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MONOCHROMATIC X-RAY AND XUV IMAGING WITH MULTILAYER OPTICS

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ABSTRACT

The development of techniques for the fabrication of multilayer coated mirrors which can function as energy selective X-ray and XUV mirrors at normal incidence has greatly expanded the options available to the astronomical spectroscopist. We have developed a rocket spectroheliograph which utilizes multilayer optics in three configurations: i) As Cassegrain telescopes for imaging at 256 Å (He II) and 173 Å (Fe IX, X); ii) As tertiary mirrors used with a conventional Wolter I telescope for imaging at 44 Å (Si XI, XII), 173 Å, and 256 Å; iii) As off-axis spherical mirrors for imaging at 44 Å and 256 Å. We report on laboratory images and performance measurements obtained with these optical systems, and briefly on Solar Observations.

I. INTRODUCTION

The development of Layered Synthetic Microstructures [1] which can provide diffracting structures suitable for soft X-ray and XUV wavelengths has allowed the fabrication of synthetic optical surfaces which can function as wavelength selective normal incidence or near normal incidence elements in astronomical X-ray and XUV telescopes [2]. These structures, generally referred to as "multilayers" provide a measure of flexibility which is not available with naturally occurring Bragg crystals since: i) The constituent materials of a multilayer can be chosen to tailor its bandwidth and reflectivity to a particular application [3]; ii) The period of a multilayer is an adjustable parameter which can be chosen to give arbitrary "lattice spacings" within the range from $30 \text{ \AA} < 2d < 400 \text{ \AA}$; iii) Multilayers can be fabricated on figured (i.e. curved) substrates.

Multilayer optics can be used in at least two distinctive ways for astronomical observations: i) as primary optical elements for collecting and imaging radiation; ii) as secondary or tertiary optical elements in conjunction with conventional Wolter grazing incidence optical systems.

When used as primary optical elements, multilayers allow the X-ray astronomer to utilize conventional Cassegrain optical systems [4] with their well known advantages of high resolution and extended field. The disadvantages of conventional Cassegrain multilayer optics are: i) the difficulty of fabricating large aperture multilayer optics; ii) the restriction of a multilayer telescope to a single wavelength bandpass; iii) the low reflection efficiency of multilayer optics below 100 Å.

When used in conjunction with Wolter optics as secondary or tertiary elements, multilayer optics can considerably improve the off-axis resolution of the compound system. Multilayer optical elements used with Wolter primary mirrors can also provide image magnification, an option which is not possible for conventional Wolter I mirror systems [5]. We refer to such systems as "Wolter-Cassegrain" optics. In addition, since the aperture of the optical system is determined by the Wolter optics, the use of an array of small secondary or tertiary multilayer optics allows a single Wolter-Cassegrain system to form images in a number of wavelength bands, potentially covering a wide wavelength interval. The disadvantages of such hybrid systems are that: i) Grazing incidence optics suffer considerably more from small angle scattering than do normal incidence optics; ii) Although the multilayer tertiary in the Wolter-Cassegrain considerably improves off-axis resolution, this is achieved at the expense of a modest decrease in on-axis resolution.

We have developed a rocket X-ray spectroheliograph payload (Figure 1) which utilizes multilayer optics in three configurations: i) as Cassegrain telescopes; ii) as tertiary mirrors in a Wolter-Cassegrain; iii) as off-axis spherical mirrors. The performance of the rocket payload is

summarized in Table 1. The multilayers used have all been fabricated by the authors at Stanford [6] using the Stanford Center for Materials Research facility developed by one of the authors (T. Barbee).

Table 1. Optical systems and solar images to be obtained from the Stanford/MSFC Solar X-Ray Telescope.

Optical System	Focal Length (m)	Resolution (arcsec)	Spectral Filter	Central Wavelength	Bandpass	Solar Lines Observed	Coronal Temperature
Cassegrain f/34	2.0	0.5 - 1.2	Mo/Si multilayer	173 Å	5 Å*	Fe IX, Fe X	1,000,000 K
			Mo/Si multilayer	250 Å	31 Å	He II Fe XIV, Fe XV	50,000 K 3,500,000 K
Wolter/Cassegrain f/44	2.54	2	W/C multilayer	44.16 Å	0.6 Å	Si XI, Si XII	2,000,000 K
			Mo/Si multilayer	173 Å	10 Å	Fe IX, Fe X	1,000,000 K
			Mo/Si multilayer	250 Å	31 Å	He II Fe XIV, Fe XV	50,000 K 3,500,000 K
Off Axis Imager f/17	0.6	2	W/C multilayer	44.16 Å	0.6 Å	Si XII	2,000,000 K
			Mo/Si multilayer	250 Å	31 Å	He II Fe XIV, Fe XV	50,000 K 3,500,000 K
Wolter I - Al Filter f/15	1.27	2	Al Filter 6.35µm	16 Å	8 Å	O VIII, Ne IX Fe XVII, Fe XVIII	2,000,000 K - 6,000,000 K

*Bandpass here is combined bandpass of two multilayer reflections and 1700 Å aluminum filter.

II. OPTICAL CONFIGURATION OF THE PAYLOAD

Cassegrain Optics: Figure 1b and 2 illustrates the configuration of the X-ray Cassegrain telescope, and the appearance of the completed telescope. The optical elements (primary and secondary) are concave and convex spherical surfaces respectively, rather than parabolic and hyperbolic surfaces. These surfaces were chosen rather than true conics because the quality of the optical surface which can be achieved for a spherical substrate is superior to the quality which can be achieved for true conic surfaces. The optical quality of the substrates is extremely critical to the performance of the multilayer. Tests on the substrates, which were fabricated by General Optics of Santa Barbara, California, show that the RMS finish of the substrate surface is approximately 3 Å. The computed resolution of the pseudo Cassegrain configuration is shown in Figure 3.

Wolter-Cassegrain: The configuration of the Wolter-Cassegrain is shown in Figure 1a. To allow the recording of images in several bandpasses simultaneously, we have used 4 separate convex spherical multilayer tertiary mirrors, each of which intercepts a 60° segment of the hollow conical beam of the Wolter I mirrors, to form an image (Figure 1c). Each tertiary mirror is tilted slightly with respect to the optical axis of the Wolter primary mirror so that the four image planes are separated. An alternative approach (which is not feasible for a short duration rocket flight) would be to place several tertiary mirrors, each of which intercepts the full beam, on a transport system to allow successive images in different bands to be obtained. The performance of a conventional Wolter I mirror is compared with the performance of Wolter-Cassegrain optical systems for magnifications of 2, 6, and 8 in Figure 4. The calculations shown in Figure 4 were carried out for the S-056 Skylab Telescope [7]. The magnification of the rocket spectroheliograph Wolter-Cassegrain system is 2.

Spherical Imager: The third optical system is a simple off-axis spherical imager. The advantage of this system is that an image is formed using only a single multilayer reflection. For solar observations at 44 Å, the Cassegrain configuration is too low in efficiency to allow images to be obtained in the observing time available during a rocket observation. The spherical imager provides an effective alternative. The disadvantages of the spherical imager are short focal length and hence a small plate scale, and astigmatism in one axis due to the off-axis configuration necessary to avoid obscuration of the aperture by the camera. Marilyn Brunner of Lockheed Palo Alto Research Laboratory has pointed out that the use of a toroidal mirror can eliminate the astigmatism problem.

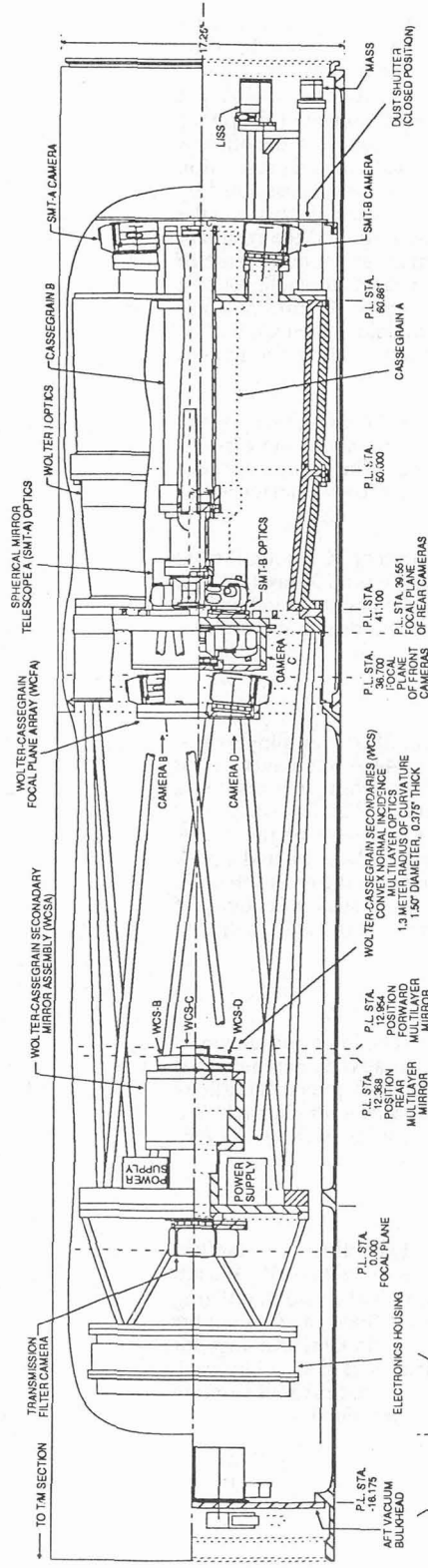


Figure 1a (above). Configuration of Stanford/MSFC Rocket Spectroheliograph.

Figure 1b (left). Cassegrain Telescope

Figure 1c (far left). Wolter-Cassegrain tertiary mirror array.

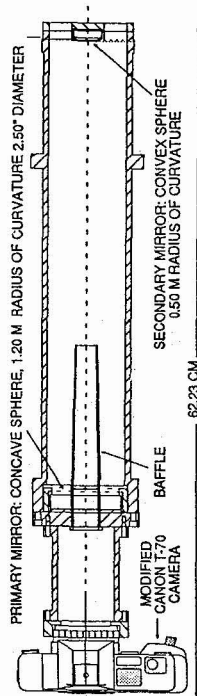


Figure 2. Multilayer Cassegrain

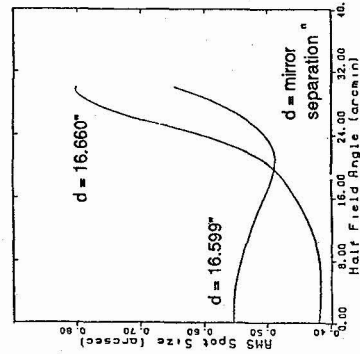
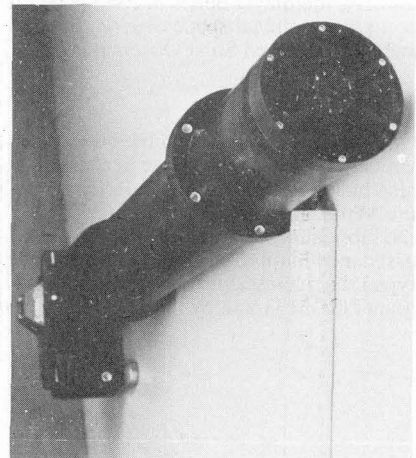


Figure 3. Predicted off-axis resolution of the Multilayer Cassegrain (ray trace by D. Gabardi and D. L. Shealy).

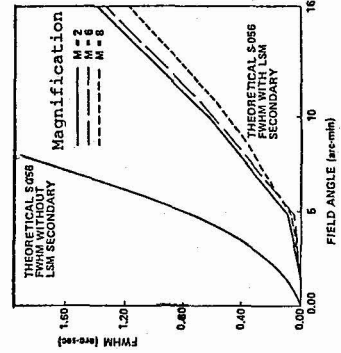


Figure 4. Predicted off-axis performance of the Wolter-Cassegrain compared with performance of a conventional Wolter I telescope.

III OPTICAL PERFORMANCE

Cassegrain: We have measured the on-axis optical performance of the Cassegrain telescope using the 300 meter long Marshall Space Flight Center (MSFC) X-Ray Test & Calibration Facility. Since this facility does not provide flux in the spectral ranges (circa 173 Å and 256 Å) that we will utilize for solar observations with the Cassegrain, we fabricated a set of optics for use at 44 Å and measured on axis resolution of 1.1 arc seconds. Even at this wavelength, the efficiency of the optics precluded an extensive set of off-axis optical performance measurements. Consequently, the off-axis performance was measured at 5000 Å, using an optical collimator. The measured off axis resolution (defined here as the ability to resolve two adjacent point sources) of 1.4 arc seconds is constrained by the diffraction limit of the telescope at 5000 Å, which is 1.9 arc seconds. The sharp decrease in the resolution of the telescope beyond 20 arc minutes off-axis is due to vignetting, and the resultant effects of diffraction. The X-ray resolution of 1.1 arc seconds at 44 Å is a more accurate measure of the performance of the pseudo Cassegrain optics of the telescope. This is approximately a factor of 2 worse than the predicted resolution of ~0.5 arc seconds (Figure 3). We ascribe the difference to mechanical distortions caused by the mounting of the primary mirror. We anticipate that we will be able to achieve the theoretical resolving power by a modification of the mount. The point images obtained at 44 Å were sharp, and showed little detectable scattering.

Wolter Cassegrain: We have measured the on-axis performance of the Wolter-Cassegrain at 44 Å, using the MSFC X-Ray Test & Calibration Facility. We have also measured the off-axis performance at 5000 Å, using the same optical collimator discussed above. The results of these measurements are shown in Figure 6. The very dramatic improvement in off-axis performance compared to a conventional Wolter I is evident.

Spherical Imager: The Spherical Imager was tested in our laboratory X-ray facility at Stanford, as well as in the MSFC X-Ray Test & Calibration Facility. Figure 7b is an X-ray (44.7 Å) image of an Air Force high resolution test target obtained at Stanford. The Marshall tests indicated a resolution of 2 arc seconds which is consistent with the astigmatism expected due to the off-axis position of the image (see figure 7a).

IV SPECTRAL PERFORMANCE

We have previously reported on the spectral performance of several of our multilayers [6]. We present additional spectral response data in Figure 8. The response of the 44 Å multilayer mirror shown in Figure 8a demonstrates a spectral resolving power $\lambda/\Delta\lambda = 47$ at fwhm (the resolving power can be readily improved to $\lambda/\Delta\lambda = 70$ by using larger sputtering sources). The flux imaged by the 44 Å multilayer will be dominated by the emission of Si XII. The response of the 173 Å multilayer mirror shown in Figure 8b demonstrates a spectral resolving power $\lambda/\Delta\lambda \sim 14$, and a peak reflectivity of 30%. The flux imaged by the 173 Å multilayer will be dominated by the emission of Fe IX and Fe X. The 250 Å multilayers have a resolving power of $\lambda/\Delta\lambda \sim 8$, and a peak reflectivity of 25%. The images formed by the 250 Å multilayers will be dominated by emission of He II, although there will be significant contributions from Fe XIV and Fe XV.

V DISCUSSION

The rocket spectroheliograph instrument described in this paper is scheduled for launch in October 1987. The laboratory measurements presented here have, we believe, already demonstrated the power and flexibility of multilayer optics for astronomical spectroscopy. The configurations utilizing multilayer optics in conjunction with Wolter optics are especially significant for planned large scale astronomical space observatories such as the Advanced X-Ray Astrophysics Facility (AXAF) and the Advanced Solar Observatory (ASO) [8].

ACKNOWLEDGMENTS

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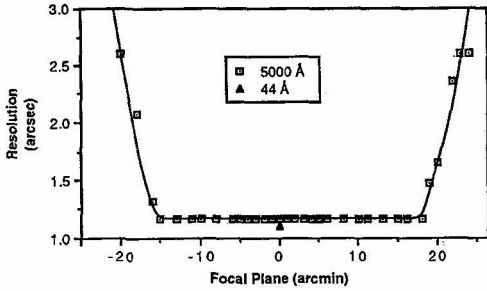


Figure 5. Measured on-axis x-ray (44 Å) and off-axis visible light resolution of Multilayer Cassegrain Telescope

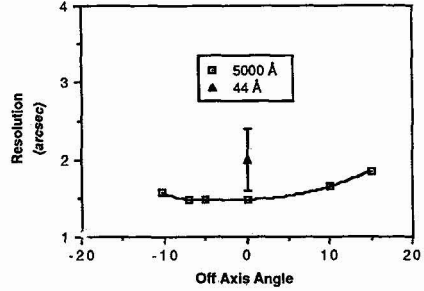


Figure 6. Measured on-axis x-ray (44 Å) and off-axis visible light resolution of Wolter-Cassegrain Telescope



Figure 7a (above). Imaging test at 44.7 Å with Spherical Off-Axis Imager Telescope in the MSFC 1000 ft vacuum chamber. Exposures are 3 hr, 1 hr, 20 min, 10 min, 4 min, 2 min, 1 min, and 30 seconds in duration. The five shortest exposures are separated by 10 arcseconds each. Plate scale on the film is 3 microns/arcsecond.

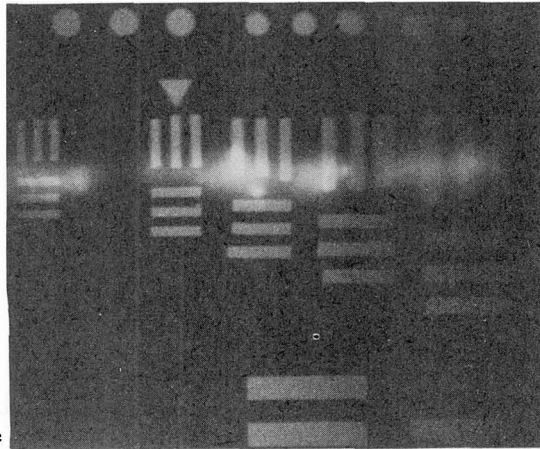


Figure 7b (right). Imaging test at 44.7 Å using a concave 0.50 m radius of curvature W/C multilayer mirror. Streak in center of the image is due to static discharges in vacuum.

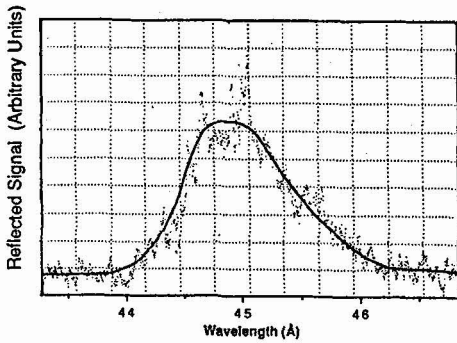


Figure 8a. Spectral bandpass of 44 Å W/C multilayer. Measurements made by John Trail.

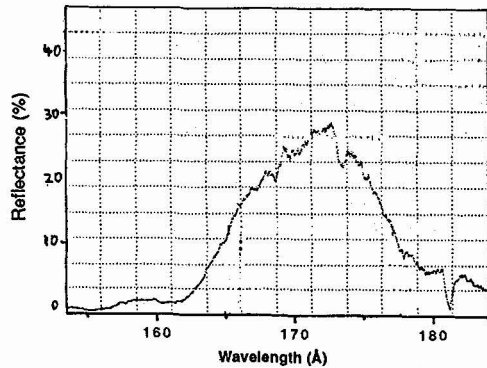
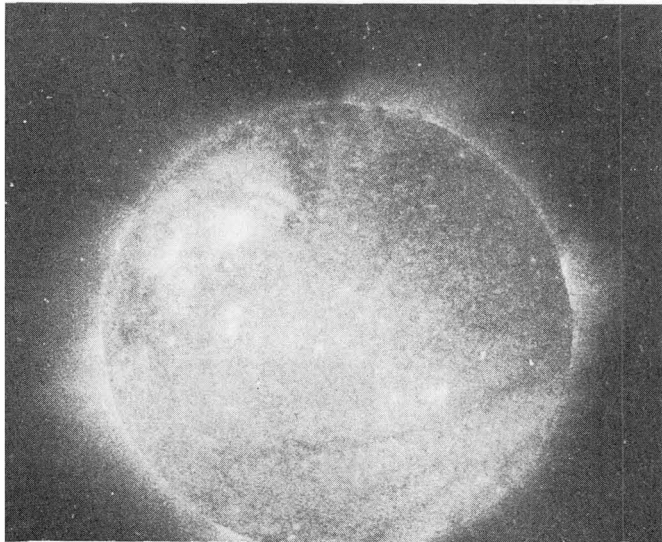


Figure 8b. Normal incidence reflectance of 175Å Mo/Si multilayer. Peak reflectance is 25 - 30%. Measurements made by John Trail.

Note Added in proof: The rocket payload describe in this paper was successfully launched on October 23, 1987, and obtained more than 100 images of the Sun. The image below is representative of the data obtained. A more detailed report on these data will be submitted to Science.

Image of the Sun obtained with 250 Å Spherical Imager Telescope. Emission over most of the solar disk is from He II. Active regions are dominated by emission from Fe XIV and Fe XV.



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