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Grazing Incidence Optics designs for future Gamma ray Missions

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ABSTRACT

Sensitive nuclear line spectroscopy for observations of prompt emission from supernovae, as well as mapping of remnants has been a primary goal of gamma-ray astrophysics since its inception. A number of key lines lie in the energy band from 10 - 600 keV. In this region of the spectrum, observations have to-date been limited by high background and poor angular resolution. In this paper, we present several designs capable of extending the sensitivity of grazing incidence optics into this energy range. In particular, we discuss a 15 m focal length design for NASA's High-Sensitivity Spectroscopic Imaging Mission (HSI) concept, as well as a 50 m focal length design which can extend ESA's XEUS mission into this band. We demonstrate that an unprecedented line sensitivity of 10^{-7} cm^{-2}s^{-1} can be achieved for the most important lines in this energy band.

Keywords: Hard X-ray/Gamma-ray optics, Multilayers, High Energy Astrophysics

1. INTRODUCTION

Next generation X-ray missions will, for the first time reach detection sensitivities comparable to those typical in the X-ray band(1-10 keV) at hard X-ray energies(E>10 keV). These missions include two balloon missions, the High Energy Focusing Telescope(HEFT) mission[1] and the InFocus mission[2] as well as the Hard X-ray Telescope(HXT) on the Constellation-X Mission[3] and possibly also Astro-G. The Con-X HXT will reach sensitivities several orders of magnitude better than achieved by any current or previous missions, with the energy band extending to ~60 keV with 1 arcminute angular resolution. These capabilities will revolutionize the study of non-thermal processes in AGN, SNR and galaxy clusters.

After the currently planned *Glast* and *Integral* missions, the top scientific priority will be to perform sensitive targeted observations of key nuclear decay lines to study both core-collapse(Type Ib and TYpe II), and Type Ia supernovae(SNe) with flux sensitivity, as well as spatial and velocity resolution sufficient to provide unique diagnostics of the dynamics, asymmetry, nucleosynthesis, and explosion mechanism in SNe throughout and beyond the local group. Key nuclear lines of particular interest are ^{44}Ti lines at 67.9 and 78.4 keV, the ^{57}Co lines at 122 keV and 136 keV and the ^{56}Ni line at 158 keV.[4]

Achieving the required line sensitivities in the hard X-ray/soft gamma-ray band requires enormous reduction in intrumental background over what will be achieved with *Integral* or other coded mask or collimated instruments. The only practical way to achieve this is to extend focusing instruments to > 170 keV, significantly beyond what is planned for the HXT on Constellation-X. In addition, angular resolution must be improved to near 20 arcsec or better, both to reduce background and to provide high-resolution mapping of extended remnants.

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Table 1 summarizes the observational requirements which dictate the instrument performance. Recent technological advances in the development of high throughput hard X-ray telecopes have made it feasible to design Gamma-ray telescopes which will meet these requirements. These developments concern both the extension of the energy band using graded period Multilayer coatings up to 200 keV or above[6,7] as well as the development of low mass, low cost, highly nested, segmented Wolter I telescopes based on the use of thin thermally formed glass segments which hold promise for imaging capabilities significantly below 1 arcmin.[8] Likewise recent developments of integral shell optics based on very thin, replicated optics can very likely meet the imaging requirement as well as potentially meeting the mass constraints of such a mission.[9,10]

In this paper we present two grazing incidence Wolter I designs capable of meeting the scientific goals. The first is a 15 m focal length design consistent with deployment on a single spacecraft using an extendable optical bench. The second case is a 50 m focal length case which can be realized either as a dedicated mission, or as an extension of the capabilities of ESA's XEUS mission.[11] In the next section we give the overall envelope and a description of the telescope optimization strategy. The following section presents the two telescope designs we have chosen to optimize. Finally a conclusion is given.

2. DESIGN ENVELOPE AND CONSIDERATIONS

Given the constraint in current launch capabilities of medium sized missions we have chosen to limit the size of the optical module(s) to be on order 1.5 m by 1.5 m by 1 m. We adopt the Wolter I geometry, as it makes the best use of a given aperture for a given focal length, and is well suited for the application of the graded bilayer multilayer designs. We have chosen to set the minimum radius of the mirror shells to 4 cm. This is governed by both practicality as well as the realization that little effective area is to be gained by going to smaller radii given the significant increase in number of mirror shells. The length of individual mirror shells have been chosen to 40 cm as this is the current projection of what can be realized in future thin shell telescope projects such as the Hard X-ray Telescope on Constellation-X.[3] The thickness of individual mirror shells have been chosen to 0.3 mm.[8] Current state-of-the-art graded multilayer deposition technology has demonstrated that coatings with a minimum bilayer thickness of ca. 20 Å can be made.[12] Future developments may decrease this number even further. As the mission goal is to emphasize throughput at 70-80 keV(with the two important ^{44}Ti lines at 67.9 and 78.4 keV) and upwards we have chosen to set the maximum on-axis graze angle such that the entire telescope aperture is active in focusing at 80 keV. With a minimum bilayer thickness of 20 Å this sets the maximum graze angle to 3.5 mrad. For a given choice of focal length this then completely determines the telescope geometry.

In this paper we have chosen to optimize two cases each with a different focal length. The first is a 15 m focal length case consistent with the HSI mission concept. The second is a 50 m focal length case. This is the focal length at which there would be only one telescope module given a maximum graze angle of 3.5 mrad and the size constraint stated above. Table 2 gives the telescope parameters resulting for each case. For the first case the energy band is up to near 200 keV but for the 50 m case we are able to get significant throughput up to and beyond another astrophysically interesting nuclear line, namely the ^{7}Be-line at 478 keV[4] and the 511 keV annihilation line so this case is optimized for energies up to 600 keV. The actual optimization is based on the method developed by P.H.Mao et al(1999).[13] The on-axis graze angle range is divided into ten groups and each group is optimized employing a figure of merit which explicitly takes into account both the effective area in the chosen energy band as well as the Field Of View(FOV) and which allows one to specify an energy weighting function and an angular weighting function. For the designs presented in this paper we have chosen to let the angular weighting correspond to a uniform illumination of the telescope over the field of view[13] and the energy weighting function, W(E) = (E[keV]+70)/100 is chosen so as to favor high energy response as the low energy response is guaranteed by the design.

3. TELESCOPE DESIGNS

We parameterize the graded multilayer designs using the power law parameterization of Joensen et al(1995).[14] In the power law distribution the i'th bilayer thickness d_i , is given by $d_i = a/(b+i)^c$. where a,b and c are constants and i is the i'th bilayer ranging from 1 to N, with i=N being the bilayer next to the substrate. The optimization results in a complete specification of the multilayer coatings by specifying the minimum bilayer thickness $d_{\min} = d_N$, the maximum bilayer thickness $d_{\max} = d_1$, the ratio between the thickness of the heavy element to the bilayer thickness(Γ), the power law index(c) and the number of bilayers(N). For each mirror group we further have the choice of material combination which is best suited for the specific graze angle range and thus energy range of the mirror group. We want the energy range of the designs to provide effective area down to ca. 5 keV and we have previously found that the optimum design has very little dependance on $d_{\rm max}$ for broad band designs such as these. For this reason we set $d_{\rm max}$ to a constant value of 300 Å for all the mirror groups.

Each mirror group is by design effective in a certain energy band and over a certain angular range. This is governed by the geometry as well as the choice of $d_{\rm min}$. Tables 3 and 4 gives the on-axis angular range, the radial range and the chosen $d_{\rm min}$ values for each mirror group. The mirror groups are logarithmically spaced in angle. Based on measured reflectances at energies up to 170 keV of realistic graded bilayer thickness coatings on realistic thermally slumped thin glass substrates[6] we have chosen an interfacial width of 4.5 Å for the optimization . The result of the optimization is a specification of the optimum number of layer pairs(N), the power law index(c) and Γ for each mirror group.[13] An upper limit on N has been set to ca. 1000 to avoid prohibitively thick coatings. This results in coatings of thickness typically less than 2 microns. Future developments in coating technology will undoubtedly push this limit to higher N-values and thus allow for even more effective designs especially for the high energy end of the bandwidth.

3.1. Results of optimization

The result of the optimization for the 15 m case is given in Table 3. Likewise the result of the optimization for the single module 50 m case is given in Table 4. Figure 1 shows the resulting on-axis as well as off-axis area which is obtained for the two cases. From the figure it is obvious that the two designs provide nearly identical effective areas up to 200 keV and that they meet the requirements of Table 1. In addition the 50 m design has significant effective area up to 550 keV. The FOV is close to 5 arcmin at 78 keV and close to 3 arcmin at 158 keV for both designs. It is remarkable that such performance can be obtained with these conservative designs. Future developments in coating technology regarding both the choice of material combninations, number of layer pairs, minimum d-spacings and interface quality will allow for even more efficient designs and provide the opportunity to optimize the design both in terms of effective area and FOV.

4. CONCLUSION

Based on current state-of-the-art graded multilayer coating technology we have demonstrated that it is feasible to design imaging and focusing optics in the gamma-ray energy band up to more than 500 keV. We have shown that effective areas in excess of 400 cm^2 are obtainable at energies up to and beyond the ^{56}Ni line at 158 keV. Assuming a modest imaging resolution of 20 arcsec this translates into an unprecedented line sensitivity of 10^{-7} cm^{-2} s^{-1} for all the astrophysically interesting nuclear lines in this energy range.

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Table 1. Observational requirements

Parameter	Requirement
Signal limited T_{obs}	10^6 s
Line Flux sensitivity	10^{-7} cm^{-2} s^{-1}
(5 σ, 10^6 s)	67.9, 78.4, 122 and 158 keV
Collecting area	> 300 cm^2(158 keV)
	> 1000 cm^2 (E < 80 keV)
Angular resolution	ca. 20 arcsec
Spectral resolution	ΔE/E < 1% at 158 keV
Energy band	> 158 keV

Table 2. Telescope parameters for the two focal length cases

	Case I	Case II
Focal length	15 m	50 m
No of modules	14	1
No of shells per module	148	628
Minimum Radius	4 cm	4 cm
Maximum Radius	21 cm	70 cm
Shell thickness	0.3 mm	0.3 mm
Shell length	40 cm	40 cm
Energy band	5-200 keV	5-600 keV
Mass of all mirror shells		
Assuming glass density	885 kg	729 kg

Table 3. Case I : 15 m Focal length case

Mirror group	Material combination	Angular range [mrad]	Radial range [cm]	$d_{\min}$ [Å]	c	Γ	N	Coating thickness [μm]
1	W/Si	1.00-1.13	4.00-4.52	37.0	0.205	0.345	110	0.539
2	W/Si	1.13-1.38	4.52-5.12	30.0	0.199	0.359	233	0.907
3	W/Si	1.28-1.45	5.12-5.80	25.0	0.209	0.347	472	1.521
4	W/Si	1.45-1.65	5.80-6.60	25.0	0.214	0.360	375	1.249
5	Ni/Si	1.65-1.87	6.60-7.48	20.0	0.266	0.441	1141	4.049
6	Ni/Si	1.87-2.12	7.48-8.48	20.0	0.258	0.427	1220	4.197
7	Ni/Si	2.12-2.40	8.48-9.60	20.0	0.248	0.420	1220	4.360
8	Ni/Si	2.40-2.72	9.60-10.9	20.0	0.300	0.450	1220	3.496
9	Ni/Si	2.72-3.08	10.9-12.3	20.0	0.283	0.437	1220	3.110
10	W/Si	3.08-3.50	12.3-14.0	25.0	0.187	0.304	585	1.852

Table 4. Case II : 50 m Focal length case

Mirror group	Material combination	Angular range [mrad]	Radial range [cm]	$d_{\min}$ [Å]	c	Γ	N	Coating thickness [μm]
1	W/Si	0.666-0.786	4.00-4.72	45.0	0.182	0.370	77	0.452
2	W/Si	0.786-0.928	4.72-5.57	35.0	0.202	0.329	195	0.875
3	W/Si	0.928-1.10	5.57-6.60	25.0	0.201	0.376	608	1.953
4	W/Si	1.10-1.29	6.60-7.74	25.0	0.204	0.344	585	1.88
5	W/Si	1.29-1.53	7.74-9.18	25.0	0.209	0.344	468	1.506
6	W/Si	1.53-1.80	9.18-10.8	25.0	0.220	0.351	375	1.242
7	Ni/Si	1.80-2.13	10.8-12.8	20.0	0.319	0.459	1220	3.272
8	Ni/Si	2.13-2.51	12.8-15.1	20.0	0.300	0.450	1220	3.272
9	Ni/Si	2.51-2.97	15.1-17.8	20.0	0.296	0.438	1220	3.272
10	W/Si	2.97-3.50	17.8-21.0	25.0	0.190	0.320	585	1.844

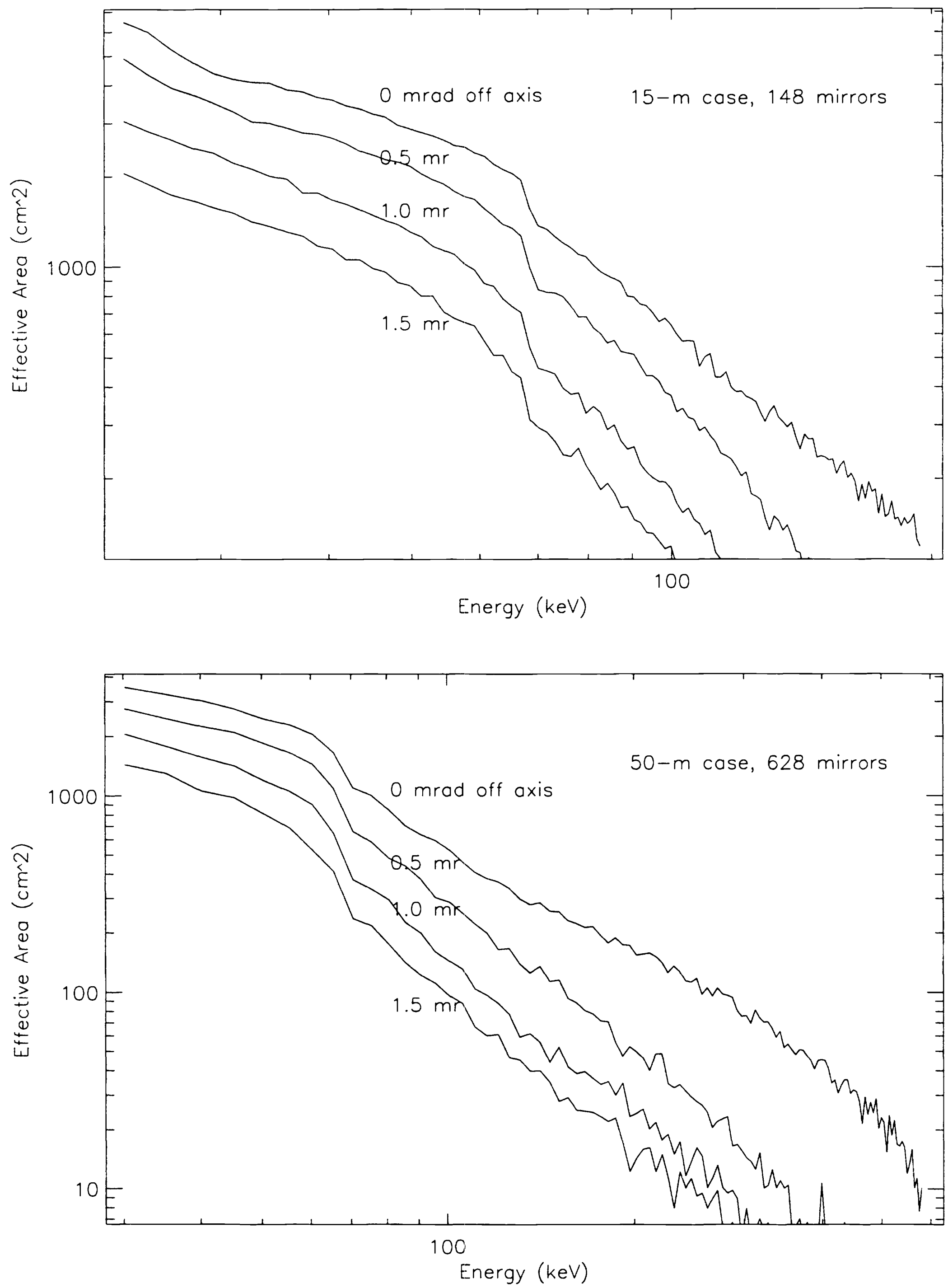

Figure 1. The calculated effective area for the 15 and 50 m focal length case. The area is calculated for on-axis, 0.5 mrad off-axis, 1.0 mrad off-axis and 1.5 mrad off axis.