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Pushing the Boundaries of X-ray Grating Spectroscopy in a Suborbital Rocket

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ABSTRACT

The Off-Plane Grating Rocket Experiment (OGRE) will greatly advance the current capabilities of soft X-ray grating spectroscopy and provide an important technological bridge towards future X-ray observatories. The OGRE sounding rocket will fly an innovative X-ray spectrograph operating at resolving powers of R ~ 2000 and effective areas > 100 cm^2 in the 0.2–1.5 keV bandpass. This represents a factor of two improvement in spectral resolution over currently operating instruments. OGRE will observe the astrophysical X-ray calibration source Capella, which has a line-dominated spectrum and will showcase the full capabilities of the OGRE spectrograph. We outline the mission design for OGRE and provide detailed overviews of relevant technologies to be integrated into the payload, including slumped glass mirrors, blazed reflection gratings customized for the off-plane mount, and electron-multiplying CCDs (EM-CCDs). The OGRE mission will bring these components to a high technology readiness level, paving the way for the use of such a spectrograph on future X-ray observatories or Explorer-class missions.

Keywords: X-ray grating spectrometer, dispersive spectroscopy, off-plane mount, suborbital rocket

1. IMPORTANCE OF HIGH RESOLUTION X-RAY SPECTROSCOPY

A high resolution X-ray spectrometer is an essential component of any future X-ray mission. Astrophysically abundant metals, such as O, Ne, Mg, Fe, Si, etc., have the majority of their emission and absorption lines in the 0.3 - 2.0 keV range. Measuring spectra in this bandpass provides astronomers with a wealth of diagnostics that can be used to characterize astrophysical plasmas and the velocity structures of energetic phenomena. Moreover, some of the principal science goals outlined by the 2010 Decadal Survey in Astrophysics, such as measuring the absorption caused by the "hot" phase of the Warm-Hot Intergalactic Medium (WHIM) along AGN sightlines, can only be addressed by high resolution soft X-ray spectra. However, current instrumentation is not capable of achieving the resolutions required to meet the science goals outlined by the astronomical community.

The Off-Plane Grating Rocket Experiment (OGRE) represents an important step towards realizing the spectral performance requirements of a future X-ray observatory in an easily scalable, cost-efficient means. OGRE will utilize an off-plane X-ray grating spectrometer similar to the instrument studied for the *International X-ray Observatory* (*IXO*) and baselined for the Notional-X-ray Grating Spectrometer (N-XGS) and the *Warm-Hot Intergalactic Medium Explorer* (*WHIMex*), which was to achieve resolving powers of R ~ 3000 and an effective area of ≥ 1000 cm^2 over the 0.3 -2.0 keV energy range (McEntaffer et al. 2011; Bautz et al. 2012). OGRE's performance leverages heavily from recent developments in the critical technologies of X-ray reflection gratings, slumped glass optics, and CCDs. A sounding rocket payload with these components offers an opportunity to flight-prove these advancements for minimal cost. Additionally, both the effective area and resolving power of OGRE are limited by payload size. Thus, spectrometer

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performance can be easily boosted if scaled to an Explorer-class or flagship mission. OGRE offers a means to push the boundaries of soft X-ray spectroscopy in a performance-driven, cost-effective mission, strengthening the proposal for a future X-ray observatory.

2. MISSION OVERVIEW

A CAD rendering of the OGRE payload is shown in Figure 1, while Table 1 summarizes the instrument characteristics and performance capabilities of the OGRE spectrometer. OGRE will be flown on a Black Brant IX sounding rocket at White Sands Missile Range (WSMR) and is slated for launch in early 2017. The experiment section will be housed in a 22” diameter rocket skin and has a focal length of 3.0 m. This payload length is the longest possible without compromising vehicle flight stability. The pointing of the rocket will be handled by a NASA-provided Celestial Attitude Control System (CACS) with a linear thrust configuration. The linear CACS should provide an absolute pointing accuracy of 2 arcseconds with a jitter of ≤ 1 arcsecond. An event list of the observed X-ray photons will be transmitted in real time using a NASA-provided telemetry interface. In addition, the data will be stored onboard in a flight computer to increase the chances of a successful observation. Recovery of the experiment payload following launch is anticipated.

OGRE will observe the stellar binary system Capella. Capella consists of two giant stars with active coronae. The plasma in these coronae ranges from 10^6 - 10^7 K so that highly ionized elements are present. Line emission processes dominate the flux from Capella, making it an ideal science target for demonstrating the capabilities of a next-generation spectrometer. In addition, the relative proximity of the system (~ 13 pc) makes Capella one of the brightest X-ray point sources in the sky. Brightness of the target is an important criterion for a sounding rocket flight, as observing time is limited compared to a dedicated observatory. Based on the performance characteristics of the Black Brant vehicle and results from previous missions, the total observing time is expected to be ~ 300 seconds. Previous measurements of Capella indicate that the OGRE spectrometer will observe a count rate of about ~ 15 counts/second in the bandpass of interest, resulting a total of ~ 4500 counts from an emission line source.

3. SPECTROMETER DESIGN

3.1 Off-Plane Grating Spectrometers

The Off-Plane X-ray Grating Spectrometer (OP-XGS) concept has been described in detail in several previous works (see, for example, McEntaffer et al. 2013). To summarize, the OP-XGS is a dispersive spectrometer consisting of three key components: focusing optics, an array of reflective gratings in the off-plane mount and an imaging detector located at the focal plane. The focusing optic serves to form a converging beam which focuses light at the focal plane of the

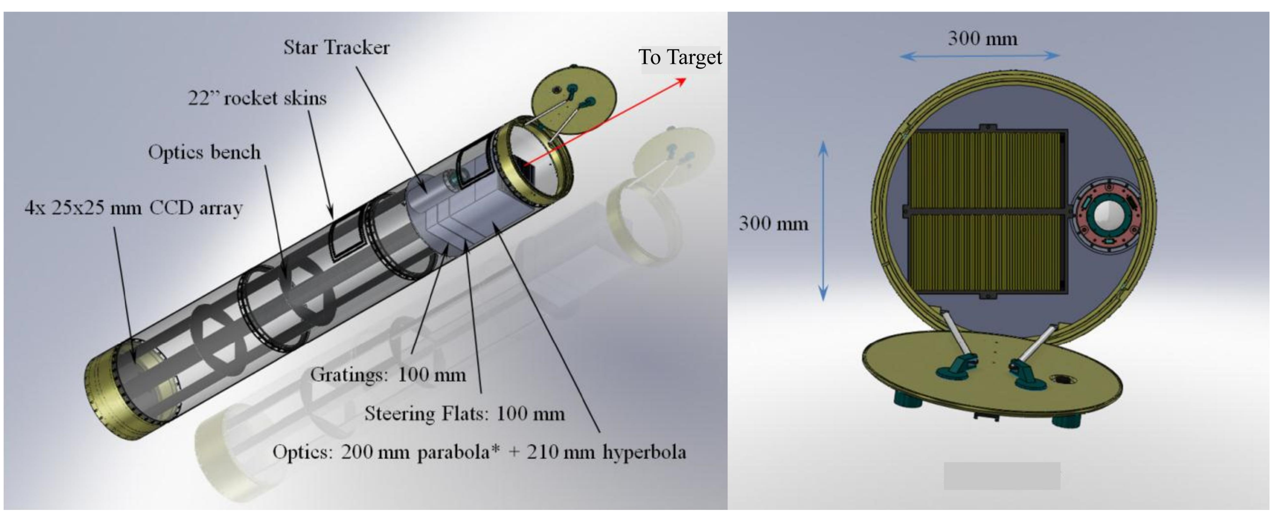

Figure 1: *Left* – A CAD model of the OGRE payload showing both the exterior rocket skins and interior instrument components. *Right* – A glance down the payload along the optical axis. The two optics modules housing the paraboloidal/hyperboloidal mirrors, steering flats and gratings are seen at 9 o’clock, while the star tracker aiding in the pointing of the instrument is seen at 3 o’clock.

Table 1 Parameters for the OGRE Instrument		
Instrument Component	Parameter	Value
Payload	Bandpass	0.2 - 1.5 keV
	Resolution ($\lambda/\Delta\lambda$)	$>$ 1000 across bandpass, $>$ 2000 @ select energies
	Effective Area	$>$ 100 cm^2 from 0.3 - 1.0 keV
	Optical Path Length	3 m
	Payload Diameter	22 in.
	Observing Time	$\sim$ 300 sec.
	Pointing Accuracy	2 arcsec.
	Jitter (rms)	1 arcsec.
Focusing Optics	Module Length	0.8 m
	Average P/H Graze	1.5°
	Average Flats Graze	1.2°
	Focus Quality	Slumped Glass $<$ 3 arcsec Single-Crystal Si $<$ 1 arcsec
Gratings	Format Size	100 mm $\times$ 100 mm
	Graze Angle	2.5°
	Blaze Angle	$\sim$ 28°
	Groove Density	$\geq$ 6000 gr/mm
Detectors	Active Area	25 mm $\times$ 100 mm
	Array Elements	e2v 207-40 EM-CCDs
	Pixel Size	13.5 μm

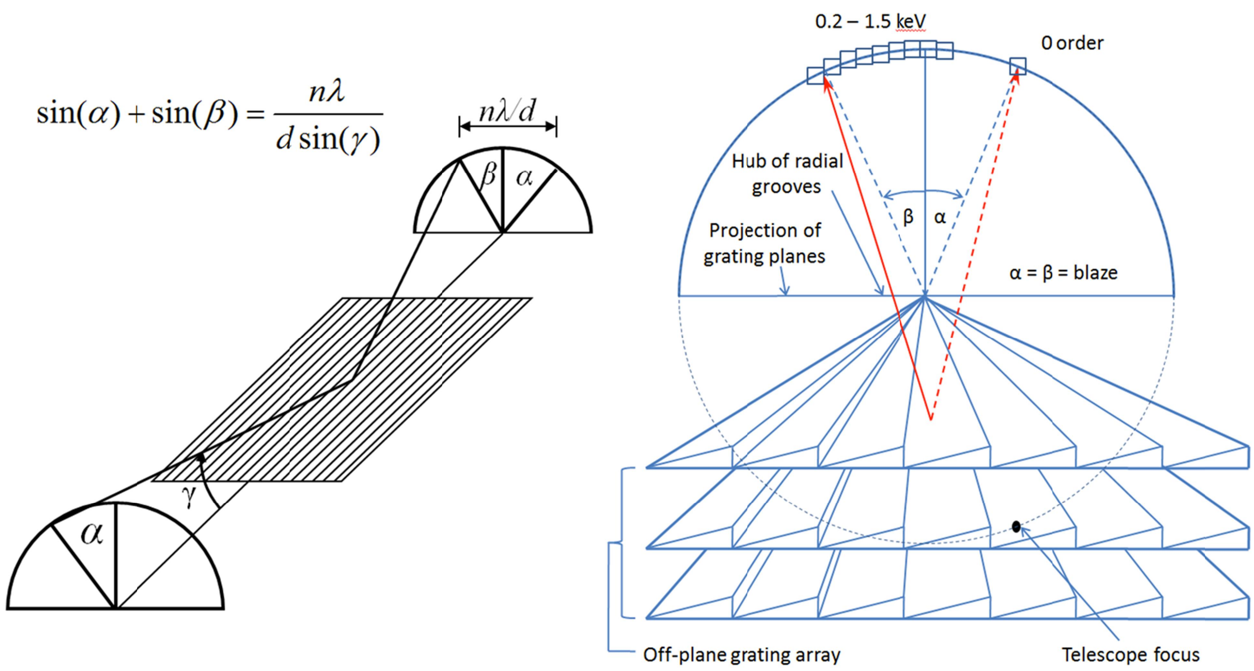

Figure 2: *Left* – A simple sketch of the off-plane geometry and the created diffraction arc. The incidence angle γ, the groove density *d*, the wavelength of light λ, and the angle between the incident beam and grating normal α determines the position of the diffracted order *n* at an angle β from the grating normal. *Right* – Diagram showing the orientation of the diffraction arc relative to the grating array. This shows the spectrometer operating in the Littrow configuration in which α = β = θ, where θ is the blaze angle. This configuration maximizes diffraction efficiency for the off-plane mount.

instrument. The converging beam is intercepted by an array of reflective gratings, positioned along the focal axis and oriented such that the grating grooves are quasi-parallel to the beam direction. When mounted in this fashion, the gratings disperse light out of the plane of incidence (hence, the "off-plane" mount) into a diffraction arc. This arc is then imaged with detectors located at the focal plane, allowing the reconstruction of a source spectrum. A sketch of the off-plane geometry is shown in Figure 2.

The geometry of the off-plane mount offers several distinct advantages over traditional in-plane spectrometers in the context of an astronomical observatory. For one, an in-plane spectrometer suffers a drop in efficiency due to groove shadowing at grazing incidence, whereas for an off-plane spectrometer, the grooves are fully illuminated when aligned to the focal axis. Additionally, an off-plane spectrometer does not suffer from vignetting at high order. The resolving power of a grating spectrometer increases when working at higher order, scaling linearly with n, the order number. Stacking gratings at grazing incidence to form an array can result in vignetting for gratings in the in-plane mount, since higher orders are dispersed upwards into the grating above. The off-plane mount, however, disperses high orders further out of the plane of incidence where there is no impediment along the optical path. Finally, off-plane gratings can achieve comparable effective areas with only one set of dedicated detector arrays by creating a grating with a blazed groove profile. The blazed profile preferentially diffracts X-rays in a given direction, meaning that detectors are only needed along a portion of the arc. Limiting the detector size can result in significant mass and cost savings for observatories without sacrificing effective area.

OGRE will benefit from the significant heritage of off-plane spectrometers and sounding rockets. Off-plane spectrometers have been employed in previous rocket payloads including CyXESS (McEntaffer et al. 2008), EXOS (Oakley et al. 2011), CODEX (Zeiger et al. 2013) and the forthcoming OGRESS payload slated for launch in Summer 2014. These previous experiences have laid the foundation for OGRE, an entirely new payload capable of achieving groundbreaking performance in soft X-ray spectroscopy. The OGRE spectrometer will be constructed with focusing optics, gratings and detectors representing the cutting-edge of soft X-ray hardware. When finished, the instrument will be the most advanced soft X-ray reflection grating spectrometer flown to date. OGRE will make use of mirrors made from either slumped glass or single-crystal silicon, an array of blazed, high groove density gratings fabricated at the University of Iowa, and an array of EM-CCDs for an improved signal-to-noise ratio (S/N). Each of these hardware components are described in detail in the following sections.

3.2 Focusing Optics

Two different optical designs are being considered for the OGRE focusing optics: 1) a cost-effective assembly with mirrors made of thermally slumped glass or 2) a full Wolter type-I telescope with mirrors made from precision cut single-crystal silicon. Slumped glass optics were initially proposed for OGRE, as these optics have a well-defined fabrication process, are cost-effective and offer adequate focusing power to meet the OGRE performance goals. On the other hand, fabricating mirrors with precision cut single-crystal silicon offers the opportunity to fly a full Wolter type-I telescope, realize improved focus possibilities, and flight-prove a new technology for use in future X-ray missions. However, the fabrication process for single-crystal silicon mirrors is not as well developed as that of thermally slumped optics, and thus may be time and cost prohibitive. A final design decision for the OGRE optics will be made sometime in Fall 2013; for completeness, an overview of both possibilities is presented here.

Segmented slumped glass optics have been studied extensively for the *Nuclear Spectroscopic Telescope Array* (*NuSTAR*) mission (Harrison et al. 2013, and references therein) and during concept studies for the *International X-ray Observatory* (*IXO*). These optics are also baselined for a number of proposed future X-ray observatories given their low cost and relative ease of fabrication. The mirror substrate is a thin sheet of float glass which is balanced over a precision ground mandrel of the desired shape. The glass is then thermally slumped over the mandrel in a slow bake process, allowing it to conform to the underlying shape of the mandrel. After cooling, the glass segment is removed and coated with a reflective material such as Au or Ir. The mandrel is then available for reuse. The slumped glass fabrication process makes the mass-production of identical optical segments for large assemblies both easy and cost-effective once the mandrels have been manufactured.

The proposed slumped glass optical assembly is distinct from a traditional Wolter type-I telescope. Using slumped glass technology to make a Wolter type-I telescope would require many mandrels to produce the requisite nested shells of paraboloid/hyperboloid pairs, for each mirror shell has a distinct radius of curvature requiring a separate mandrel. As the initial procurement of the mandrels is the most time-intensive and expensive aspect of the slumped glass fabrication process, smaller missions can realize a significant cost-savings via an instrument design that uses as few mandrels as possible. In keeping with this principle, the slumped glass optics for OGRE will be fabricated using a single paraboloidal/hyperboloidal mandrel pair. The design choice to use a single mandrel must be offset by the incorporation of a third steering optic along the focal path. As all OGRE mirrors will possess the same radius of curvature, each paraboloidal/hyperboloidal pair will have a unique focus when aligned to the same grazing incidence angle. The distinct foci will be merged by an assembly of grazing incidence steering flats to form a single focus at the focal plane. The same design was studied for the *WHIMex* concept mission (Cash et al. 2011). Such an optical design allows the construction of a telescope with a large collecting area and a single focus in a cost-effective manner.

The implementation of the aforementioned design on OGRE would involve two separate but identical optics modules containing slumped glass mirrors. The OGRE optics modules house all of the elements along the spectrometer focal path – i.e., the modules will contain the paraboloidal/hyperboloidal mirrors, the steering flats and the dispersive gratings (Figure 3). Containing both the focusing and dispersive elements within a single module eases the process of co-alignment. In a similar fashion, the process of aligning the optics to the detectors will be aided by cantilevering the optics modules off of the detector bulkhead. This serves to ensure that all the spectrometer elements are held fixed relative to one another. The slumped glass mirrors housed in the optics modules are 30° azimuthal sections of full Wolter

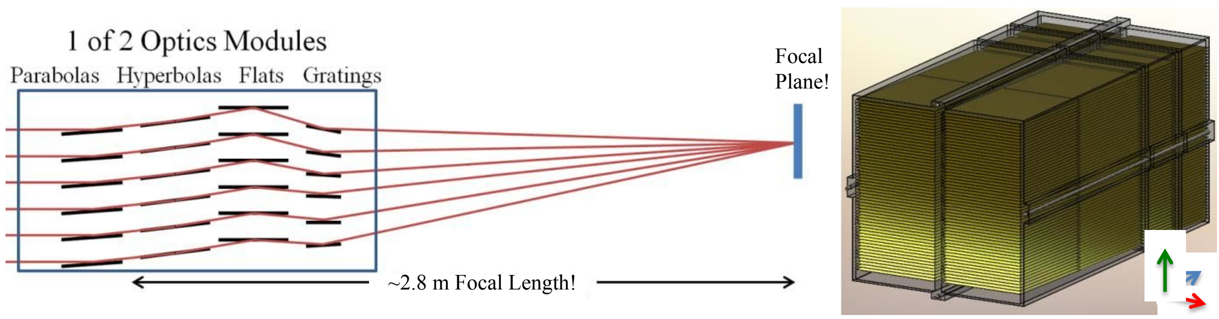

Figure 3: *Left* – A cartoon of the OGRE optical path. In this drawing, the dispersion direction is out of the page. *Right* – A CAD rendering of the OGRE optics module containing slumped glass mirrors, steering flats and dispersive gratings. The orientation vectors in the lower right corner show the dispersion direction (red), module height (green) and length along the focal axis (blue).

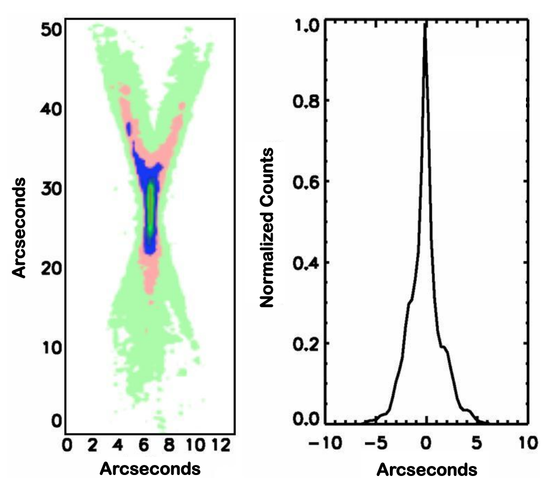

Figure 4: Image (left) and power distribution (right) from a 30° azimuthal segment of a single slumped glass paraboloid/hyperboloid mirror pair. The signature "bowtie" focus of a limited azimuthal span can clearly be seen in the image, while the right shows the slumped glass optics are capable of achieving a 1.4'' FWHM in the dispersion direction.

type-I shells. The Wolter type-I paraboloid and hyperboloid are parameterized by a radius of curvature R_0 of 290 mm, focal length Z_0 of 2787.5 mm, and average graze angle $\alpha \sim 1.5°$. The optics modules measure 150 mm in the dispersion direction, 300 mm in height, and ~800 mm long. The module height and paraboloid/hyperboloid dimensions allow for the placement of ~55 mirror pairs per module, yielding a total geometric collecting area of 415 cm^2.

In limiting the azimuthal span of the mirror to 30° rather than employing a full shell, the resolution capability of the OGRE spectrograph is significantly increased. This is a consequence of anisotropic scattering off of the mirror surface. A full shell of mirrors creates a circularly symmetric point spread function (PSF). The circularly symmetric distribution of photons means that the half-power diameter (HPD), or the angular diameter required to encircle half of the incoming flux, is an unambiguous measure of the focus quality of an optic. However, scattering off of an optical surface preferentially occurs in the plane of the incoming light. Therefore, when a limited azimuthal span of a shell is used to focus light, the point spread function is not circularly symmetric but instead has a signature "bowtie" shape (Figure 4; Cash 1987). If the thin dimension of the bowtie is oriented so as to coincide with the dispersion direction, a reduction in line width, and hence an increase in spectral resolving power, can be achieved. Given the current performance of mirror modules populated with slumped glass optics (Zhang et al. 2012) and the described subaperture effect, we anticipate that a telescope focus of < 3 arcseconds in the dispersion direction can be achieved with this design.

Another option for the OGRE focusing optics would be to build a full Wolter type-I telescope using precision-cut, single crystal silicon mirrors. The primary advantage of using monocrystalline silicon to fabricate optics is that it is free of internal stresses. The lack of internal stresses makes the substrate less susceptible to distortion during the fabrication process, resulting in a better quality mirror. This method of mirror fabrication also reaps substantial benefits from the semiconductor industry. In the past few decades, large bricks of monocrystalline silicon have become commercially available and economical to buy in the quantities required for telescope fabrication. In addition, precision polishing techniques have become both cheaper and capable of achieving better figure qualities. These advances mean that much of the technology development required for making single-crystal silicon mirrors is already in-hand.

The fabrication process for a thin, monocrystalline silicon mirror (Figure 5) begins with a block of cut silicon which has been chemically etched to remove any surface damage. Next, the desired optical shape is cut and the surface polished with a commercially available polishing technique. The mirror figure can be tested and qualified at this point, allowing for the possibility of an iterative process to improve the mirror's focusing power over several polishing cycles. When the required figure is achieved, the optical surface is removed by slicing a thin face-sheet from the silicon block. This eliminates the excess silicon and serves to lightweight the mirrors. However, the cutting process creates surface damage on the back (convex) side of the mirror, which imposes new stress and distorts the thin mirror's figure. A chemical etch and/or annealing can remove this surface/subsurface damage and should restore the original figure, as it is again one monolithic crystal free of any internal stresses. The lack of internal stress and the quality of precision polishing techniques may make large, lightweight X-ray telescopes with ≤ 1 arcsecond spatial resolutions feasible within the coming decade.

To use single-crystal silicon mirrors for the OGRE telescope would be truly groundbreaking, as it would be the first mission to fly mirrors manufactured using this technique. However, this fabrication technique is still in the development stages. Hence, it may prove to be time-prohibitive to manufacture a full assembly of mirrors on the OGRE launch

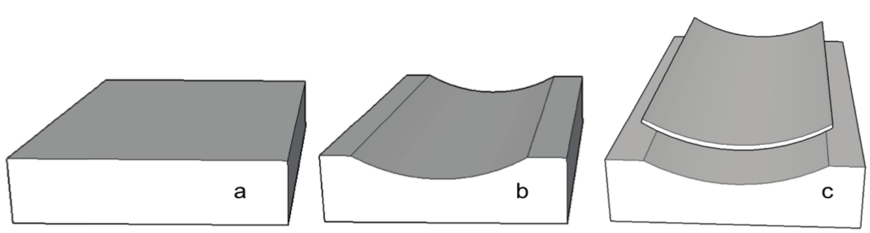

Figure 5: A diagram depicting the fabrication of a single-crystal silicon mirror substrate. First, a block of monocrystalline silicon is cut and chemically etched so as to remove all stress from the cutting process (a). Next, the desired mirror shape is cut, etched to remove damage and polished to achieve the mirror's optical surface (b). Finally, a thin segment containing the optical surface is sliced from the block and the convex side etched to restore the original figure quality (c).

timeline. It is also unclear whether the single-crystal silicon mirrors could be fabricated within the original optics budget. Zhang et al. 2013 report on the ongoing development, recent fabrication milestones and anticipated progress of monocrystalline silicon mirrors. We anticipate making a downselect between the two telescope design options considered here by the end of 2013.

3.3 Gratings for the Off-Plane Mount

The OGRE spectrometer will also require high groove density X-ray reflection gratings specialized for the off-plane mount. Similar to variable line spacings for in-plane diffraction gratings, the geometrical considerations of the off-plane mount requires an adaptation to a simple periodic groove pattern in order to achieve high resolving powers. This adaption is a radial "fanning" of the grooves to match the convergence of the incident beam (Cash 1983). To see the need for a radially ruled groove pattern, consider a grating placed in a converging beam. The relative angle between the grooves and the incident X-rays will vary over the face of the grating for a parallel groove pattern. This relative angle (α in Figure 2) enters into the grating equation, such that the variation in this relative angle would result in an aberration in the diffracted spot. However, if the grating is radially ruled, the relative angle between the X-rays and the grooves is constant over the grating face, allowing for optimal resolution.

The OGRE gratings will also have blazed groove profiles to improve diffraction efficiency. A laminar groove profile disperses light to positive and negative orders equally. By sculpting the groove profile to be triangular, a process known as blazing, the grating will preferentially disperse light to one side of zero order. This phenomenon can be exploited to increase the total efficiency per detector area for a single detector array. The blaze angle can be customized to optimize diffraction efficiency in a given bandpass, increasing a spectrometer's effective area near particular spectral lines of interest. Finally, blazed gratings have the additional benefit of putting more photons into higher orders, which increases the spectral resolving power of an instrument.

In addition to these custom features, the OGRE array of off-plane gratings must also have high groove densities (~6000 gr/mm) to optimize spectral resolution, and be replicated over large (100 mm x 100 mm) formats to achieve reasonable collecting areas. A procedure for fabricating such gratings has been proposed and is currently under study at the University of Iowa. The fabrication process combines several microfabrication techniques, namely electron-beam writing, projection photolithography, nanoimprint lithography and an anisotropic chemical etch, to produce a silicon grating substrate with the required characteristics. First, a grating "master" with a laminar, high-density, radially ruled groove pattern must be produced. LightSmyth Technologies has developed a technique to produce grating masters meeting these requirements and has fabricated several dozen masters over small formats (25 mm x 32 mm) for use in grating development studies (McEntaffer et al. 2013). To make the master, an electron-beam writing tool is first used to manufacture a photomask at 4x the scale of the grating. Reduction projection lithography is then used to pattern photoresist which has been spin-coated onto a single-crystal silicon wafer. A reactive ion etch (RIE) is then used to transfer the pattern into the silicon substrate and produce the grating master. This process is capable of achieving a feature size of 0.25 nm and is a high density (up 7200 gr/mm), high fidelity step-wise approximation to a radially ruled groove pattern. However, the master grating has a laminar, not blazed, groove profile.

The mass-production of identical flight gratings with blazed facets can be achieved through subsequent replication of the grating master and chemical post-processing techniques. Figure 6 provides a step-by-step summary of the replication process. First, a layer of nitride is placed onto an off-axis cut silicon wafer through chemical vapor deposition. This is followed by a layer of nanoimprint resist which is spin-coated atop the nitride (1). Nanoimprint lithography (NIL) is then employed to transfer the radially ruled groove pattern of the master grating into the resist layer (2). An RIE deepens the groove troughs, etching through the residual resist and nitride layer to the silicon substrate (3). Following a rinse in acetone to remove the remaining resist, the substrate surface is left with strips of nitride matching the master groove pattern (4). These nitride strips will serve as a mask for the next steps, in which a chemical wet etch is employed to produce blazed groove facets (5). A potassium hydroxide (KOH) wet etch on a crystal of pure silicon will preferentially etch along the (111) crystallographic plane, removing the substrate material down to this plane. If the silicon wafer is cut off-axis such that the (111) plane is oriented at the desired blaze angle relative to the wafer normal, a KOH wet etch will blaze groove facets where bare silicon is exposed between the nitride strips. Thus, the nitride mask ensures that the original groove density and radial pattern is replicated on the silicon substrate while the KOH etch serves to sculpt an atomically smooth, blazed groove profile. This technique of using a nitride mask and a KOH wet etch has been previously used to produce blazed gratings (Chang et al. 2003). The nitride strips are then removed with a hydrogen

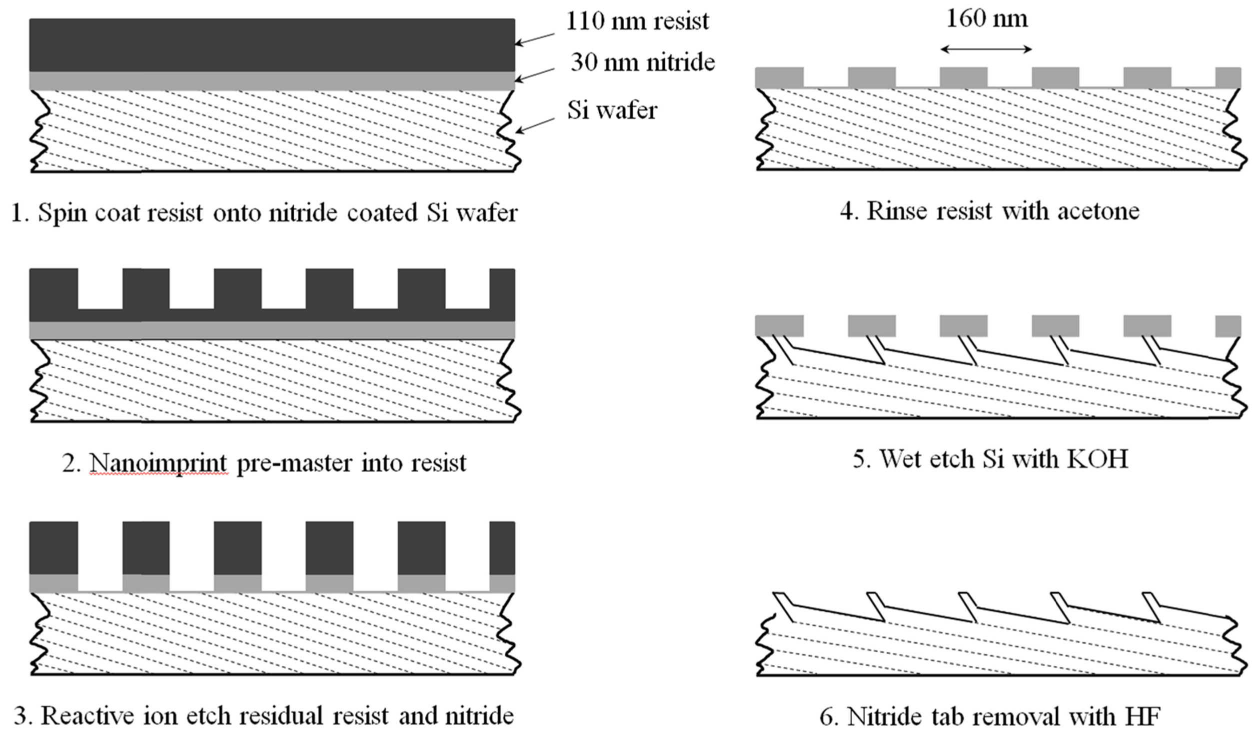

Figure 6: An illustration of the replication process to produce blazed flight gratings.

fluoride (HF) rinse (6). Lastly, the silicon substrate will be coated with an X-ray reflective material, such as gold or iridium, to produce the flight grating. This described process will be used to produce the ~ 100 gratings required for the OGRE spectrometer. Trade studies to refine the fabrication recipe are currently ongoing, and the acquisition of a NIL tool in Fall 2013 will permit the production of prototype gratings within the coming year.

The OGRE gratings will be housed in the same optics module as the focusing optics and will be aligned to a constant graze angle of 2.5°. The distance between the point of incidence on the grating and the focal plane, known as the throw, should be maximized for high dispersion. Packing the optics tightly along the OGRE focal axis results in a throw of approximately 2.3 m. The required tolerances for the alignment of the OGRE gratings have been calculated and are achievable using techniques of moderate precision, such as a monolithic grating mount or manipulation with picomotor actuators (Allured et al. 2013).

3.4 Detectors

CCDs have considerable heritage in X-ray instrumentation and are already commonly flown as detectors for imaging spectroscopy missions. However, OGRE has several science-driven requirements that complicate the design of the CCD camera system. For one, the OGRE spectrometer must maintain high efficiencies near the soft energy cutoff (~ 0.2 keV) in order to achieve effective areas of > 100 cm^2 over the bandpass of interest. Secondly, the detectors must possess a native energy resolution of better than 0.2 keV FWHM in order to separate spatially overlapping orders and correctly reconstruct the source spectrum. The CCDs also must have pixels small enough to resolve features within the diffraction arc. As a photon's spatial position has a one-to-one correspondence in wavelength space for a given order, the CCD pixel size places a limiting threshold on the spectral bin size of the spectrometer. The pixel size requirement for the OGRE camera is somewhat relaxed, however, as the optical FWHM of the diffracted spot is anticipated to be roughly ~ 45 μm in size (3 arcseconds at 3 meters), whereas a typical pixel size for the CCDs being considered is 10 – 15 μm. Lastly, the camera system must cover a large effective area in a cost-effective manner. The low energy cutoff of an off-plane spectrometer is determined by the horizontal extent of the CCD array relative to the zero order. Given a specific dispersion, this requires an array of a certain horizontal width to cover the bandpass of interest. Furthermore, increasing the dispersion of the spectrometer spreads the same wavelength range out over a greater spatial extent. Hence, higher dispersion (which yields better spectrometer resolution) comes either at the cost of a larger detector array or the loss of photons at low energies. As additional CCDs increases overall cost, the design of the OGRE camera system must balance the science goals of high resolution and a 0.2 keV low energy cut-off with budgetary constraints.

To meet all these requirements, OGRE will employ a camera system consisting of an array of four back-illuminated EM-CCDs to image the diffraction arc at the focal plane. The use of EM-CCDs will further improve detector efficiency at low energies. EM-CCDs differ from traditional CCDs in that the signal passes through an electron multiplication register before chip readout, which serves to amplify the input signal. As amplification occurs before the charge is output, readout noise is suppressed, and the overall signal-to-noise (S/N) ratio of the device is improved. The improvement in S/N greatly increases the detectability of low energy photons, thus helping to maintain high effective areas near the soft energy cut-off. The level of gain applied to the signal will be dictated by the native energy resolution requirement of < 0.2 keV. Tutt et al. 2011 show that operating EM-CCDs with significant gain degrades the native energy resolution of the CCD and can interfere with order separation. However, by operating the EM-CCDs with modest gain levels, the OGRE camera should satisfy the requirement of preserving a native energy resolution of < 0.2 keV while benefitting from an increased S/N.

The camera design baselined for OGRE assumes the use of two slumped glass optics modules and places an array of detectors along the diffraction arc. Figure 7 shows the focal plane layout of the diffraction arc and the nominal position of the EM-CCDs in the detector array. The extent of the detector array permits the detection of both diffracted orders and the zero order spots from both modules simultaneously, which is required for spectral calibration. As each optics module creates a distinct arc of diffraction, capturing the spectra with a single set of CCDs requires blazing the gratings in opposite directions. This serves to disperse the spectra in opposing directions, placing low orders from one module on the same chip as high orders from the other. A small vertical offset (~10 mm) between the modules ensures that there is no overlap between the two separate diffraction arcs while keeping both on the detector array. This focal plane layout is similar to the proposed *WHIMex* mission and maximizes the resolving power of an off-plane spectrometer with two distinct optics modules. Dispersing the spectra in opposing directions also provides a beneficial redundancy in that, should one EM-CCD fail in flight, the remaining detectors are still sufficient to sample the full bandpass of interest. The CCDs baselined for the OGRE camera are e2v 207-40 EM-CCDs, which measure 25 x 25 mm and have a pixel size of 13.5 µm. The camera system, including the CCD array and interface electronics, will be built and integrated into a flight housing by XCAM Ltd.

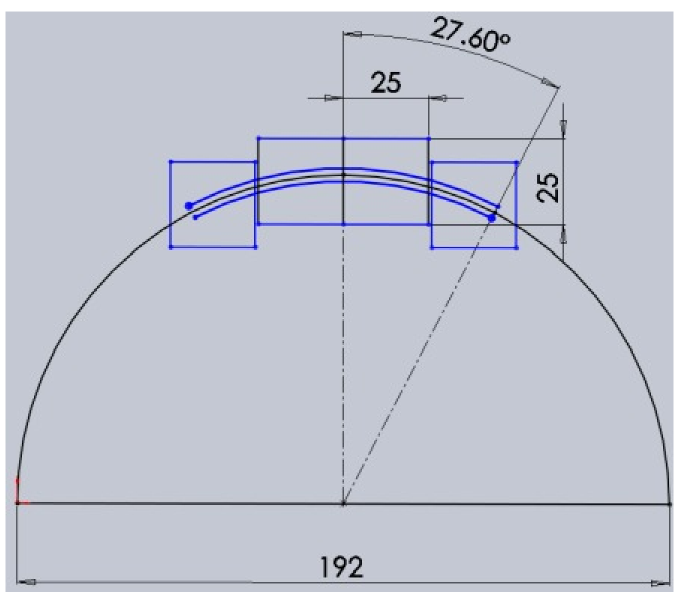

Figure 7: Layout of the OGRE spectrometer focal plane. Blue squares mark the position of the CCDs while the inner blue curves designate the position of the diffraction arcs from the optics modules. All measurements are given in millimeters.

4. PERFORMANCE AND TIMELINE

Both the expected effective area and resolving power for the OGRE spectrometer have been calculated and are plotted in Figure 8. The effective area curve begins with the geometric collecting area and accounts for the reflection efficiency of the gold coated paraboloidal/hyperboloidal mirror pairs, grazing incidence flats, the absolute (i.e. reflectivity included) diffraction efficiency of the gratings and the quantum efficiency of the e2v 207-40 EM-CCDs with an optical blocking filter. Contributions from both optics modules are summed to arrive at the plotted effective area curve. This calculation shows that OGRE will easily meet the science requirement of > 100 cm^2 for the 0.3 – 1.0 keV energy range and possess moderate effective areas down to the low energy cutoff of the instrument. As for resolving power, the right panel of Figure 8 shows that the OGRE spectrometer will possess resolutions of R > 1000 across the 0.3 –1.0 keV energy range and have peak resolutions of R > 2000 at 58 Å (~0.2 keV) in 1st order, 29 Å (~0.4 keV) in 2nd order, and 14.5 Å (~0.6 keV) in 3rd order.

As for mission timeline, the optical and mechanical design of the OGRE spectrometer is currently being finalized. We anticipate selecting a manufacturing technique for the OGRE focusing optics in Fall 2013. Trade studies to refine the process of blazed grating fabrication will commence before the end of 2013, while an investigation of the electronics interface for the OGRE camera will begin in early 2014. The next period of our program, Fall 2014 – Spring 2016, is dedicated to the procurement and manufacture of the focusing optics, gratings, and camera system. Integration and performance testing will follow the assembly in Summer 2016, with payload qualification and flight anticipated in Spring 2017.

5. CONCLUSION

The OGRE mission represents a key stepping stone toward to future X-ray observatories with high resolution spectrometers. The cutting-edge OGRE spectrometer will make use of advancements in the fabrication and alignment of focusing optics, a new technique to manufacture reflection gratings for the off-plane mount, and EM-CCDs to achieve resolving powers of R ~ 2000 and effective areas of < 100 cm^2 in the soft X-ray bandpass. The construction and successful flight of this spectrometer will result in the highest resolution spectrum ever taken of an astrophysical source in the soft X-ray bandpass. The OGRE mission will also bring all of the relevant technologies to a high readiness level, laying the foundations for the use of other high resolution X-ray spectrometers onboard future X-ray observatories. Such spectrometers will be essential to address the questions posed by the 2010 Astronomy and Astrophysics Decadal Survey and open the doors to new X-ray science.

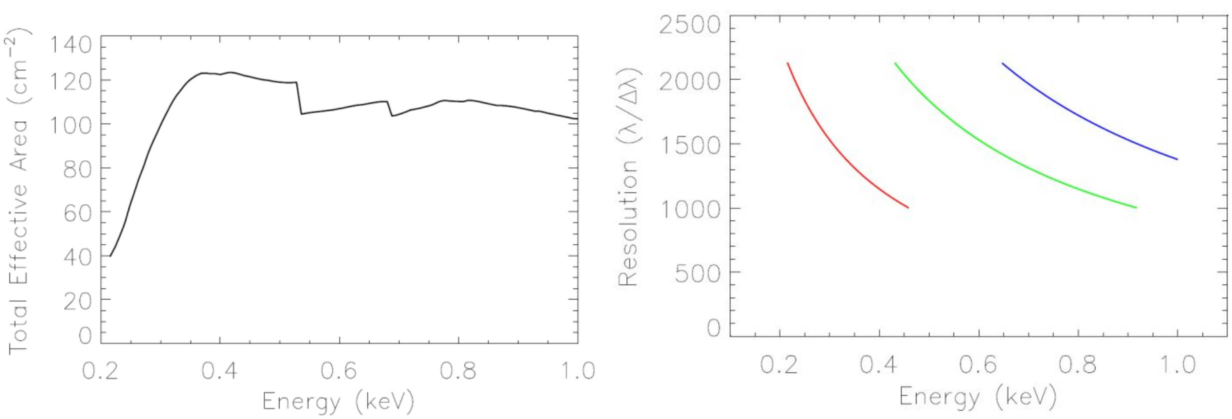

Figure 8: Calculated effective area (left) and resolving power (right) of the OGRE spectrometer. The effective area curve demonstrates that OGRE will meet the effective area requirement of > 100 cm^2 over the 0.3 – 1.0 keV range, while the plot of the expected spectral resolving power shows OGRE should achieve peak resolutions of R > 2000.

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