Laboratory progress in soft X-ray polarimetry

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ABSTRACT

We present continued development of components for measuring linear X-ray polarization over the 0.2-0.8 keV (15-62 Angstrom) band. We present results from measurements of new laterally graded multilayer mirrors and critical angle transmission gratings essential to the approach. While the lab is designed to verify components to be used in a soft X-ray polarimeter, it is reconfigurable and has been used to verify grating efficiencies with our new CCD detector. Our development work is the basis for a sounding rocket mission (Rocket Experiment Demonstration of a Soft X-ray Polarimeter) and future orbital missions.

Keywords: X-ray optics, critical angle transmission grating, REDSoX polarimeter, multilayer mirror, polarimetry

1. SCIENCE GOALS

There are wide-ranging science goals that can be addressed with the use of X-ray polarimetry. Accretion onto a compact object (white dwarf, neutron star or black hole) is believed to be the mechanism for the production of large amounts of energy in the X-ray band. There are several orbital missions (IXPE, PRAXyS, and XIPE) in development, however none of these will cover the soft X-ray band (sensitivity in the 0.1-1.0 keV range).[1] Measurement of absorption edges in neutron star atmospheres and demonstration of vacuum birefringence (vacuum polarization) are important science goals that require soft X-ray polarization measurements.

2. POLARIMETER CONCEPT AND SUBORBITAL MISSION DESIGN

The concept of the soft X-ray polarimeter was described in a previous SPIE proceeding.[2] This concept makes use of critical angle transmission (CAT) gratings produced at MIT in the Space Nanotechnology Lab (SNL) and laterally graded multilayer coated mirrors (LGMLs) to select for polarization. We use a broad-band focusing mirror to focus incoming X-rays. The transmission gratings are then used to disperse the converging X-ray beam such that the energy of the dispersed light incident on the LGML matches up with its corresponding Bragg peak on the mirror. The mirror is set at a 45 degree angle with respect to the incoming light, which will provide us with a greater than 90% selection of s-polarization from the incoming beam. The useful bandpass of this instrument will be roughly 0.15-0.7 keV.

We have proposed a suborbital mission, the Rocket Experiment Demonstration of a Soft X-ray Polarimeter (the REDSoX Polarimeter),[1] which aims to make the first measurement of the linear X-ray polarization of an extragalactic source below 1 keV. Our chosen target is the blazar Mk 421, for which we predict a minimal detectable polarization (MDP) of 11% for a 300 second exposure. We received funding for raytracing[3] and mechanical engineering[4] and have submitted a proposal to NASA APRA for funding for the development and flight of the payload. Flights are planned in 2021 and 2022.

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Optics for EUV, X-Ray, and Gamma-Ray Astronomy VIII, edited by Stephen L. O'Dell, Giovanni Pareschi, Proc. of SPIE Vol. 10399, 1039916 · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2274205

Engineering drawings of the rocket design are shown in figure 1. The nine shell, Wolter 1 optic will be fabricated by Marshall Space Flight Center and Media Lario, and is planned to have an effective area of 640 cm^2 and a half power diameter (HPD) of 15-25 arcseconds. The focal length will be 2.5 meters, and the optical bench is composed of a set of carbon fiber standoffs. The CAT gratings will be mounted in 60 degree sectors.

The focal plane sits on a liquid nitrogen box, which will be filled before flight. The focal plane contains one direct imaging EMCCD and three LGMLs with accompanying EMCCDs for polarization measurement. See[3] for details on the optical design and[4] for details on the mechanical engineering of the payload.

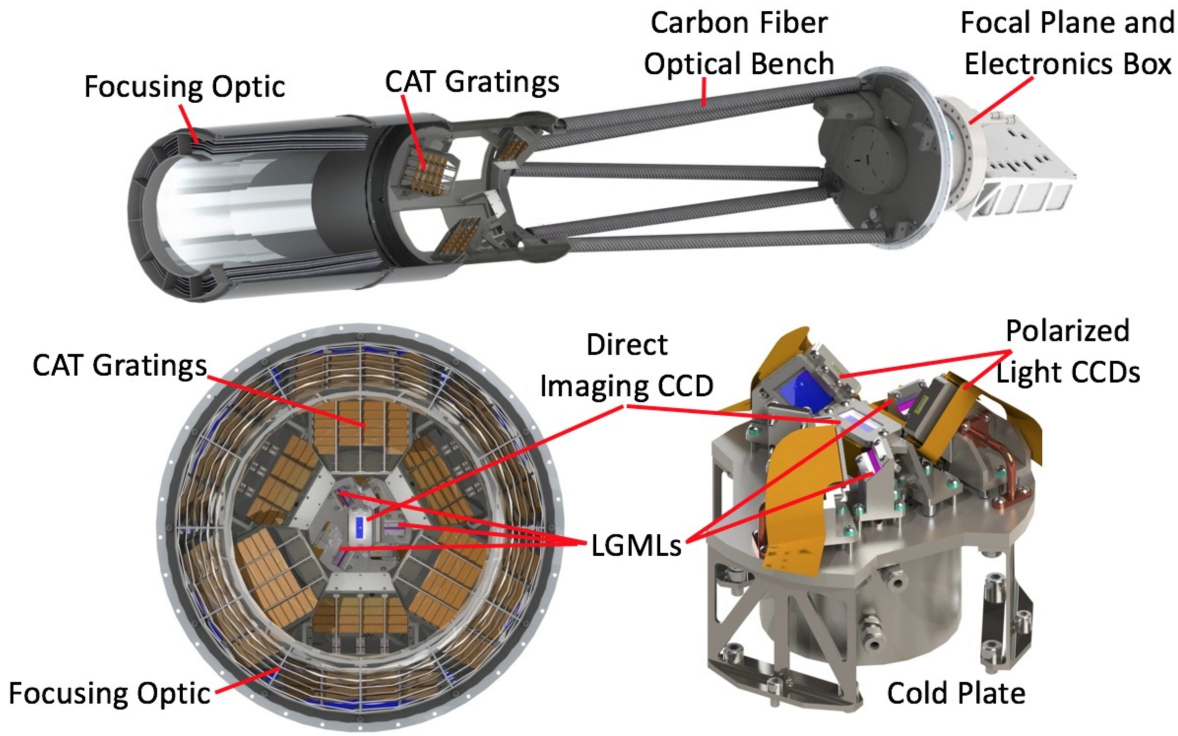

Figure 1. Top: A cutaway of the science payload, showing the locations of the focusing optic, CAT gratings, carbon fiber optical bench and focal plane. Bottom left: a view of the inside of the payload from the aft end looking towards the focal plane. Bottom right: CAD representation of the focal plane, including the liquid nitrogen box on which it sits. Important components are labeled in each image.

3. THE MIT POLARIMETRY BEAMLINE

The MIT polarimetry beamline is a facility that has been re-purposed from its original life as a calibration facility for the Chandra HETG gratings. An image of the facility is shown in figure 2.

The beamline as shown in figure 2 is roughly 20 meters long and has three chambers (source, grating and detector). Each chamber has an independent turbo pump and the system runs at around 10^{-6} torr. The X-ray source is a Manson source with several interchangeable anodes to produce various line energies. The grating chamber is shown in figure 3. Each of the stages in the grating chamber is on an actuator, allowing horizontal control of the aperture plate and slit plate, and horizontal, vertical and rotational control of the grating plate.

The detector chamber contains our Princeton Instruments CCD detector, which is mounted on a moveable X-Y stage so that the detector can be moved to intercept different regions of the incoming dispersed beam. The Princeton Instruments CCD is run at -50 C and is equipped with an optical blocking filter from Luxel. Quick look data is provided by Python analysis code, drawing data from files created by Labview software written to run the detector and store its data.

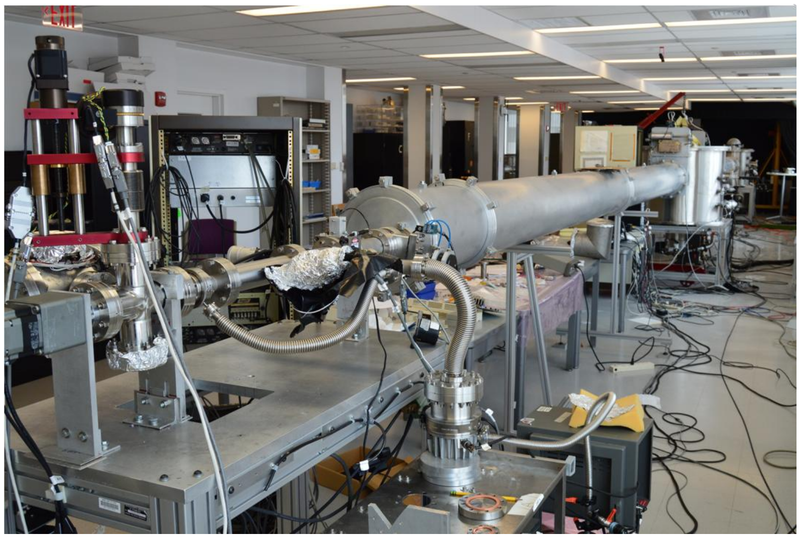

Figure 2. The MIT polarimetry beamline. On the far left of the image, the source chamber contains the high voltage Manson source, which is shining onto an LGML mounted on a translational and rotational stage. Reflected, polarized light then travels down the beamline into the grating chamber, where it is attenuated into a slit and incident on gratings mounted in the chamber. The light is dispersed by the grating and travels down the beamline to the detector chamber containing our CCD package.

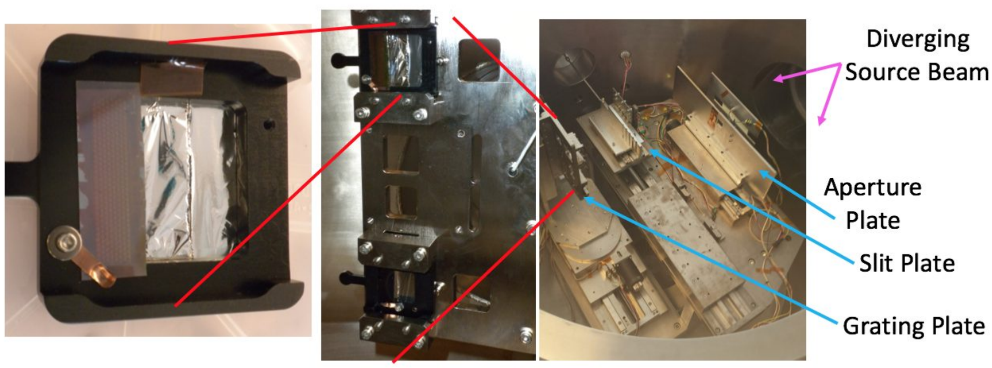

Figure 3. Right: A picture of the inside of the grating chamber. The diverging source beam enters from the right hand side of the image, where it is attenuated by a baffle cutting out all but a horizontal beam about an inch in height. It is then incident on the aperture plate, which has a one inch square aperture to attenuate the beam and block scattered light. It is then incident on the slit plate, on which a slit with width from 3 mil up to 1 mm can be selected, and finally is incident on the grating plate (center), which can hold 2 grating holders (left) and provides open apertures for alignment purposes. A CAT grating is mounted in a Chandra Low Energy Grating (LEG) grating mount with mylar across the open portion to block scattered light in the far left image.

4. PROGRESS ON LATERALLY GRADED MULTILAYERS

We have previously reported on the progress in developing multilayer mirrors for our soft X-ray polarimetry applications.[5] There has been significant progress in developing mirror coatings with good reflectivity across the entire desired bandpass(30-70 Angstroms). An image of the reflectivity of various mirror coatings due to their Bragg peaks measured at even spacings across the mirrors is shown in figure 4.

A picture of the LGML currently in use in the system is shown on the right of figure 4. The mirrors are roughly 25 by 47 mm in size. The LGML in the image is mounted to a translational stage so that we can control the location the incoming X-ray beam is incident on the mirror, and thus select the energy of reflected light. For this setup we had to use kapton 'shims' to correct a very slight warp in the mirror. This warp was discovered

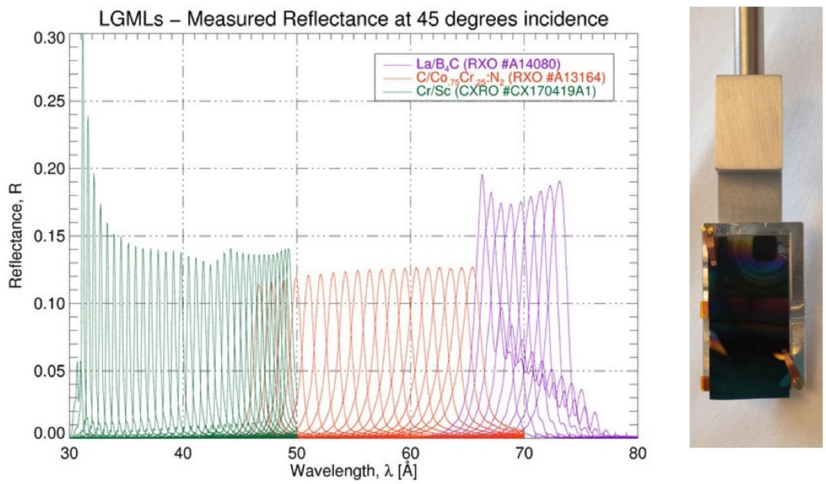

Figure 4. Left: X-ray reflectivity of three different types of multilayers measured at regular spacings across the surface of the multilayers. A mosaic of these mirrors will provide good reflectivity across the entire bandpass of the flight instrument. Right: an image of the LGML currently in use in the system. It is mounted on a translational stage to allow selection of energy for the reflected X-ray beam.

while performing alignment with an optical laser and moving the mirror. The warp is not large enough to cause a problem in the payload, where light travel distance from the LGML to the detector is very small. It was only noticeable in the beamline because of the large light travel distance between the mirror and the detector.

The three types of mirrors shown in fig 4 (La/B_4C, $C/Co_{.75}Cr_{.25}{:}N_2$, and Cr/Sc) provide good reflectivity across the entire desired bandpass. We plan to use a mosaic of these mirrors to provide full wavelength coverage for the flight instrument. Development is in progress on new types of LGMLs to extend the bandpass to lower wavelengths.

5. CAT GRATINGS

The critical angle transmission gratings used in our system are produced in the MIT SNL. See the proceedings paper[6] for more information on their design and current development status. Scanning electron microscope (SEM) images of the structure of the gratings can be seen in figure 6. The L2 (hexagonal) support structure provides the main structure of the gratings, while the L1 support structure (vertical bars in the lower portions of the images) support the grating bars themselves (small horizontal bars that can be seen in the lower frames of the images). The gratings are etched from silicon wafers. Efficiency measurements for the gratings are typically performed at offsite facilities. The MIT polarimetry beamline presents an opportunity to test gratings quickly on campus, which will be ideal for testing the gratings produced for the Arcus mission, which has been selected in the current Explorer round for Phase A concept study.[7]

We have performed several rounds of spectral resolution and efficiency tests on 5 older CAT gratings in the MIT beamline. The measured efficiencies have been around 25 % as expected. This includes absorption by the L1 and L2 supports. A low energy spectrum measured using a titanium oxide anode is shown in figure 5. The Ti-L lines are well resolved, showing excellent energy resolution in the soft X-ray band. This spectrum was acquired with the beamline in its full length configuration. The length of the beamline was designed for testing gratings from the Chandra HETG instrument, which dispersed to much smaller angles than the CAT gratings do. This requires us to take several images at different detector positions to acquire even the first order dispersion. Since grating testing for Arcus will require testing out to further orders, the beamline has been reconfigured to significantly reduce the distance between the grating and detector chambers. This is discussed in more detail below.

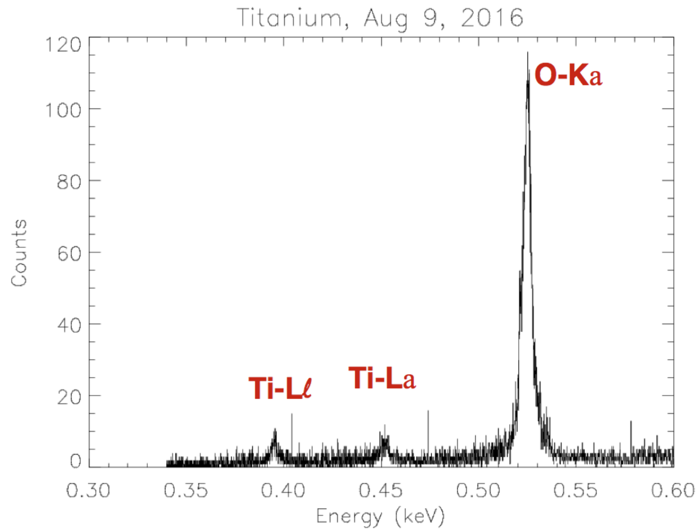

Figure 5. Low energy spectrum acquired using a TiO anode dispersed by a CAT grating. The Ti-L lines are well resolved.

6. ROCKET DESIGN FEASIBILITY TESTING

The sounding rocket platform introduces several unique requirements on the payload. The first and most stringent is vibration. During launch the sounding rocket vibration is around 12.7g_{rms} over a broad spectrum up to several kiloHertz.[8] As the gratings had not been tested under vibration, we undertook testing to qualify them for a flight.

We used a system developed to test detector assemblies for the NICER mission at MIT. An audio transducer is outfitted with an adapter plate to allow mounting of samples and an accelerometer. Software controls the vibration to produce a specified vibration spectrum at the accelerometer. This is a small in-house setup that is much less expensive and less time consuming than taking samples to a vibration table. It is somewhat limited in that it cannot produce sounding rocket vibration levels, however we were able to shake to the NASA General Environmental Verification Standard (GEVS) spectrum, which is used to qualify equipment for satellite missions.

We began with a grating that had previously been damaged (so that if vibration was destructive we wouldn't lose a flight-quality sample). We took optical images and X-ray efficiency measurements of the sample, then submitted it to a random GEVS shake in all three axes. We then took more optical images and repeated the X-ray efficiency measurements. The optical images showed no changes in the grating and efficiency measurements were the same before and after shake. From these data we are confident that the CAT gratings will be able to endure vibration conditions without quality degradation.

Another unique requirement for sounding rocket payloads is size. The outer skin of a sounding rocket is at most 22 inches in diameter. This requires the payload to be relatively compact. As shown in figure 1, the LGMLs will be mounted on the cold plate along with the CCDs. We were concerned about differences in the coefficient of thermal expansion between the different layers of the multilayer and/or the silicon wafer causing some sort of peeling of the layers with thermal cycling. To test whether or not this would be an issue, we mounted a mirror on the cold plate of a liquid nitrogen-cooled stage that was used for a previous detector in our system. The system was pumped out, then we then cooled the stage to 77 K as quickly as the system would allow, held it at that temperature for about a half an hour, then allowed it to warm up. The mirror was inspected under an optical microscope before and after and we saw no evidence of peeling or chipping. We plan to check that the reflectivity does not change with temperature as well, but this test is a good indication that the mirrors will be able to function cold.

Finally, the optical design of the telescope (see companion paper[3]) requires that the blaze condition of the gratings be met at each point across the gratings. Since the X-ray beam is converging at the point it intersects with the gratings, we will need to curve the gratings to maintain the blaze condition. The three main points we wanted to address with testing are whether or not the grating bend causes any physical damage to the grating, affects resolution, or affects efficiency. In order to test these points we performed two different tests.

With the first test we assessed whether or not the bend causes any physical damage to the grating. We began by taking SEM images of the grating at several different locations and magnifications. We then mounted the grating on a curved surface with the smallest radius of curvature (ROC) that would be necessary for the instrument (1.5 meters). The gratings were quite easy to bend and we were able to achieve the bend by simply mounting the grating with our usual small copper clips. We then unmounted the grating and took additional SEM images and compared the two. A set of before and after images from this test are shown in figure 6. We saw no change in any part of the grating resulting from the bend test.

The second part of our testing required that we mount a bent grating in the beamline. To this end we designed a new grating mount that has a curved mounting surface. A picture of a grating mounted bent is shown in figure 6. Spectra and efficiency measurements were taken on a flat mount and on the bent mount. Data are still in processing to determine whether or not the efficiency was affected. The spectral resolution was unchanged due to bending.

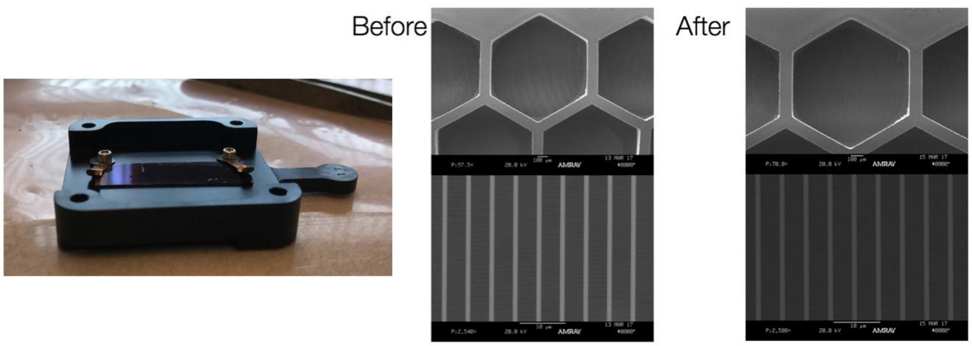

Figure 6. Left: CAT grating mounted on a curved mount, bent with a ROC of 1.5 meters. The mount is designed to mount a curved grating in the system, so that efficiency and spectral resolution can be acquired in the configuration in which the gratings will be flown. Center and Right: before and after SEM images of the grating support structures and bars. The bend does not cause any visible damage to either L1 or L2 support structures or the grating bars.

7. SYSTEM RECONFIGURATION

We have recently reconfigured the system to optimize for CAT grating testing. Since the CAT gratings disperse further than the HETG gratings the system was previously designed for, we shortened the distance between the grating chamber and the detector chamber. The new system configuration is shown in figure 7.

We have performed some initial tests in the new configuration with very positive results. The left panel in figure 8 shows the energy versus position of events on the CCD, demonstrating several orders of dispersion that were not accessible in the previous configuration. The right panel in figure 8 shows the counts in the oxygen-K line by order, demonstrating that the fifth order dispersion has much more power than the lower orders as expected. This type of data is easily achieved in the beamline's new configuration so testing of gratings for Arcus Phase A should be easily achieved in the MIT beamline. This will also afford us the ability to cross-check data obtained with the gratings at other facilities.

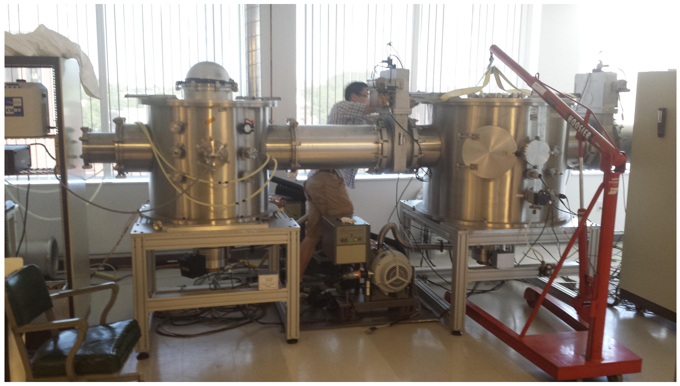

Figure 7. The grating (right) and detector (left) chambers in the new system configuration. The distance between them was originally roughly 10 meters. It is now about 2 meters.

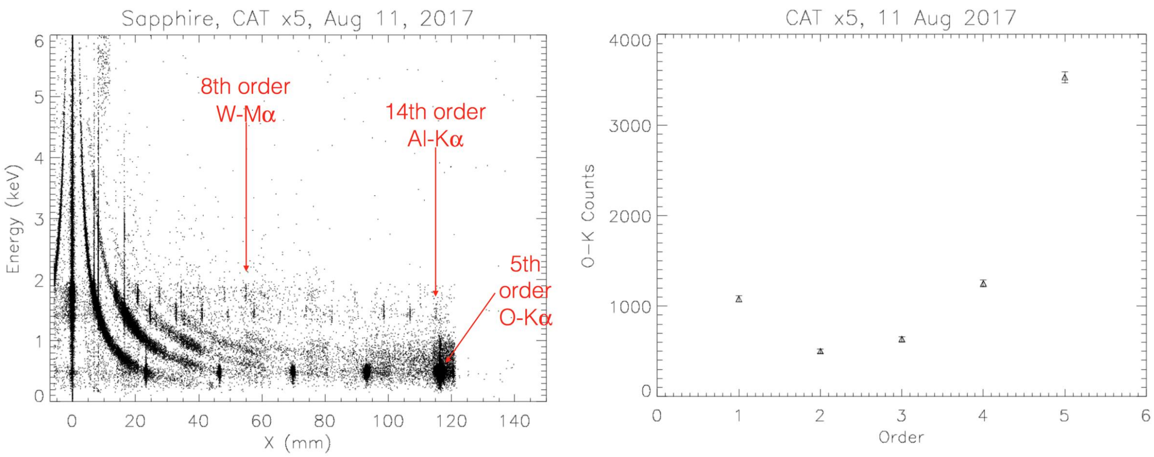

Figure 8. Left: Energy versus position of events on the CCD viewing a Sapphire anode through a slit and CAT grating with the new system configuration. Several orders of dispersion are visible. Right: Counts in the Oxygen K line for several orders dispersed by the CAT gratings. The fifth order contains significantly more power than the lower orders.

ACKNOWLEDGMENTS

Support for this work was provided in part by the National Aeronautics and Space Administration grant NNX17AE11G as well as a development grant from the MIT Kavli Institute. Thanks to A. Bruccoleri (Izentis, LLC) for the SEM images for our grating bend tests, and Mark Egan (MIT) for assistance with the use of the NICER shake facility. The author would also like to thank the office of the Dean of Science at MIT and the MIT Kavli Institute for funding travel for her nursing child and a caretaker, allowing her to travel to present this work.

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