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ABSTRACT

We describe the experimental apparatus in use to test an off-plane reflection grating for the soft x-ray (0.3-1.0 keV) bandpass. The grating is a prototype for the X-ray Grating Spectrometer on the International X-ray Observatory (IXO). It has holographically-ruled radial grooves to match the converging beam of a 6.5 m focal length telescope. Laboratory tests are ongoing, with ray tracing indicating that a resolution (ΔE/E) >3,000 is achievable across the 0.3-1.0 keV bandpass — the requirement to achieve IXO science goals.

Keywords: x-ray spectroscopy; International X-ray Observatory; diffraction grating; off-plane grating

1. INTRODUCTION

High resolution x-ray spectroscopy of celestial sources has eluded astronomers for decades as they worked with proportional counters and low-resolution and inefficient spectrometers. With the International X-ray Observatory (IXO) on the horizon and the acknowledgement of the wealth of physics accessible only through spectroscopy, the push for improved resolution has increased: IXO science goals call for a resolution (R=ΔE/E) greater than 3,000 in the soft x-ray bandpass (0.3-1.0 keV). Among other things, the high resolution (Figure 1) will allow measurements of redshifts of extragalactic sources and line broadening and improved diagnostics of hot interstellar gas by distinguishing blended lines.

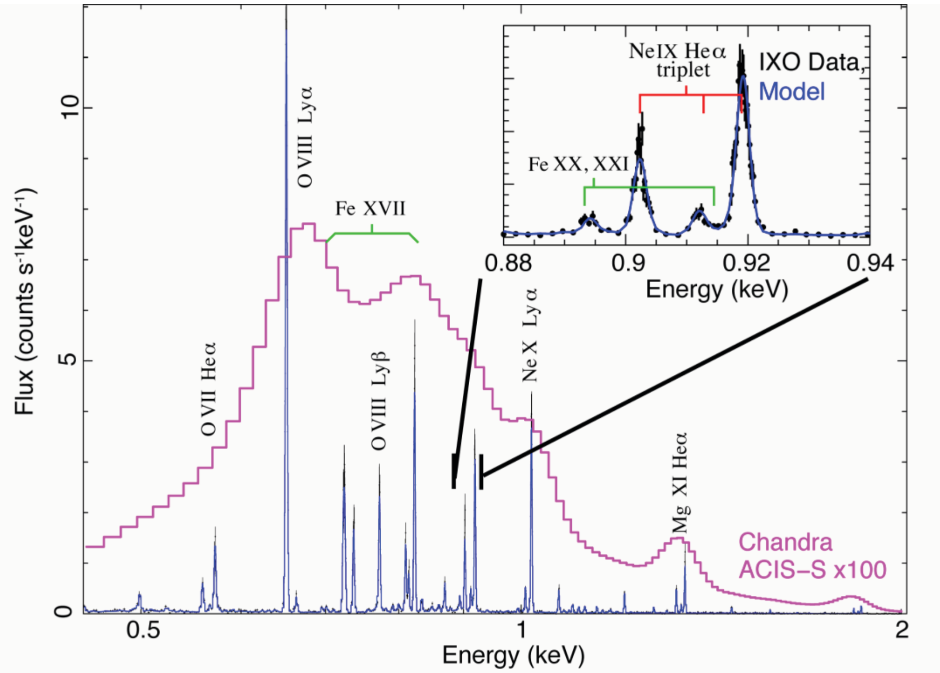

Figure 1: Comparison of modeled IXO spectrum of a galactic 'superwind' with that of ACIS (on Chandra).[1] The resolution of Chandra in this bandpass is ~100, while IXO is ~3,000. The IXO XGS is designed to operate from 0.3 to 1.0 keV.

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Off-plane diffraction gratings, with grooves quasi-parallel to the incident light (Figure 2) offer high throughput due to the grazing incidence reflection on the grating surface. Additionally, manufacturing tolerances are eased because errors in ruling the gratings produce scatter in the in-plane direction, orthogonal to the off-plane dispersion. Grazing angles in off-plane gratings also do not produce groove shadowing, an unfortunate loss of efficiency for grazing incidence gratings in an in-plane mount. The diffraction is described by the grating equation

$$\sin\alpha + \sin\beta = \frac{m\lambda}{d\sin\gamma} \ , \qquad \text{Eq. 1}$$

where m is the order, λ is the wavelength, d is the groove spacing, γ is the angle between the plane of the grating and the incident rays, α is the azimuthal angle of incidence relative to the groove direction, and β is the azimuthal angle of diffraction.[2] Off-plane grating resolution, although achieving R~100 in sounding rocket flights,[3,4] has been limited in part by the finite width of the diffraction grating and the difficulty of creating a collimated beam in an efficient x-ray telescope. The converging beam results in variations in α and γ prior to reflection that correspond to variations in β and γ after reflection and produce a broadened spot at the detector. This is not a problem in collimated beams where all photons arrive at the same angle, but collimation requires costly bounces off additional optics, reducing the effective area of the telescope and increasing alignment and manufacturing challenges.

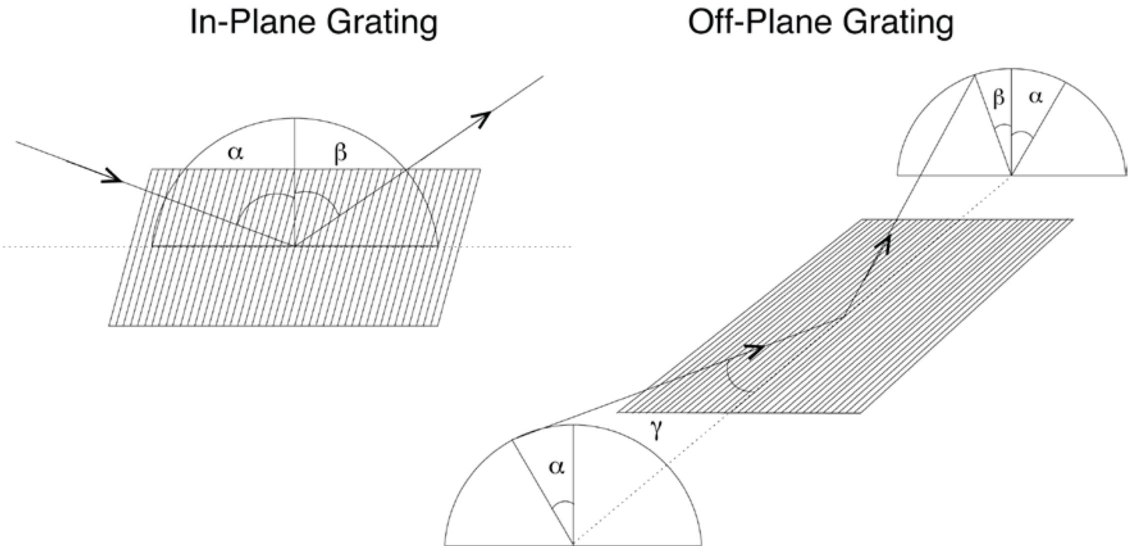

Figure 2: Comparison of the in-plane and off-plane geometries.[4] The radially-grooved grating discussed herein has grooves that converge toward the detector rather than the traditional parallel rulings depicted in this figure.

We present the preliminary results from tests of an off-plane diffraction grating while focusing on the test setup that will allow high resolution tests in the future. The grating is holographically-ruled with grooves that converge to match the converging beam of a 6.5 m focal length telescope, removing the blurring effect described above. Section 2 describes the experimental apparatus, including greater detail of the grating design and the optics used to test its resolution. Section 3 describes the (preliminary) test results and presents a discussion of the results and a roadmap for future tests.

2. EXPERIMENTAL APARATUS

In order to test the resolving power of the diffraction grating, an 18 m beamline comprising three chambers with 25 cm and 10 cm diameter connecting pipes was constructed at the University of Colorado (Figure 3). The chambers house a soft x-ray source at one end, focusing optics and a diffraction grating in the middle, and a microchannel plate detector at the far end. The vacuum pressure was maintained at ~7x10^{-8} atm at the x-ray source end and 3x10^{-9} atm at the detector end.

The "Manson Model 2 Mini-Focus Ultrasoft X-ray Source" (hereafter "the Manson source") was purchased from the J. E. Manson Co., Inc. (now Austin Instruments, Inc.). It is an electron impact source that generates x-rays by focusing an electron beam across a high voltage (6 keV, with a current of 0.8 mA) and onto an anode of a desired material (e.g., Ni, Al, Cu, Ti, etc.) to produce spectral lines. The beam is focused to produce a small spot on the anode that radiates isotropically from the surface into 2π steradians with a flux of ~10^{12} ph s^{-1} sr^{-1} in the soft x-ray bandpass. Photons produced by the Manson source travel through a Luxel Corp., polyimide filter (150 nm Al, 27 nm C, Ni mesh) to prevent visible and ultraviolet light from scattering down the beamline, and then travel 10.0 m of 25 cm pipe to the first optic.

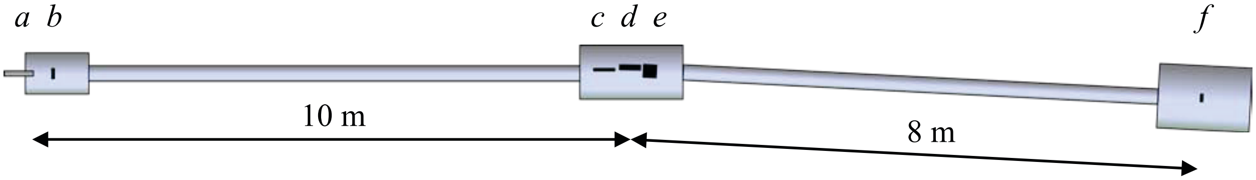

Figure 3: Bird's-eye schematic (not to scale) of the University of Colorado beamline. Photon travel is left to right, being generated at (*a*) the Manson source, passing though (*b*) the Al filter and to (*c, d*) the Kirkpatrick-Baez optics before being diffracted off (*e*) the grating; the Ranicon detector (*f*) lies a further 7.5 m from the detector. The deflection of the detector arm is ~3° from the source-optics line.

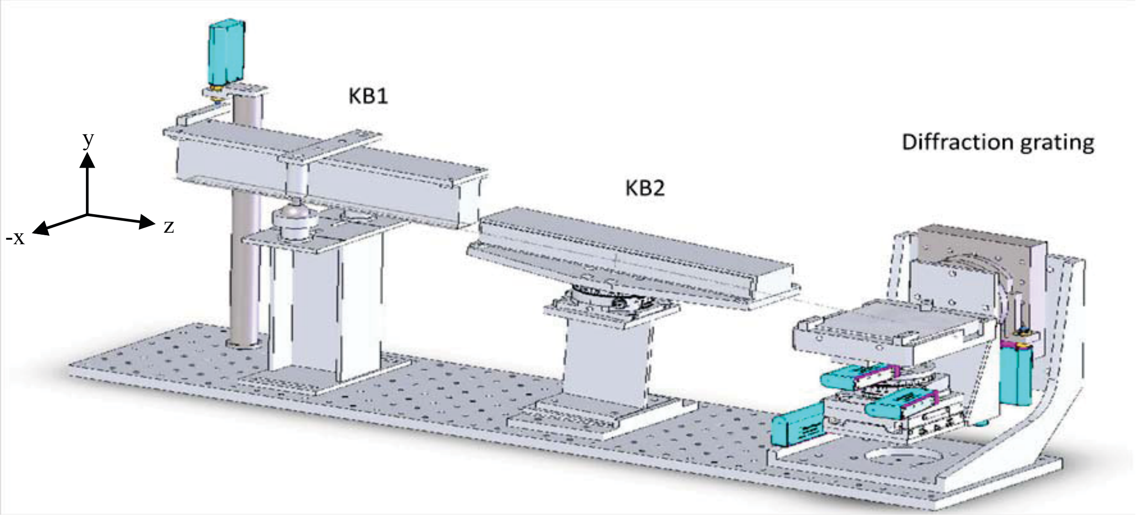

Figure 4: The Kirkpatrick-Baez optics (KB1 and KB2), the radially-grooved diffraction grating, and their mounting structures. Photons travel from left to right, with the Manson source 10 m to the left and the Ranicon detector 8 m to the right of the central optic. The mirrors are mounted on rotational stages with one small stepper motor each for focusing; the grating is mounted with five degrees of freedom (missing *z* translation) with motors to control all but *y* translation.

Two 30 cm x 2 cm sections of long-radius spheres (r~400 m) form a Kirkpatrick-Baez telescope with an 8.0 m focal length. The reflective surfaces are coated with tungsten and polished to 5 Å rms. The mirrors (denoted KB1 and KB2; Figure 4) sit orthogonally at grazing incidence of 1.5°- 2°, giving an effective area of ~1 cm^2. Taking *z* as the direction of travel of the photons and *x* to be horizontal, KB1 focuses the *y* dimension and KB2 focuses the *x* dimension. The center of KB2 lies 10.0 m from the Manson source and 8.0 m from the detector. (The ideal configuration would place KB2 equidistant between the source and the detector, but laboratory space constraints prevent this.) After the mirrors, the grating is mounted in the *xz*-plane. The mirrors were mounted to allow focusing only (1 degree of freedom each); the grating, a far more complex optic, was mounted with 5 degrees of freedom: pitch (*y* rotation), yaw (*x* rotation), roll (*z* rotation), and *x* and *y* translation.

The diffraction grating, manufactured by HORIBA Jobin-Yvon, was designed to compensate for blurring of the off-plane mount in the converging beam of a telescope (discussed in Section 1) by varying the groove density across the length of the grating. Although a radial etching would have been truest to the converging beam of a telescope, manufacturing constraints of the holographic etching process dictated that it more closely resemble a fleur-de-lis pattern. The sinusoidal grooves have a pseudo-blaze of ~10° and a groove density of ~4200 grooves mm^{-1} (varying across the length of the detector). Due to the narrow beam created by our Kirkpatrick-Baez optics, the 10 cm x 10 cm grating was illuminated only in a <1 cm x 10 cm swath.

A Quantar Ranicon microchannel plate detector (hereafter "the Ranicon") was placed ~7.5 m from the grating (8.0 m from the center of KB2). The Ranicon has a spatial resolution of ~60 μm. A focal length of 8.0 m and a throw distance of 7.5 m was chosen (rather than the 6.5 m focal length for which the grating was designed) because limitations in the Ranicon resolution place a more stringent limit on our observable resolution than any theoretical limit placed by the mirrors or the grating, so given the available equipment the longer throw allows us to measure a higher resolution.

Ray tracing (Figure 5) shows that, even in an 8 m focal length telescope rather than a 6.5 m, a resolution >5,000 is achievable with all optics manufactured and positioned ideally and with a (non-physical) geometric point of emission from the Manson source. Realistically, the Manson source does not generate a geometric point, the mirrors and motors are the detritus of experiments of bygone decades, and our detector has a much poorer resolution than the several micron pixels necessary to measure such high resolution from an 8 m throw. We are working to overcome the limitations of reality.

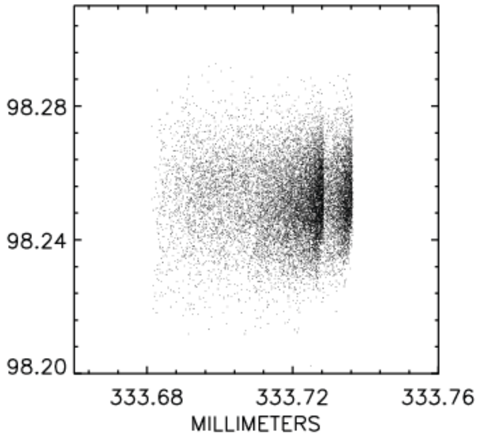

Figure 5: Ray trace of the grating test facility, assuming an optimal point source and a detector with infinitely small pixels. The two spectral lines are separated by one part in 5,000 (IXO science requirements mandate R > 3,000) at 13.3 Å (929.7 eV), the wavelength of first-order Cu Lα.

3. RESULTS AND DISCUSSION

3.1 Present Results

The best resolution achieved with this radially-grooved grating to date is ~50, well short of the IXO goal of 3,000. Ray tracing, even with a moderately large Manson source size (250 μm), indicates that we should be able to achieve a resolution >3,000 across the entire soft x-ray bandpass. However, the system has seven degrees of freedom, some of which are coupled (e.g., changing the graze angle of KB2 to focus changes the angle and the grooves illuminated on the grating), making focusing the system a seven-dimensional (mechanically, under vacuum) optimization problem. Worsening the already-daunting optimization, we do not have the ability to precisely measure positions of optics to determine if we are near the theoretically optimal positions and must rely on the detector images for feedback.

Tests of the beamline with a low-density grating with parallel grooves show that the system is capable of characterizing gratings out to high orders. Figure 7 shows such a spectrum from a Mg source with a 300 groove mm^{-1} grating (2° blaze, parallel grooves), comprising 3600 s exposures stitched together. The spectrum includes Mg (9.9 Å, 1,253 eV), O (23.6 Å, 525 eV) and C (44.7 Å, 277 eV). Figure 8 shows the actual detector image for a spectrum of the C K-line only (using a C anode) with the same grating.

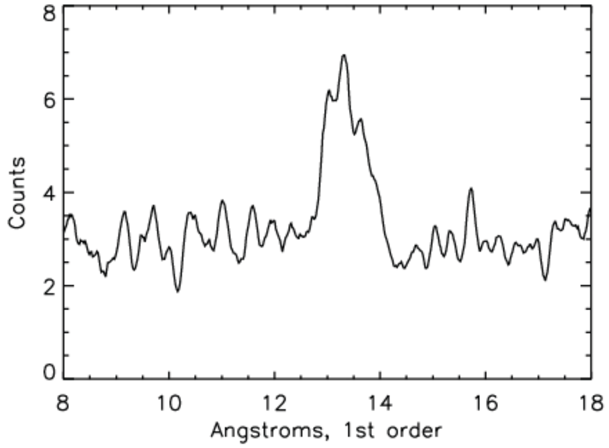

Figure 6: Copper Lα first-order (929.7 eV; 13.3 Å). The spectrum has been smoothed by a factor of 10 to reduce noise, and the *y*-axis quantifies relative count rates; all structure other than the main line is noise. The low-resolution spectrum is preliminary and not indicative of the potential of the grating or of the optics. Optimization of the source, optics, and detector will improve the resolution significantly.

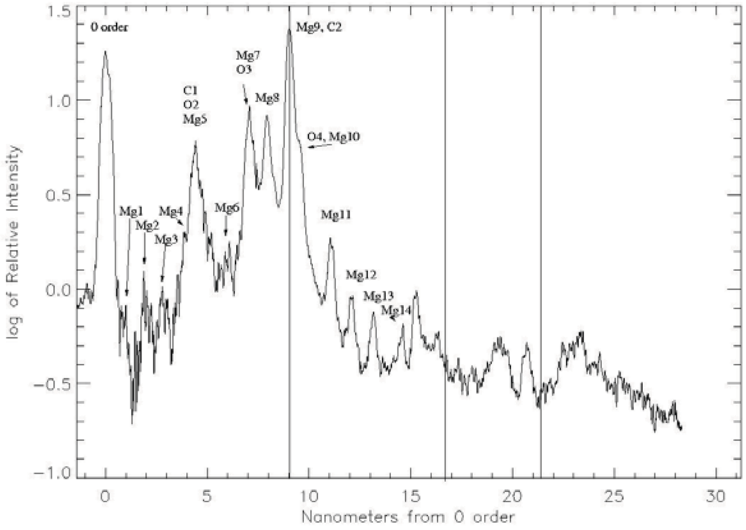

Figure 7: Spectrum of an Mg anode after diffraction by a 300 groove mm^{-1} off-plane grating in our test facility. The first 14 orders of Mg (9.9 Å), the first four orders of O (23.6 Å) and the first two orders of C (44.7 Å) orders are indicated. Vertical lines indicate where multiple images were stitched together, as the spectrum is larger than the Ranicon field of view. The *x*-axis is in nm from 0 order (non-diffracted) for a first-order line. Note the peak of the grating blaze in the 7-10 nm region.

3.2 Planned Improvements

There is no indication that our current results are limited either by the Kirkpatrick-Baez mirrors or by the diffraction grating. Our current results demonstrate limited equipment, namely the Manson source, the diameter of our vacuum system, and the Ranicon detector, which are all scheduled for improvements, as well as a need for better alignment techniques. The detector will be replaced with a high resolution (several μm pixels) and high quantum efficiency CCD, while the Manson spot size can be reduced (at the cost of many photons) with a pinhole. The narrow pipe of our vacuum system, with an interior diameter <100 mm that is fixed in position near the grating, also presents a practical limit to our results and limits our dispersion to ~20 Å in first order. Although monetarily and temporally expensive, changing the sizes of pipes, bellows, and flanges will be necessary to demonstrate grating characteristics at higher orders and at longer wavelengths.

Recent characterization of the system has shown that our limiting factor is, at present, the Manson source spot size. The image size produced by our optics at the focal plane defines a limit to our achievable resolution, and stopping down the Manson aperture has shown a commensurate decrease in the spot size at the detector. Our optics are imaging a ~250 μm spot, a factor of ~100 larger than what is desirable for our ultimate resolution tests and a factor of several larger than the resolution of our Ranicon MCP detector (thus requiring the new CCD). Adding a pinhole in front of the Manson source will fix this problem at the cost of most of our photons.

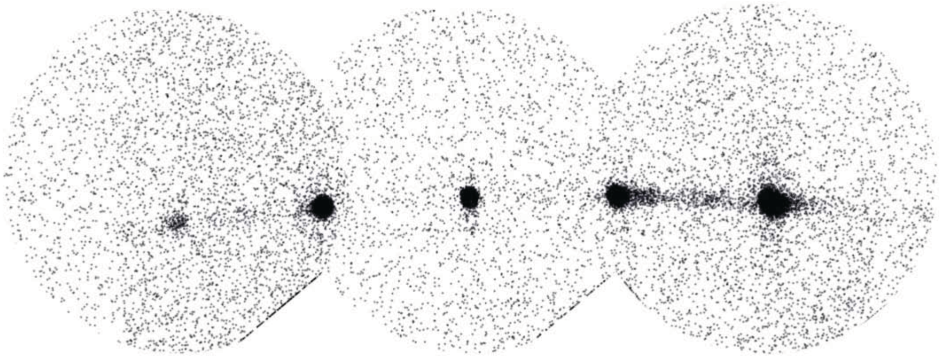

Figure 8: Three Ranicon images of the C K-line (44.7 Å) with a diffraction grating with 300 groove per millimeter parallel grooves. The central spot is the non-diffracted 0 order, with two orders on either side and a visible streak of continuum emission across the blaze of the grating (between first and second order). Exposure times for the three images vary.

3.3 IXO implementation

The grating being tested is a prototype for the X-ray Grating Spectrometer (XGS), a proposed soft x-ray (0.3-1.0 keV) spectrometer built around an array of off-plane gratings. The tested design will need to be modified to match the IXO focal length, but the purpose of the test is to verify that the radial etching removes the blurring discussed in Section 1. Since off-plane gratings at grazing incidence have small cross-sectional areas to incident photons, achieving the 1000 cm^2 of effective area required for the soft x-ray spectrometer on IXO requires multiple arrays of grazing-incidence gratings. Arrays of off-plane gratings already have been shown to be robust to the harsh launch conditions of sounding rockets.[3,4]

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