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XUV multilayered optics for astrophysics

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Résumé. — A l'heure actuelle, plusieurs laboratoires ont réalisé des optiques interférentielles pour l'ultraviolet extrême à l'aide de miroirs multicouches, leur utilisation sur des expériences embarquées a commencé. Beaucoup d'autres applications sont prévues car les futurs instruments basés sur l'emploi des miroirs multicouches ouvrent de nouvelles possibilités pour les observations astronomiques. Cet article passe en revue l'état actuel de ce type d'instrumentation, les résultats obtenus et quelques projets en cours employant ce type d'optique interférentielle X-UV.

Abstract. — High quality multilayered optics operating in the extreme ultraviolet are now being fabricated by a number of laboratories and their use in astronomical observations from space has already begun. Many other applications are planned and future instruments involving multilayers hold great promise for the field of astrophysics. This paper presents an overview of the current status of multilayer-based astronomical instrumentation, observations that have already occured and some plans for the future.

Introduction.

Recent progress in the fabrication of thin film multilayered coatings has made their application to astronomical instruments both practical and attractive. The first image of a solar active region using normal-incidence multilayer optics was obtained [1] during a sounding rocket flight in 1985 and full disk images of the sun in extreme ultraviolet lines have been recently acquired [2]. Many other applications of multilayer optics in astronomy are now being planned or are under development. Soon after the initial successes [3, 4] in fabricating multilayers in the late 1970s, their potential applications in X-ray and EUV astronomical instruments were discussed by Underwood, Barbie and Keith [5]. Since then, many more applications of multilayers in astronomy have been discussed in the literature [6-16].

The use of vacuum deposited multilayers on optical surfaces allows normal incidence reflection at wavelengths longer than approximately 20 A. Many astrophysically important emission lines occur in this region of the spectrum and their investigation allows the temperature, density and spatial structure of the emitting plasma to be studied. Presently, however, the multilayer performance is severely degraded at the shorter wavelengths by substrate surface roughness and interdiffusion of materials in the thin layers. Depositing multilayers on grazing incidence optics, whose grazing angles may be much larger than for specular reflection, allows this range to be extended to shorter wavelengths.

Since multilayer optics reflect efficiently only in narrow bandpasses, they may be used to isolate astrophysically important emission lines for study more effectively than with the use of grazing incidence optics and transmission filters. This effect may also be used to discriminate against background from the strong geo-coronal XUV emission lines, particularly in folded optics where double reflection occurs. Because they can operate at normal incidence, multilayer optics have less aberrations than grazing incidence optics, thus providing better angular resolution over a much broader field in imaging applications. In addition, because the reflection is actually a diffraction and therefore coherent, whereas any scattering is incoherent, the effects of scattering are greatly reduced in a multilayer telescope. Grazing incidence optics, however, are able to image at shorter wavelengths, reflect over a much larger spectral range and therefore have greater sensitivity for comparable effective area. Multilayer optics and grazing incidence optics are thus complimentary and may even be combined effectively in a hybrid system for certain astronomical applications.

Multilayer coated flats may be used to replace natural crystals in Bragg spectrometers and polarimeters for astronomical observations. This allows the instruments to be tailored to the wavelengths of interest by depositing the proper layer spacing. If suitable care is taken, it is also possible to produce a graded-thickness multilayer which overcomes the vignetting problem for imaging objects of large angular size.

Progress in astrophysical applications.

1. LABORATORY IMAGING EXPERIMENTS. — Since the most obvious use of multilayer optics in astronomy is in telescopes, the first laboratory experiments by astrophysicsts involved imaging. Underwood and Barbee [17, 6] obtained an image of a grid using normal-incidence multilayer optics. The grid was back-illuminated by 44.7 A X-rays that were imaged onto film by a W-C multilayer deposited on a silicon wafer. This wafer was then bent to approximate a spherical mirror. An angular resolution of about 40 arc sec was achieved with that system. Henry, Spiller and Weisskopf [18] reported on the performance of the first multilayer to be successfully fabricated on a figured surface. The mirror was 7.6 cm in diameter with a focal length of 5.2 m and had a Re-W, C multilayer appropriate for reflecting 67.6 A X-rays deposited on its surface. An image of a point source obtained at normal incidence with this mirror has a FWHM of 1 arc sec, limited by detector resolution and mirror aberrations.

Considerable progress has been made in France in developing multilayer optics for solar physics research. In preparing to fabricate a Ritchey-Chretien telescope for imaging He II emission at 304 A, Chauvineau and co-workers [19] describe a clever way of aspherizing the mirrors prior to multilayer deposition. This was done by starting with spherical mirrors, very close to the required contours, and vacuum depositing a coating whose thickness varies over the mirrors surface to acheve the required hyperbolic figures. Delaboudinière [11] has designed a multilayer telescope for solar XUV observations and performed tests simulating exposure of the optics to solar radiation for purposes of space qualifying the multilayers. A slight degradation in reflectivity measured at 304 A was observed but it may have been from a surface contamination.

In preparation for a sounding rocket experiment the group at Stanford University report [15] the laboratory test of a W-C multilayer mirror at 44.7 A. A 2.5 cm diameter mirror with a 0.5 m radius of curvature was used to image a back-illuminated transmission test target onto Tri-X film. Both visible light and X-rays were used and an angular resolution of 10 arc sec was achieved in each case, limited by aberrations of the mirror at the 3 degrees off-axis angle of the experiment.

2. OBSERVATIONS FROM SPACE. — The first astronomical application [1] of multilayer imaging optics occurred during a NASA sounding rocket flight in October 1985. This telescope was developed jointly by teams lead by Bruner at the Lockheed Palo Alto Research Laboratory and by Underwood at the Lawrence Berkeley Laboratory. The mirror was coated with a W-C multilayer designed for imaging the strong Si-XII line pair at 44.16 and 44.02 A from solar active regions. It was 3.8 cm in diameter with a 1 m focal length and operated at an off-axis angle of 1.7 degrees. Visible and ultraviolet light were excluded by Al coated polypropylene filters in front of the KODAK SO-212 film used to record the image. Due to a problem in a telemetry command link, only two exposures were obtained. The longer exposure of 70 sec provided the image of an active region near the solar equator about two thirds of the way toward the west limb. The angular resolution achieved in this image was in the 5-10 arc sec range with an aberration limit of 3 arc sec.

Another NASA sounding rocket payload with several normal incidence multilayer telescopes designed for solar observations was flown on 23 October 1987. The experiment was conducted by Walker and Lindblom of Stanford University with collaborators at Lawrence Livermore Laboratory and the Marshall Space Flight Center. The payload contained two Cassegrainian multilayer telescopes operating at 173 A and 256 A, two telescopes using off-axis spherical mirrors with bandpasses at 44 A and 173 A and a hybrid telescope with several multilayer mirrors refocusing the converging beam of a grazing incidence Wolter I system. Further details of the instrument are given in [2, 15]. A special version of Kodak T-max 100 film was used to record the images and over 100 photographs were obtained with exposures ranging from 0.5 to 200 sec. Many of these images are of excellent quality [2, 20] and show much detail with angular resolution down to a few arc sec. These photographs indicate the excellent performance that multilayer optics have for use in astrophysics and their very great potential for future applications.

3. DESIGN OF A HIGH RESOLUTION RITCHEY-CHRETIEN TELESCOPE. — In a joint collaboration between the Smithsonian Astrophysical Observatory and personnel from the IBM Watson Research Center, a large-aperture Ritchey-Chretien telescope has been built and coated for use at a soft X-ray Solar coronal wavelength [12]. The flight optics are a pair of hyperbolic mirrors in Cassegrain configuration. This design permits sub-arcsecond resolution

over a wide field of view and the 750 cm focal length produces the plate scale necessary to match the telescope's 0.1 arcsecond on-axis resolution to that of fine grain photographic emulsion. The primary mirror in this payload is 25 cm diameter, with a 3.5 X secondary and the speed is f/30.

The data are recorded on 70 mm film, using a Hasselblad 500 EL/M camera and a special order film manufactured by Kodak. The optics were hand polished to a smoothness of approx. 4 angstroms, and tests on a 13″ Zygo laser interferometer show that the overall figure quality of the telescope is better than lambda/60 at 5 000 angstroms.

Multilayer coatings were applied to the mirrors at IBM by Spiller, after a lengthy series of test and calibration runs. Production of mirrors suitable for Solar studies involved many factors, including :

(1) each of the mirrors, primary and secondary, must include within its passband the coronal emission line of interest ;

(2) the passbands of the two mirrors must be identical to within a small fraction of their individual bandwidths ;

(3) the coating uniformity of the mirrors must be better than the multilayer bandwidth. Note that at the chosen wavelength of 63.5 Angstrom the multilayer passband is of order 1 %. All of these problems are substantially simplified at XUV wavelengths of 200-300 Angstroms, for which the passband is about 10 % ;

(4) in order to obtain high reflectivity, the coating must have sharp, smooth boundaries between layers. When roughness, due either to the substrate or to the deposition process, becomes greater than 1/12th the wavelength to be reflected, the actual performance of the multilayer degrades substantially in comparison to the theoretical value.

The coating quality achieved in the SAO/IBM payload is illustrated in figure 1. The agreement between desired and achieved wavelength of peak reflectivity is quite good, of order 0.1 Angstrom. Also the uniformity of the coating on the large primary mirror is 1 % and the overlap with the secondary mirror is acceptable. However, the peak reflectivity is only 4.2 % per reflection ; this is much lower than the theoretical maximum. The low reflectivity is attributed to higher than expected boundary roughness in the Co-C multilayer. Stability of the coatings was investigated in detail during production of these mirrors. The results can be summarized as

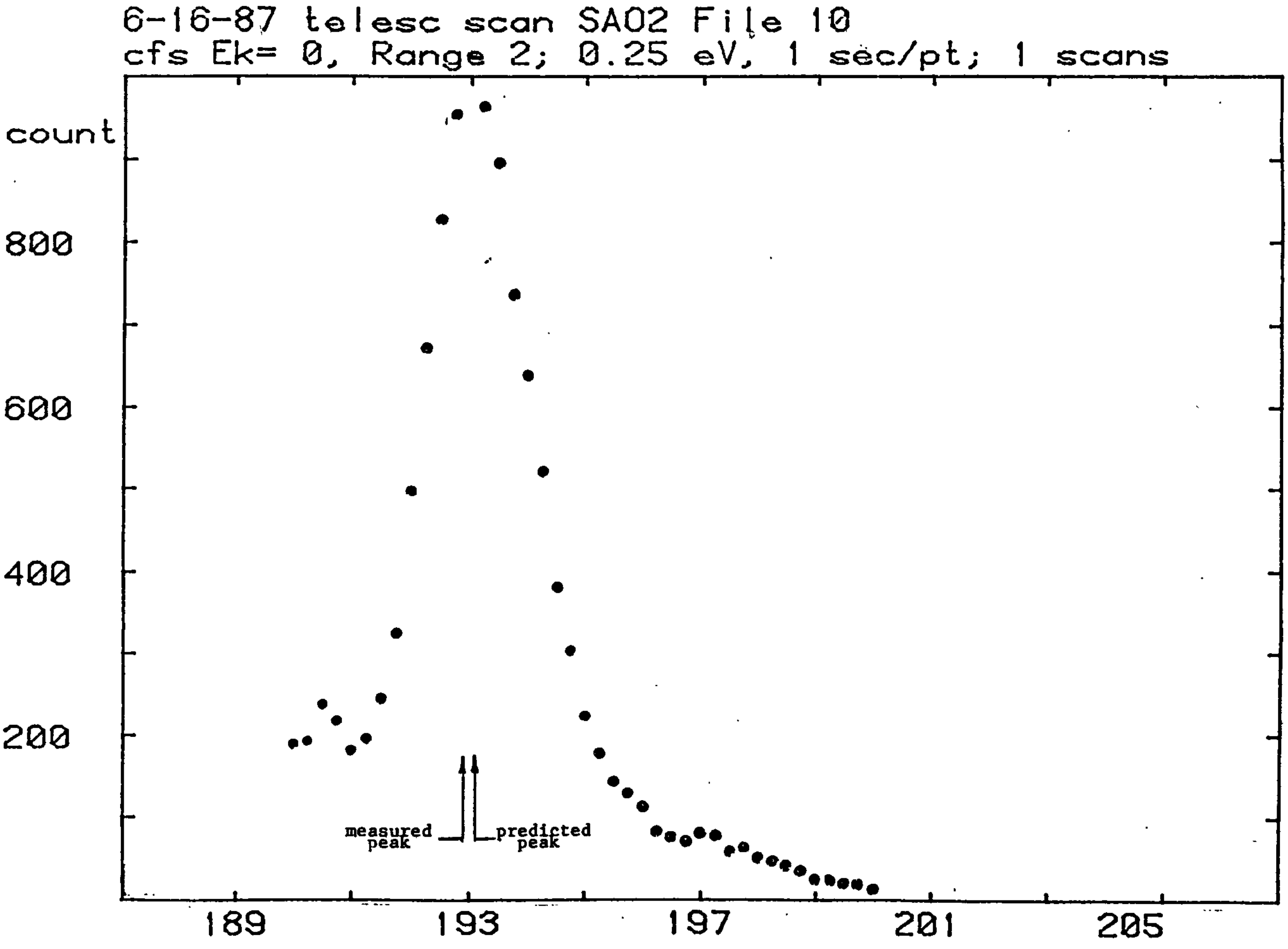

Fig. 1. — Measured bandpass of the multilayer mirror used in the SAO/IBM rocket payload.

follows : some material combinations, such as W-C, give good performance but are found to change thickness with time at room temperature. The amount of the drift is 5 % to 7 % and it is not possible to predict in advance the exact amount that a given coating will drift. However, depositing onto a warm substrate is found to produce a coating which does not show any further drift. In this case, monitoring of the reflectivity during deposition allows a reliable determination of the coating's properties.

Alternatively, some materials combinations, such as Ni-C and Co-C are found to be stable for long periods of time at room temperature. These materials have the additional advantage that they have been flown in space and are known to survive in orbit. Their only drawback is that if they are heated above 200 degree C for several hours they crystallize and the multilayer reflectivity is lost.

4. INSTRUMENT DESIGN STUDIES.

— In addition to pointing out applications of normal incidence multilayer optics to astronomy, Underwood, Barbee and Shealy [6] discussed a hybrid system that combined multilayer optics with a grazing incidence telescope. This allows the telescope focal length to be adjusted to better match its plate scale to the available detector. The multilayer also provides filtering that is useful in some applications, particularly if several multilayer secondaries are available in a turret arrangement. Detailed studies of the imaging qualities of such a hybrid system were carried out by Shealy and Hoover [21] and Shealy, Hoover and Gabardi [22].

A different hybrid system, in which multilayers are deposited directly on the surface of a grazing incidence Wolter I telescope, has been studied by Catura and co-workers [23]. This allows the telescope to image much higher energy X-rays by Bragg reflection from the multilayer than by the normal specular reflection. It the Bragg bandpass is chosen at sufficiently high energy, the multilayer may be overcoated with a thin specularly reflecting layer that the Bragg reflected X-rays are able to penetrate. The study indicated that a useful effective area could be obtained for imaging the astrophysically important iron line emission at 6.7 keV in a telescope that normally cuts off at 2.5 keV. Their calculations also showed it possible to image up to 25 keV X-rays with their particular telescope design and in principal could be extended to even higher energies.

There are applications in astronomy where tailoring the multilayer bandpass is advantageous. Lee [24] has considered tailoring the multilayer response by varying layer thicknesses as a function of depth in the stack and for uniform layers in depth that vary in thickness over the surface. Stern *et al.* [9] discuss methods of varying a multilayer's response by changing the relative thickness of the two materials while holding the multilayer period fixed and also by varying the period across the surface. These authors also discuss using multilayer-coated gratings operating in an Echelle mode and compare the performances of a multilayer and a grazing incidence telescope for EUV astronomy. Meekins and coworkers at the Naval Research Laboratory have developed a formalism to aid in multilayer design for optimizing reflectivity in both narrow [25] and broad [26] bandpasses by varying the thickness of layers in the stack.

Keski-Kuha and colleagues at the Goddard Space Flight Center have been involved in study [13] and development [27] of multilayer optics for the wavelength range from 200 to 500 A. Ir-Si multilayers were designed for both broad and narrow bandpasses. Test samples were fabricated and their reflectivity measured for comparison with the response calculated from optical constants. The overall character of the two reflectivities were in reasonable agreement with the measured values falling somewhat below those calculated.

Future plans.

The three sounding rocket payloads designed for imaging observations of the sun, that are described above, are planned for re-flights over the next several years. The instruments are expected to evolve by changing the wavelengths of the multilayer bandpasses and perhaps by adding more telescopes. Imaging the sun at XUV wavelengths with multilayer optics is one of few experiments that can obtain significant new results in the short duration of a sounding rocket flight.

The focal plane crystal spectrometer being designed by the Massachusetts Institute of Technology for NASA's Advanced X-ray Astrophysics Facility [AXAF] will use multilayers in addition to crysals as Bragg diffractors. This instrument has curved diffractors that intercept the diverging beam behind the telescope's focus at nearly constant Bragg angle and refocuses the diffracted X-rays onto a position sensitive proportional counter. The 2d spacing of the multilayers are planned to be 36.5 and 100 A. AXAF is now planned to be flown in the mid-1990s. Further details are given by Canizares and co-workers [28, 29].

McCammon and colleagues at the University of Wisconsin have developed a Bragg spectrograph to study spectral features in the diffuse X-ray background. The instrument involves curved surfaces coated by lead stearate multilayers that Bragg reflect the X-rays onto collimated position sensitive proportional counters. The spectrograph is to be flown as a space shuttle payload and is currently scheduled for a June 1991 launch. A prototype of the diffuse X-ray spectrograph has been developed as a sounding rocket payload and flown several times to obtain background counting rates and engineering data.

Several investigations involving multilayer instruments have been proposed for the ESA-NASA SOHO mission. An extreme ultraviolet imaging telescope has been proposed by Delaboudinière of the Laboratoire de Physique Stellaire et Planétaire in France and his collaborators. It involves Cassegrainian optics coated by multilayers. For purposes of reducing the size and weight of the instrument, four bandpasses were combined in a single telescope. The four quadrants of a single primary mirror are coated with different multilayers and corresponding quadrants of the secondary have multilayers to match the primary. A bandpass is selected by a rotating shutter in front of the telescope that has an open quadrant so that only one multilayer is illuminated at a time. A single CCD detector records images from each bandpass sequentially. By virtue of the single set of optics and detector, the images from different bandpasses are well registered, one to another.

An X-ray telescope proposed for SOHO by Schmidt of the Max-Planck-Institut für Aeronomie incorporates multilayer mirrors for their spectroscopic capability. The proposed design uses a grazing incidence telescope and several small, flat multilayer mirrors which « pick off » part of the beam and send a monochromatic image to a side camera ; a separate camera is provided for each wavelength. The mirrors operate at angles of 10-15 degrees (grazing) and the bandwidth of each mirror is 2 %. This translates into an angular bandwidth of 1/4 degree, which is smaller than the angular size of the Sun. The mirrors must therefore be graded in thickness by 4 % (in one direction only) in order to avoid severe vignetting of the image. Spectral diagnostics at active region temperatures are provided by images in lines such as O VII at 21.6 A and Fe XVII at 17.0 A. Additional topological information in the transition region and corona are provided by a broadband XUV feed which employs an uncoated polished SiC flat.

Plans to fly an Extreme Ultraviolet Imaging Telescope Array [EUVITA] as a joint mission between the U.S.S.R. and the U.K. are now underway [30]. The instrument consists of four co-aligned telescopes with multilayer coated optics that reflect in selected bandpasses in the range from 60 to 250 A. The objective of the mission is to study non-solar EUV sources. Microchannel plates will be used as image sensors and the EUVITA is planned for flight on the U.S.S.R.'s Spectrum X mission in late 1992.

A imaging polarimeter involving multilayer optics will be launched on the PHOBOS mission in July 1988 by the U.S.S.R. This instrument is designed for solar observations in the He II line at 304 A and has been fabricated by Dr. Jitnik at the Lebedev Institute.

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