Grazing incidence imaging from 10 to 40 keV

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The prospects for imaging x rays at energies from 10 to 40 keV with grazing incidence optics are explored. The scientific rationale and existing laboratory measurements are reviewed. Measurements of reflectivity using possible mirror materials are described. Iridium-coated float glass gives an improved performance over gold by the factor predicted by theory but both had a lower absolute level. This may be due to a lower density of the thin metal layer caused by the deposition method. The reflectivity of a sample of iridium-coated float glass was measured at small grazing angles (25–5 min of arc) at energies of 8, 17, and 26 keV. High reflectivity (>50%) was seen out to angles of 33, 16, and 11 min of arc, respectively. These are close to the theoretical values. A design for a high energy imaging telescope of the Explorer class is described.

I. Introduction

It is clear now that the advent of grazing incidence optics in x-ray astronomy has transformed the subject into one of the major disciplines of astrophysics. The Einstein Observatory (HEAO-2) covered the energy range from ~0.1 to ~3.5 keV and this is still the highest energy to which grazing incidence mirrors have been used in a mission. The more recent EXOSAT and ROSAT mirrors both cut off above ~2 keV. X-ray imaging up to ~10 keV is expected only when AXAF and the high throughput missions SPECTRA, ASTRO-D, and XMM fly.

At higher energies (10–40 keV) true imaging is not currently being considered. Coded aperture designs (e.g., EXITE[1]) are being built and these do provide min of arc imaging and simultaneous background monitoring. However they do not realize the great background reduction, and hence sensitivity, that focusing provides. The lack of imaging is holding back the sensitivity of observations in this energy band in spite of the potential importance of the science that it could provide. The HEAO-A4 catalog of hard x-ray sources[2] is the largest to date and lists only some seventy sources in the 13–40-keV band, of which seven are extragalactic. This is in contrast to the thousands of sources accessible to an imaging telescope of smaller effective area. The cause is simply that the detection threshold of 1/75 Crab, some 1000 times higher than that of the Einstein Observatory, is set by the high background count rate. Table I lists some of the scientific prospects for the 10–40-keV energy band if sufficient sensitivity were available. They cover a wide range of topics in many branches of astronomy.

For x-ray astronomers the most obvious advantage of imaging at high energies is that the spectra of faint objects can be measured up at energies where the diffuse x-ray background spectrum is not only well measured[3] but also has a spectral feature (the exponential roll-off at ~35 keV). To find a spectral match between some candidate class of object (e.g., quasars) and the x-ray background in this energy range would be a major discovery. It would make a much stronger case for their integrated emission being the origin of the x-ray background than any amount of indirect argument from source counts or spectra at low energies, such as we have been forced to use up to now.

Seeing this problem in high energy x-ray instrumentation we decided to explore the possibilities for true x-ray imaging in the 10–40-keV range. The grazing angle at 30 keV is ~10 min of arc. Bilderback and Hubbard[4] have demonstrated that uncoated float glass reflects well up to 40 keV, but only at tiny grazing angles of ~2 min of arc. At 10-min of arc grazing angle the reflectivity they measured drops sharply beyond 10 keV. Bilderback and Hubbard[5] also showed that highly polished optical flats coated with platinum (these were AXAF test flats) also reflected well up to 40 keV, in this case for grazing angles of 6.8 min of arc. Bilderback and Hubbard did not measure the image quality obtained in these studies. Their reflected beam was measured with a detector having a 1° opening angle. At small grazing angles a well-concentrated

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Table I. Imaging Science at 10–40 keV

X-ray background	Measure spectra of candidate point sources in region where XRB has a feature
Quasars/AGN	Multicomponent spectra AGN in cDs and clusters (distinguish from hot gas)
Galaxies	Color–color diagram (compare galactic sources)
	Binary content of Ellipticals
	Spectra of starbursts (binaries or hot gas?)
Pulsars/SNR	In SNR (distinguish from hot gas) spectra of synchrotron nebulae
Radio galaxies	Inverse Compton from radio lobes (M87); also detection in clusters
γ-Rays	Source identifications
	Low energy spectra, variability
Galactic sources	Faint galaxy population (need >3-keV sensitivity because of galactic N_H), e.g., cataclysmic variables—only 4 magnetic CVs known
	Cyclotron lines in faint sources
Sunyaev-Zeldovich effect	Present μ-wave measurements predict cluster temperatures of ~15 keV, needs hard response to check

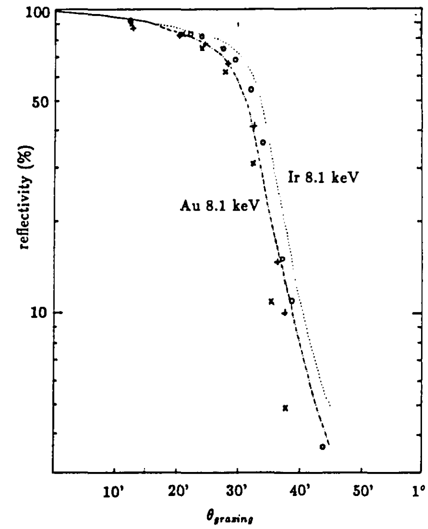

Fig. 1. Comparison of gold and iridium reflectivities at 8.1 keV (Cu–K): ○, 175-Å layer of iridium on float glass; ×, +, two examples of a 500-Å gold layer on float glass.

image is essential to realizing the background reducing potential of imaging. For a typical 3-m focal length a 10-min of arc grazing angle gives a mirror diameter of 1.7 cm and a geometric area of ~230 mm^2. If the effective area of the mirror is 20% of the geometric (see below), to obtain a background reduction factor >10 the image spot must have a radius of <1.2 mm or ~1 min of arc.

It is also clear that with such small mirror diameters the only ways to get significant collecting area at high energies are either to go to very long focal lengths, ≥100 m, or to have multiple, modular mirrors. The second alternative is more practical and we propose a method of achieving useful areas in a later section. With such small mirror diameters it is essential to use thin mirror materials, either float glass or preferably foils[6] if they can make a small enough image.

We therefore decided to measure the reflectivity of coated float glass samples with an imaging detector as a first step to obtaining estimates of the reflectivity obtainable in a small beam size using real candidate mirror materials. Our first investigation was a comparison of gold and iridium as reflecting materials. We did this since, while gold is commonly used in grazing incidence optics, iridium has a potential for higher reflectivities because of its higher bulk density. We followed this by measuring the reflectivity as a function of grazing angle of an iridium-coated sample at high energies.

To understand the implications of the encouraging results of the reflectivity measurements we investigated a mirror design that could form an Explorer class payload. We find that a factor of 15 improvement in sensitivity over previous experiments is readily achievable.

II. Reflectivity Measurements

We have modified the IPC test facility to allow mirror samples to be measured at small grazing angles and at energies up to 40 keV. The main element that allows control of the grazing angle is a two-stage (rotation plus 1-D translation) platform with accurate readouts (to ±1 min of arc). The high energy x-ray source is based on a 50-kV power supply. Niobium, tin, and praseodymium are used as fluorescence targets to produce lines at ~17.5 keV (Nb–Kα,β), ~26.5 keV (Sn–Kα,β), and ~38 keV (P–Kα,β), respectively. The IPC was filled with xenon at 1 atm. The energy resolution of the IPC was measured to be 12% at 22 keV using a radioactive cadmium 109 source.

A. Comparison of Iridium and Gold as X-Ray Reflectors

Gold is normally used as the reflecting surface on x-ray mirrors because of its high bulk density (ρ = 19.3). The solid element with the highest bulk density is iridium (ρ = 22.4) and so it should, in principle, have a higher x-ray reflectivity. At high energies this is particularly important since it would allow 10% larger grazing angles to be used and hence 20% higher aperture utilization. No laboratory measurements of iridium x-ray reflectivity have been reported however. We have therefore compared the reflectivity of gold and iridium evaporatively coated samples of flat glass up to energies of 8.1 keV (Cu–Kα). Figure 1 shows the results of these tests.

Our two gold samples both had a thickness of 500 Å. The iridium coating had a thickness of 175 Å. Although this is thinner than the gold sample it should be adequate for x-ray reflection. At 30 keV the maximum 1/e electric field depth in iridium is ~11 Å.[7,8] This gives an estimate of the depth of the iridium layer needed for specular reflection.

At each energy the measured iridium reflectivity exceeds the measured gold reflectivity, as predicted. However both the gold and iridium data fall below the curves of theoretical performance. Data on a similarly prepared 400-Å thick iridium layer indicate a similar result.[9] This suggests that our 175-Å layer is thick enough. These theoretical curves are based on calculations of the optical constants, as used in the Fresnel equations. They assume an infinitely smooth, flat surface and this approximation becomes important near the critical angle. The use of actual measured values is thus critical and is preferable to the theoretical values. Our data are currently limited to one sample of iridium-coated glass. (The vapor deposition process is expensive for iridium since it requires a large amount of raw material.) Variations from sample to sample may occur depending on the details of the coating process. This is true of our gold-coated samples. Figure 1 shows that our two samples of gold-coated glass differ by quite large factors at large grazing angles. The difference is ~30% at 32 min of arc. The causes of this changeability need investigation.

One possible explanation is that the density of the evaporatively deposited layer is not as high as for the bulk material. A good fit to the observed iridium data can be produced by allowing the density to be a free parameter. Doing this gives a value of 19.36 for the density of the iridium coating, compared with 22.4 for the bulk material. This fitted value is similar to the bulk density of gold and indeed the iridium data fall close to the theoretical curve for gold. Alternative deposition techniques, such as sputtering, need to be examined to see if they give higher densities.

B. Iridium Reflectivity at 17 and 26 keV

Since iridium gave better reflectivity than gold by the expected amount, we adopted iridium as our base line reflector. We then measured the same 175-Å sample at higher energies, 17.5 and 26.5 keV. Measurements at 38 keV using a praseodymium target are planned. The results of these measurements are shown in Fig. 2, together with the 8.1-keV measurements from Fig. 1 as a comparison.

The reflectivities are 30% at the critical angles of 17.5 min of arc (17 keV) and 11.4 min of arc (26 keV), respectively. Theoretical curves of reflectivity[7,8] are also shown in Fig. 1. They predict the shape of the measured function well but slightly overpredict the reflectivity at small angles and underpredict it at large angles. The theoretical values were derived using predicted optical constants rather than measured values. Measured optical constants and accurate theoretical predictions are not readily available above 10 keV.

The mismatch at large angles could be due to an incorrect assignment of the line energy. At large angles the reflectivity is sensitive to the precise energy. The effective energy of our measurements is not accurately determined since the measured line is a blend of the K–α and K–β lines and the K–α line is more absorbed by the niobium or tin filters that are used to block the continuum radiation from the source. The

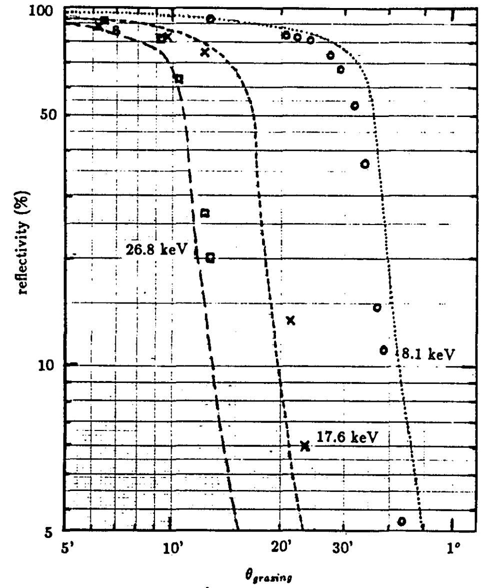

Fig. 2. Reflectivity of a 175-Å layer of iridium on float glass at 8.1 keV (○, Cu–K), 17.6 keV (×, Nb–K), and 26.8 keV (□, Sn–K). Theoretical curves for the three energies are shown: that for 8.1 keV (dots) is based on measured optical constants; those for 17.6 keV (short dashes) and 26.8 keV (long dashes) are based on predicted optical constants (see text).

measured FWHM of the line in the IPC is 30%. The intrinsic resolution of the IPC at these energies is 12% FWHM (as measured from a radioactive cadmium 109 source) so that a blend of the two K lines should give a FWHM of 26%, consistent with the measured value. The effective energy we measure will lie between the two lines which for niobium are at 16.5 and 18.6 keV and for tin are at 25.1 and 28.4 keV. Varying the energy of the incoming radiation to fit the measured reflectivity at the ~20% level gives energies of 15.6 and 25.2 keV for niobium and tin, respectively. These energies are too low to be the actual effective energies we are using so that the higher reflectivities we measure compared with the prediction must be due to the limitations of the simple theory used.

Our reflectivity measurements agree well with the values found by Bilderback and Hubbard[5] for platinum. They found reflectivities at 17 keV of 88% and 70% at 6.9 and 14 min of arc and at 27 keV they found 86% reflectivity at 6.9 min of arc.

The agreement of our reflectivity measurements in a small (~3-min of arc) beam size shows that large angle scattering due to poor surface roughness is not an important factor even at wavelengths as short as 0.5 Å (27 keV).

III. High Energy Telescope: Multifocus Kirkpatrick-Baez Mirrors

Since the frontal area of a high energy mirror is only ~12 cm² for a focal length of the order of 3 m, it is essential to combine many mirror modules to obtain a useful effective area. For reasonable aperture utilization efficiencies a 10 × 10 array of modules will give a 150-cm² effective area. The detector area onto which the images are focused sums to 1 cm^2 giving an imaging advantage of 150 at the lower (15–25-keV) range and 60 at higher energies (25–40 keV).

The individual construction of many such small mirrors would be difficult and time-consuming. We propose a telescope made of highly nested reflectors in a 35-cm square aperture. Possible materials include thin glass and metal foils. We consider both a conservative design using the rigidity of float glass and a design using metal foils. For the front mirror a series of Kirkpatrick-Baez fan-shaped mirrors of 1.75-cm radius would be laid parallel to one another, forming a square frontal surface (Fig. 3). The rear mirror would be an identical configuration (with appropriately altered grazing angles) turned through 90°. Viewed from the front the glass plates form a criss-cross pattern. Each of the intersections of the front and rear plates forms a single small mirror module. The difficulties of making the 100 small mirrors are at least square rooted by this means. The availability of suitable float glass plates is demonstrated by the LAMAR success using even larger plates. The difficulties of mounting metal foils in this arrangement are under investigation but do not seem to be insurmountable at this stage.

This mirror module forms 100 separate images with ~5-min of arc fields of view at the focal plane and thus requires either 100 small detectors or, more simply, a large area position sensitive detector. A 30- × 30-cm IPC has been constructed at SAO and functioned well. A xenon-filled IPC was used for our high energy measurements and behaved nominally with the expected $\sqrt{E}$ improvement in energy resolution to 12% at 22 keV. In many regards a high energy IPC behind such a mirror would be simpler than the Einstein IPC. It would need no gas flow system since a thick entrance window could be used. (This would remove the response below 2–3 keV but this is not designed as a telescope for low energy use.) The crisscross pattern of the images would form a natural pattern to use for the window support structure (ribs) and so no effective area need be lost in this way. The same crisscross pattern of black bands would also provide a valuable simultaneous monitor of the particle background in the same detector.

We have calculated the effective area achievable with such a design. Figure 4 shows the area vs energy for reasonable design parameters. The reflectivity used for these calculations was that given by the simple theory of Sec. II. Our measurements suggest higher values at large grazing angles so that the effective area shown in Fig. 4 is probably an underestimate. The complete instrument will be described in more detail in a forthcoming publication.

To estimate the sensitivity of this instrument we have assumed background rates of 2.5×10^{-4} ct cm^{-2} s^{-1} keV^{-1} through the 10–40-keV band. This is some 2.5 times the HEAO-A2 experiment and is comparable with, e.g., those obtained on the Ginga satellite. We have calculated the resulting sensitivity in two bands, 12–25 and 25–40 keV with those of typical x-ray sources and other hard x-ray missions for a short (3000-s) and a long (10^5-s) exposures. The foil reflectors are ~30 times more sensitive than the HEAO-A4 survey in the 15–25-keV band. Since the HEAO-A4 survey detected seven active galactic nuclei (AGN) this instrument should be able to detect more than 1000 AGN in a minimal 3000-s exposure. It is also 12 times more sensitive than HEAO-A4 in the 25–40-keV range in the same short exposure. In a deep exposure it is over 150 times more sensitive than HEAO-A4. At this level the sky contains nearly 15,000 AGN.

An alternative way of exploring its sensitivity is to ask what low energy sources would be detectable by

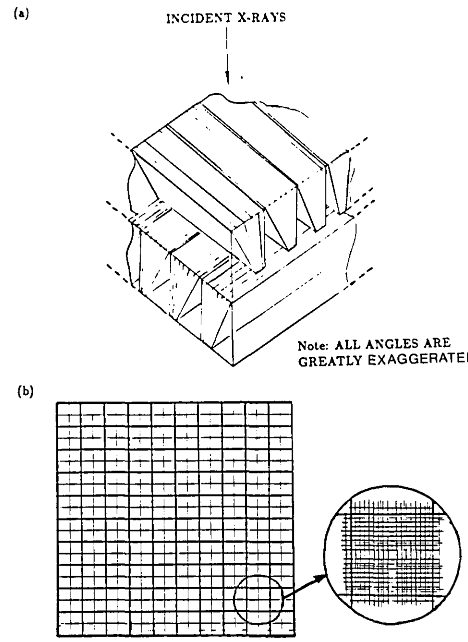

Fig. 3. Illustrations of the multifocus Kirkpatrick-Baez geometry: (a) isometric view showing crossed sets of mirrors. Each intersection of a front and a rear fan forms a separate telescope. Note: All the angles shown are greatly exaggerated. In practice since the grazing angles are never >20 min of arc, the reflectors are essentially parallel. (b) Top view of a 10 × 10 module instrument with an expanded view of one module showing the arrangement of the plates.

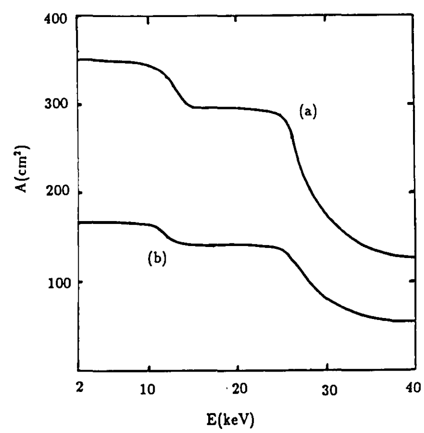

Fig. 4. Effective area of the proposed 3-m 35- × 35-cm instrument as a function of energy for (a) 0.1-mm foils, (b) 0.7-mm float glass.

this instrument. We use AGN as an example. A 0.05-μJy ($\sim$0.05 IPC ct s^{-1} $\sim$0.05 UFU) source is detectable at $>5\sigma$ in 3000 s even if it has a power-law photon index of 2.0. For a 3C273 like spectrum (α_{ph} = 1.5), the source would be detected at over 1000σ. 3C273 itself is almost 100 times brighter than these example sources.

If the float glass reflectors are used instead the sensitivity is halved. A 0.1-μJy source should be substituted in the quasar examples. The deep pointings would be $\sim$85 times more sensitive than HEAO-A4.

The design used for Fig. 4 produces a 1-mm image spot or $\sim$1 min of arc at a 3-m focal length. This is fixed by the simplifying requirement that the plates be single flats. If the mirrors were made in three segments of 12 cm length each, the spot size could be reduced to 0.33 mm. This would give an extra factor of $\sim$10 reduction in background. Mirror alignment becomes a significant problem at this level. This needs investigation.

IV. Conclusion

Measurements at high energies using realistic candidate mirror materials and a small field-of-view detector have demonstrated that grazing incidence optics have potential for the building of astronomical telescopes. Simulations of a multifocus Kirkpatrick-Baez mirror design with min of arc resolution shows that a significant effective area can be obtained with a modest instrument. A 35-cm square mirror/detector with a 3-m focal length can easily achieve a factor of 30 sensitivity improvement over the best instruments flown to date and can obtain spectra of 0.05 UFU quasars out to 35 keV.

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