physical optics. It looks back to a methodology that was considered before the adoption of grazing incidence optics for X-ray astronomy, which is the reason for the appearance of the phrase Back to the Future in the title of this paper. While the optics to be described will not be difficult to construct and are very low mass they have extremely long focal lengths, resulting in very complex mission operations.

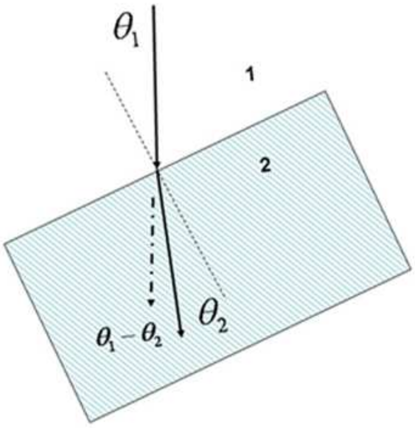
2. Transmitting X-ray optics

An optic that transmits radiation has an inherent advantage in resolution over an optic that reflects radiation, particularly reflection at grazing incidence, which occurs within a small angular range. If the figure of a reflector has a slope error of α then the direction of the reflected ray will have an error of 2α. Fig. 1 shows what occurs when a ray is transmitted i.e. refracted by an optic that has a slope error. In the left panel a ray (solid line) arrives at an interface between two media. Contrary to the usual practice of depicting the vacuum as a clear medium, in this case it is the shaded region labeled 2. The clear region 1 is a metal, which has a lower index of refraction in the X-ray band than the vacuum by a very small amount. The dash-dot line is a continuation of the direction of the incident ray. We assume the interface should have been perpendicular to the incoming ray where it would have had no effect upon its direction. However, a slope error in the optic causes the interface to be tilted at a finite angle of θ_1. The angle of the refracted ray (dash-dot line) is θ_2 so the error in the direction of the refracted ray is $\theta_1 - \theta_2$. Applying Snell's law relating the indices of refraction to the ray's direction θ_2 is calculated in the right panel of Fig. 1. All angles are small so the angle and its sine are essentially the same. The error is proportional to the difference in the indices of refraction. In the X-ray band the difference between beryllium and vacuum is of order 10^{-6} to 10^{-5}. Therefore the error is very small as shown in the right panel of Fig. 1.

While the very small differences in the indices of refraction in the X-ray band between a vacuum and a metal (or any material) results in lower sensitivity to slope errors it also results in weak focusing power. Consequently the focal lengths of focusing, transmitting X-ray optics are very long.

3. Diffractive-refractive X-ray optics

A Fresnel zone plate acts as an imaging optic. In fact small zone plates are used routinely for very high resolution X-ray microscopy at synchrotron radiation facilities. In 1968 researchers at Tubingen University obtained X-ray images of the sun from a sounding rocket with a very small Fresnel zone plate (Elwert 1968). However, soon afterwards, both grazing incidence and normal incidence X-ray tele-



$$N_1 \cdot Sin(\theta_1) = N_2 \cdot Sin(\theta_2) \quad Sin(\theta_2) = \frac{N_1}{N_2} \cdot Sin(\theta_1)$$

$$Sin(\theta_1) - Sin(\theta_2) = Sin(\theta_1) \cdot \left(1 - \frac{N_1}{N_2}\right)$$

$$N_1 = 1 - \delta \quad N_2 = 1$$

$$Sin(\theta_1) - Sin(\theta_2) = Sin(\theta_1) \cdot \left(1 - \frac{1-\delta}{1}\right)$$

$$Sin(\theta_1) - Sin(\theta_2) = Sin(\theta_1) \cdot \delta$$

$$\delta = 10^{-5}$$

Fig. 1. The left panel shows an X-ray emerging from a metal (1) and entering the vacuum, which is shown as a shaded region (2), contrary to the usual practice of depicting a vacuum as a clear medium. The inclination of the interface represents a slope error in the optic. The right panel is a set of equations estimating the error in the direction of the ray after it enters the vacuum and proceeds towards the detector.

scopes began obtaining much higher resolution and higher throughput X-ray images of the solar corona and cosmic X-ray sources. That and the issue of chromatic aberration ended further interest in the use of zone plates as focusing devices in astronomy. Now that the angular resolution of grazing incidence reflective X-ray optics is close to or has already achieved the best it is capable of in practice several papers have re-considered diffractive optics-refractive optics, now with much larger Fresnel zone plates mated with refractive lenses in a configuration that provides some compensation for chromatic aberration (Skinner 2002; Gorenstein 2003; Braig &Predehl 2007).

There are several styles of Fresnel zone plates. The basic device consists of equal area radial zones that are alternately completely transparent and opaque (with of course a very open support structure). There are also multilevel zone plates where there are no open zones. Instead the thickness of the zone plate material is varied such that X-rays of a particular energy from more area arrive at the focus in phase. The result is a more efficient device overall but with a more complex efficiency as a function of energy. We consider only the basic zone plate.

Refractive lenses are also used in X-ray synchrotron radiation facilities to focus or concentrate X-ray beams. Their focusing power is weak because their index of refraction is only very slightly below l. Unlike Fresnel zone plates, which are always converging lenses, refractive lenses may be either converging or diverging devices. Because the index of refraction of the lens material is always less than 1 in the X-ray band the sign of the curvature is the opposite of that of visible light lenses. A convex lens causes an X-ray beam to diverge.

Zone plates are highly chromatic. Their focal length varies linearly with the energy. This is not a problem at the synchrotron radiation facilities because the very high intensity of their X-ray beams allows researchers using synchrotron radiation to work with very small area devices and narrow bandwidths that are not suitable for astronomy. The references cited above have shown that a system composed of a Fresnel zone plate and a refractive lens can be configured to function as an X-ray imaging telescope with reduced chromatic aberration in a small but significant energy band. To reduce absorption the lens is contoured into a Fresnel lens, not to be confused with the Fresnel zone plate. Unless the regions

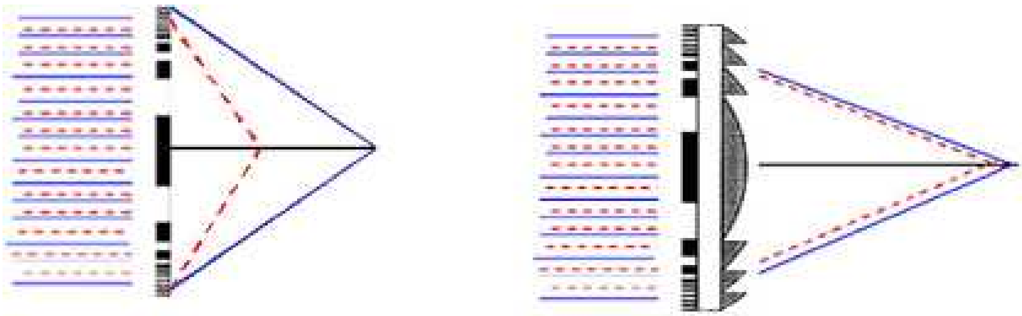


Fig. 2. The left panel shows chromatic aberration when a Fresnel zone plate acts like a lens. When a diverging refractive lens is in contact with the zone plate (right panel) chromatic aberration is corrected at the mili arc second level within an energy band of 10%.

are made with very high precision to transmit coherently, each ring is essentially an independent lens. The narrower rings are subject to diffraction but it can be below the mili arc second level. Greatly reduced chromatic aberration is possible because the focal length of a Fresnel zone plate, which is always a converging optic, varies linearly with energy whereas the focal length of the refractive lens, which is configured as a convex diverging optic, varies with the square of the energy. At the energy where the focal length of the refracting lens is minus twice the focal length of the zone plate the derivative of the focal length as a function of energy is zero, i.e. chromatic aberration is nullified.

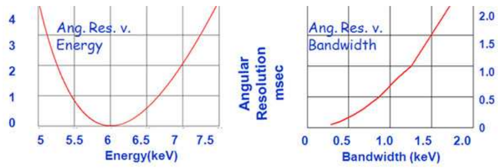


Fig. 3. The performance of a diffractive, refractive pair like the one shown in Fig. 2. In this case the focal length of the refractive lens is minus twice the focal length of the zone plate at 6 keV. The right panel shows the average angular resolution of the pair as a function of the bandwidth, which is determined by the energy resolution of the detector.

Absorption by the lens has to be taken into account. The resolution can be corrected to second order to achieve a resolution of the order ten micro arc seconds by separating the zone plate and the refractive lens a specific distance that is energy dependent. However, that requires even more complex mission operations and will not be considered any further.

4. Performance

4.1. Effective area, mass, and background

Absorption by a refractive lens made of beryllium imposes a lower limit of 3 to 4 keV upon the bandwidth. Lithium lenses would allow access to lower energies and in fact small Li lenses with a protective coating are used at some synchrotron radiation beam lines. In sizes required for astronomy Li would be a hazardous material. Assuming the mean thickness of the Fresnel zone plate and refractive lens are both 1 mm the mass of 1.5 m diameter zone plate-lens doublet made of Be is 4.5 kg. Allowing a factor of 2 for support structure the mass of the telescope would be about 10 kg. For comparison the mass of the Chandra telescope is 1000 kg and the mass of three XMM-Newton mirrors is 1500 kg. The effective area at 6 keV is 1000 cm^2 and the 1 mili arc second bandwidth is 1.5 keV. The product of the bandwidth x area/mass is 120 keV-cm^2/kg, which is superior to both Chandra and XMM. A larger number of photons is required to make use of the better angular resolution. To truly image an X-ray emitting region whose angular size is 100 mili arc seconds on a scale of 10 mili arc seconds with good statistics requires one hundred times larger number of photons than Chandra needs to merely detect it as a point source. Consequently a telescope with much higher resolution than Chandra is limited to imaging only the more intense sources.

4.2. Limitations of diffractive-refractive X-ray telescopes

The diffractive-refractive system has several significant limitations. Because of absorption by lens the efficiency is low below 3 keV where photon fluxes are generally higher. Because of the feeble focusing power focal lengths are extremely long, of the order of 1000 km and longer. The diameter of the diffractive-refractive telescope could be made much larger but that would result in even longer focal length. The mission architecture consists of optics and detector aboard separate spacecraft and engaging in long distance formation flying (NASA's term), a technology that requires considerable development to occur. The lateral alignment of the detector with the optics spacecraft should be in error by no more than a fraction of the detector size or about 0.25 m. There is more tolerance along the axial direction, about 100 m. The optics behave as a thin lens, which means that the pointing need not be highly accurate, no more than Chandra's accuracy. Only one of the two spacecraft, for example the detector spacecraft, can be in a true orbit. The other spacecraft requires a propulsion system such as ion engines to overcome the gravity gradient force in order to maintain alignment with the detector. Changing targets requires that one of the two spacecraft move to a new position whose distance from the original position is of the order of the focal length. To conserve fuel changes in position should occur as slowly as possible. It would be best to have duplicate optics (or detector) spacecraft, one observing while the other proceeds to the next target.

While the field of view is intrinsically rather large the long focal length and practical limits on the size of the detector limit the field of view. With an optic that has a focal length of 1000 km a 2.5 m x 2.5 m array of X-ray CCDs would have a field of view of 0.5 arc seconds. Broader coverage would require a raster of pointing positions or a larger detector array. A very large focal plane scale results in a high level of background from cosmic ray primaries. However there are many fewer secondary cosmic rays because the optics is far removed and the detector spacecraft is much lower mass than Chandra and XMM-Newton. The diffuse cosmic ray background would be limited by a local collimator in front of the detector array.

4.3. Enlarging the bandwidth

As shown in Fig. 3 the bandwidth of the system is determined by the energy range above and below the prime energy. At the mili arc second level the energy resolution of a CCD, typically 0.15 keV at 6 keV, is satisfactory for selecting the energy band. The bandwidth can be enlarged by employing multiple systems observing in parallel or in series. The parallel system would consist of a matrix of several zone plate-lens pairs with the same focal length but tuned to different energies and having separate detectors. The systems should be shielded from each other to exclude the out of focus X-rays from their neighbors that are in their energy bands. The telescope of a system that observes in series is divided into sections of azimuth. Each azimuth section is tuned to a different energy and exposed one at a time. An azimuth segment will produce a complete image but the point source response probably has more structure in its wings than a full 360 degree optic. The point response of an azimuth segment was not simulated.

5. Mission operations

Observing with an optic that has a thousand kilometer focal length requires very complex mission operations. In fact mission operations are by far the most challenging aspect of the entire system. In comparison fabrication of the optics and assembling a CCD array for the detector should be simple. The technology for

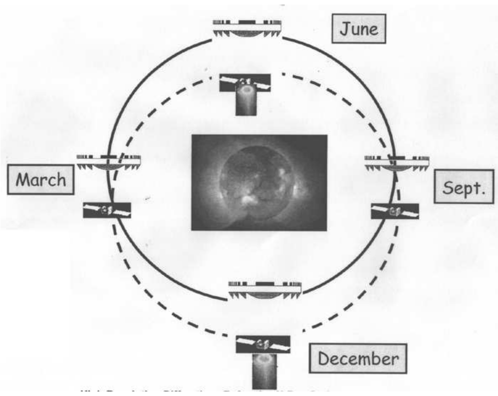


Fig. 4. Two spacecraft, one with the optics the other with the detector are going around the sun. In this illustration the optics spacecraft is in a true solar circular orbit (solid line). With a varying force exerted by propulsion engines (spacecraft with plume) to counteract the effect of the gravity gradient the detector spacecraft trajectory (dashed line) remains at the focus of the optics. One of the two spacecraft is off the ecliptic plane up to an amount equal to the focal length.

maintaining the lateral alignment within a few cm of two spacecraft that are separated by 1000 km does not yet exist as no program has required it. However, there does not seem to be a fundamental barrier that precludes it. The two spacecraft have to be in a region where the gravity gradient is small. A solar orbit like that of the Spitzer Infrared Space Telescope should be suitable. As shown in Fig. 4, only one of the two spacecraft can be in a true orbit. In this case it is the optics spacecraft whose orbit is the solid curve.

With the optics spacecraft pointed at the target the center of detector should be should be no more than a few cm off from the optics to target direction. A few cm error corresponds to a few mili arc seconds displacement of the center of the field of view. There is much more tolerance in the pointing direction of the optics, which is a thin lens. The position of the image position is not highly sensitive to pointing errors. The tolerance in the distance between the optics and detector spacecraft is a few tens of meters. The distance between the two spacecraft should be relatively easy to measure with synchronized timing signals. One of the two spacecraft would be in a true solar orbit along the ecliptic circle at a distance of 1 AU from the Sun. The other would be generally off the ecliptic plane at a distance from the Sun that differs from 1 AU by an amount up to the focal length. It would be powered by a propulsion system that provides the force needed to counteract changes in the magnitude and direction of the Sun's gravity that is required to maintain the alignment of the two spacecraft. For a one ton spacecraft the maximum force is about 80 microN. The force will vary in magnitude and direction depending on the target direction and the phase of the orbit, which will vary over the course of a year. Much more propulsive force, 0.4 N maximum, is needed to change targets by moving one of the two spacecraft 1000 km to a new position in 10^5 sec. The force is reduced to 0.1 N and the total propellant consumption is halved if the time allocated to changing targets is increased to $2x10^5$ sec. A second optics or detector spacecraft will save considerable time if one is proceeding to the next target while the first is observing. The force estimates are likely to be very pessimistic because after the extraneous systems are disposed of the mass of both the detector and optics spacecraft would be considerably less than 1 ton.

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