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X-ray Optics for WHIMEx,
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The x-ray astronomy community has never flown a celestial source spectrograph that can resolve natural line widths in absorption the way the ultraviolet community did with OAO-3 Copernicus back in 1972. Yet there is important science to be mined there, and right now, the large flagship missions like the International X-ray Observatory are not progressing toward launch. WHIMEx is an Explorer concept proposed earlier this year to open up that science regime in the next few years. The concept features a modified off-plane grating spectrograph design that will support high resolution ($\lambda/\delta\lambda \sim 4000$) in the soft x-ray band with a high packing density that will enable a modest cost space mission. We discuss the design and capabilities for the WHIMEx mission. Its prime science goal is detecting high temperature oxygen in the Intergalactic Medium, but it has a broad range of science potential cutting across all of x-ray astronomy and should give us a new window on the Universe.

Keywords: X-ray Optics; x-ray spectroscopy

1. X-ray Optics for Spectroscopy

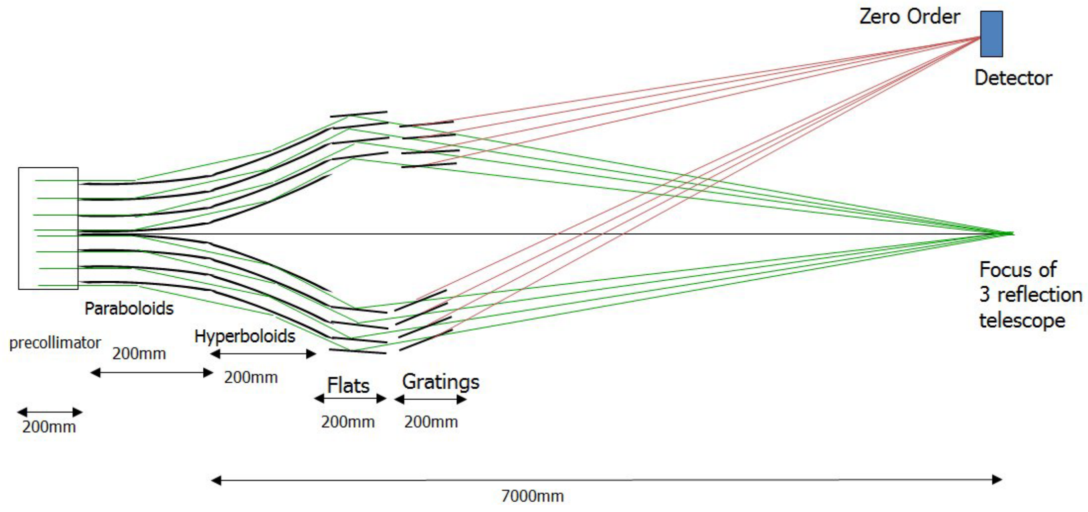

Figure 1: The basic concept behind the four reflection optic is shown. Identical paraboloid/hyperboloid telescopes are mounted in a parallel array. The output of each p-h channel is redirected by a fanned array of flat mirrors to a focus, effectively creating a three element telescope. This converging beam is then caught by a radial grating and dispersed. Because of the convergence created by the steering flats, each grating is identical and mounted at the same angle with respect to the incident beam.

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X-ray spectroscopy of celestial sources is now a well-established discipline in astronomy. Sources with a cosmic composition of elements at temperatures in excess of 10^6K are rich in spectral diagnostics that allow us to probe the physical properties of the extreme objects that create the ultra-high temperatures.

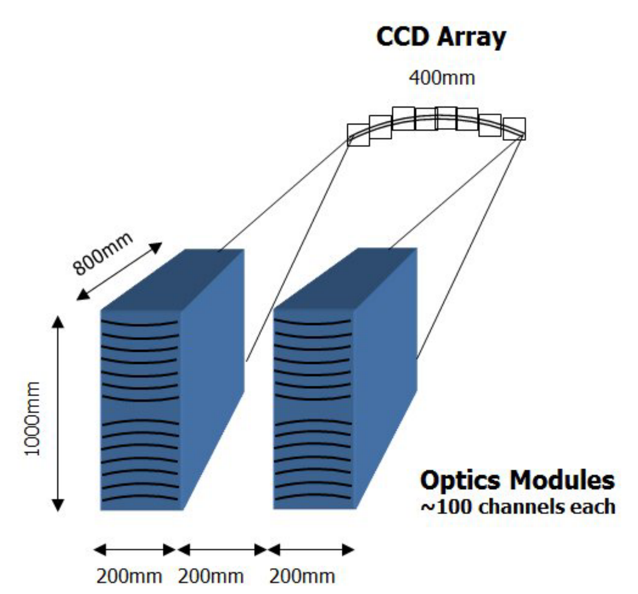


Figure 2: To maximize the effects of subaperturing, the paraboloid/hyperboloids must be narrow. Aperture is built up by stacking in the vertical direction. Multiple spectra may be placed on a single arc of CCD detectors.

There are two classes of x-ray spectrographs – detectors that are sensitive to the energy of the incident photon, and dispersive elements that rely on crystals or gratings to physically separate the various wavelengths. While the detector systems have very high quantum efficiency, they have not achieved very high spectral resolution in the band below 1keV, where the CNO lines are abundant. Of the dispersive systems that can achieve high resolution, blazed diffraction gratings provide the best efficiency. Of the blazed diffraction gratings, currently off-plane gratings appear to offer the most practical route to a flight system.

For over a decade the x-ray astronomy community has worked on the Constellation-X and International X-ray Observatory[1,2] as the likely seat for high resolution spectroscopy because of the large collecting area offered by the large primary x-ray telescopes. However, the recent ranking of #4 by the Decadal Review means that IXO will not be started in the near future.[3]

Yet the science addressed by IXO was rated very highly in the same review, so investigation of alternative mission architectures that can address the key science is clearly of broad interest. And the key piece of science that can be addressed with high resolution is the Warm Hot Intergalactic Medium (WHIM). It is now believed that the vast stretches of space between the galaxies contain most of the regular matter (baryons) in the universe, and that this intergalactic matter is mostly very hot, some of it requiring x-ray instruments to even detect.[4]

But right now, the only missions that are moving forward are Explorers. This paper describes how we can address the WHIM science within the limited cost and mass constraints of an Explorer and show the scientific power of the instrument. The key is to create highly compact x-ray optics that make the most of the available resources.

2. A New Optimization

WHIMEx was optimized to pursue high resolution with adequate collecting area in a low cost package. More details can be found in other papers in this conference. McEntaffer et al[5] discuss the optics in more detail, and Lillie et al[6] discuss the mission as a whole.

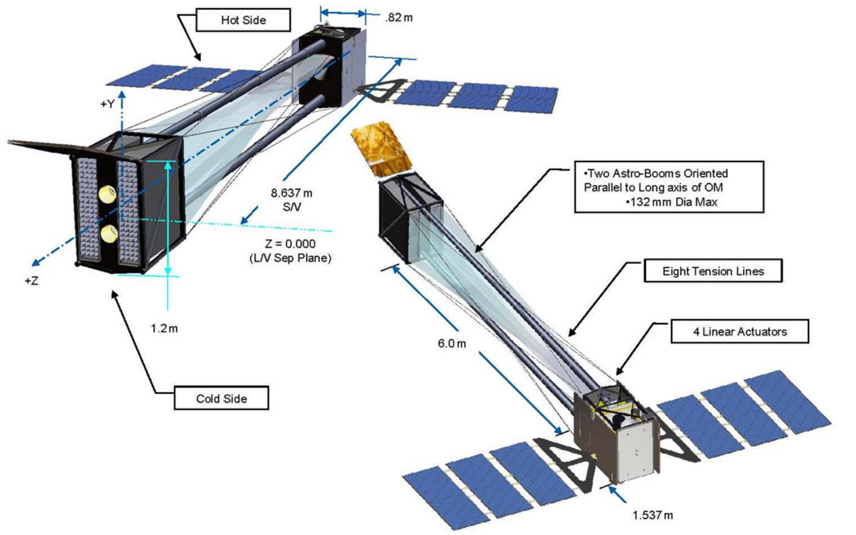
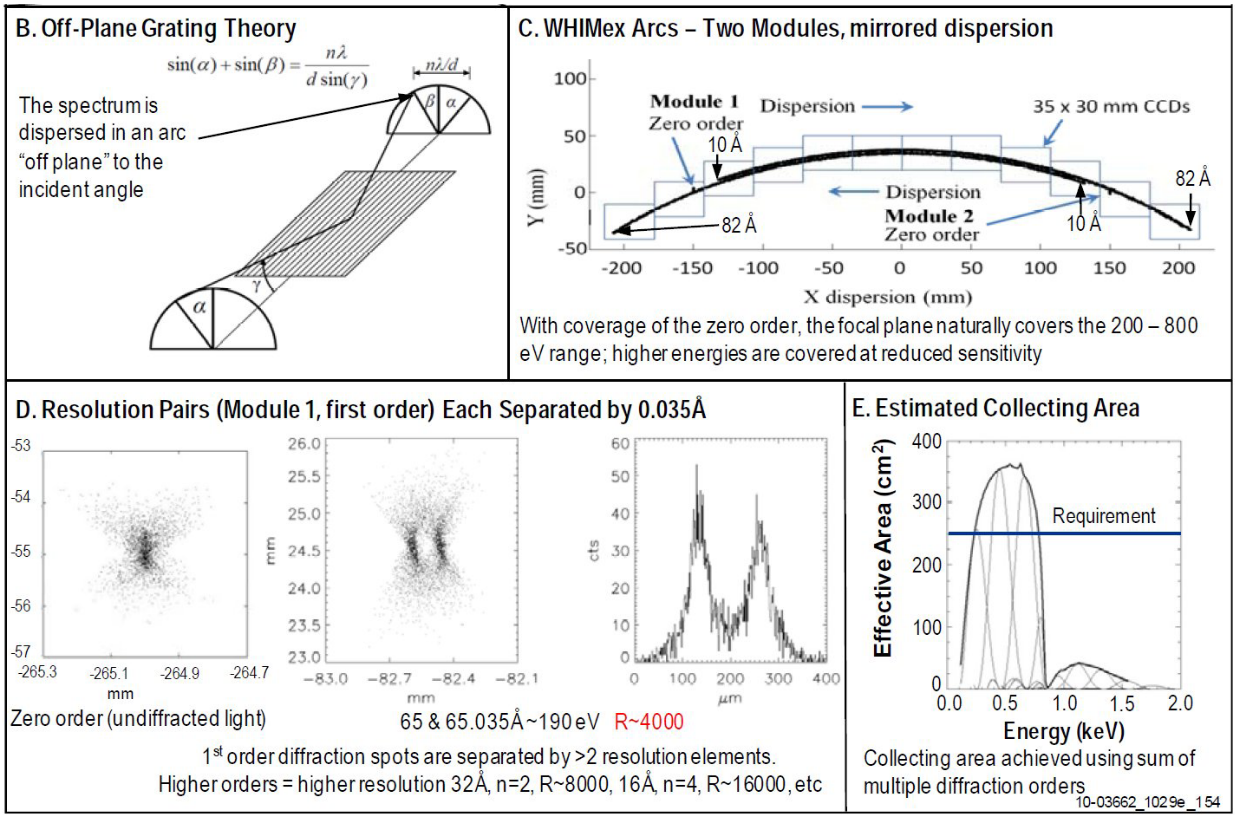


Figure 3: Preliminary CAD rendering of a spacecraft suitable for supporting the spectrograph. A boom deploys the prime optics to their 7m focal length after launch.

To achieve the required resolution, the system must be dispersive, there must be optics of appropriate resolution, and a system of adequate focal length to support the dispersion. To obtain the needed high collecting area, a sufficient area of x-ray optics must be packed into the envelope without exceeding mass constraints for launch.

We extend the grating design that was optimized for IXO[7,8,9] and re-optimize it for an Explorer envelope. We needed to keep (or even improve upon) the spectral resolution of the IXO designs, but can compromise on collecting area. First, the IXO gratings never needed the full aperture of the IXO


B. Off-Plane Grating Theory

$$\sin(\alpha)+\sin(\beta)=\frac{n\lambda}{d\sin(\gamma)}$$

The spectrum is dispersed in an arc "off plane" to the incident angle

C. WHIMex Arcs – Two Modules, mirrored dispersion

With coverage of the zero order, the focal plane naturally covers the 200 – 800 eV range; higher energies are covered at reduced sensitivity

D. Resolution Pairs (Module 1, first order) Each Separated by 0.035Å

Zero order (undiffracted light)

65 & 65.035Å ~190 eV R~4000

1st order diffraction spots are separated by >2 resolution elements.

Higher orders = higher resolution 32Å, n=2, R~8000, 16Å, n=4, R~16000, etc

E. Estimated Collecting Area

Collecting area achieved using sum of multiple diffraction orders

Figure 4: Estimated resolution and collecting area are shown as a function of photon energy for a full system. An average resolution of 4000 is achieved, along with hundreds of square centimeters of collecting area.

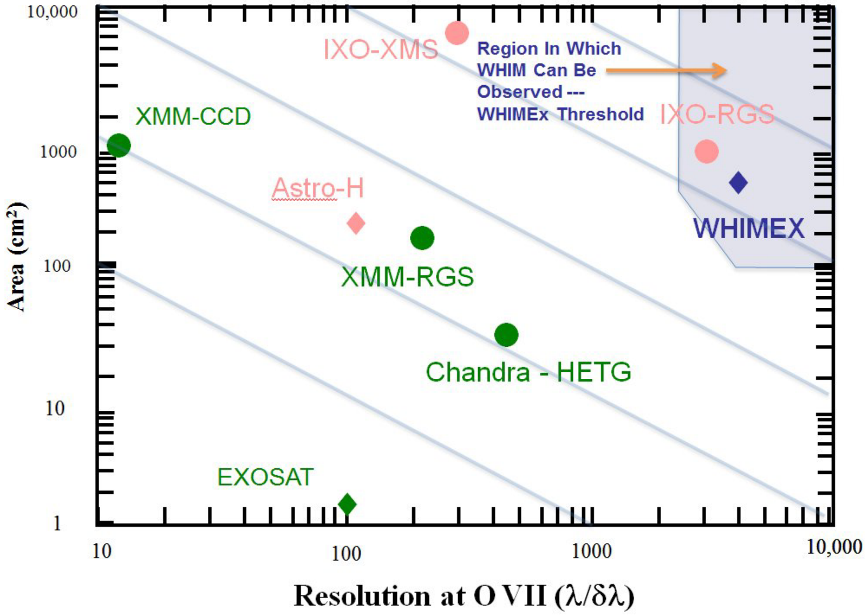


Figure 5: Spectral resolution at the critical OVII absorption line is shown versus effective collecting area for the past and present x-ray observatories. We compare instruments that are in study or fabrication. The diagonal lines are at constant figure of merit, which is the product of area and resolution. WHIMEx would provide an order of magnitude improvement in both axes over Chandra and would be able to provide two orders of magnitude improvement in study of intergalactic gas.

primary to achieve its required 1000cm^2. And second, in a dedicated Explorer, all the observing time will be available for prime targets, so 300cm^2 is an adequate total effective area.

One problem with IXO that appears to have hurt its chances for flight was that the telescope optics were not deemed flight ready. IXO was to achieve 5 arcseconds of resolution while optics of only 10 arcseconds had been demonstrated.[10]. For this reason we deemed it wise to return to using 15" optics as we had in Constellation-X studies. Resolution of 4000 is achievable with 15" by making full use of subaperturing.[11,12]

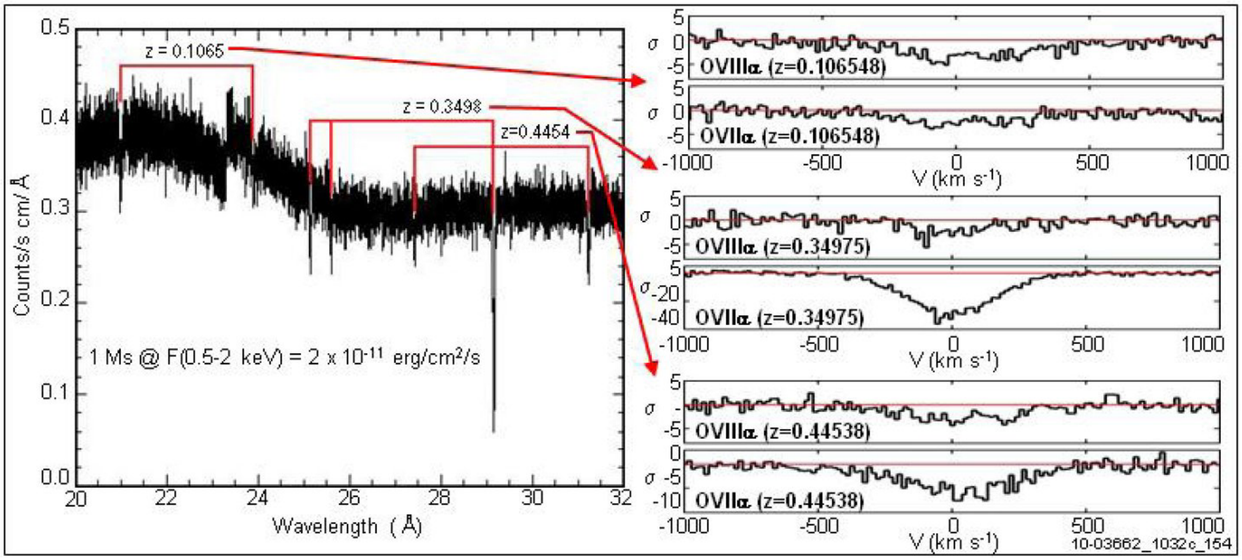


Figure 6: A simulation of a distant AGN seen through the WHIM. Strong absorption features from OVII and OVIII are clearly seen from hot filaments of gas between the galaxies.

To achieve several hundred square centimeters of collecting area we will need to close–pack many paraboloid-hyperboloid segments (Figures 1 and 2). A typical size for the entrance to a channel is 0.2x10cm yielding 2cm^2 of geometric collecting area per channel. With reflection losses and diffraction efficiency included, this leads to a nominal 0.5cm^2 of effective collecting area per channel. So we will need about 700 channels. The spectra from these channels must be co-aligned so that all the diffracted light is concentrated in just a few, largely astigmatic spectra. Details of the optics design process were discussed in an earlier conference[13].

3. The WHIMEx Design

This design has recently been submitted to a NASA Explorer opportunity under the mission name of WHIMEx. At the writing of this paper, the proposal is under review and we do not know the outcome. Details of the WHIMEx design are beyond the scope of this paper and will be published later, but a few words about the mission and the optimal arrangement are in order at this point.

Renderings of the WHIMEx spacecraft are shown in Figure 3. The optimal focal length is about 7 meters, which is too long to fit in an affordable launch fairing. So, the spacecraft features a deployable boom that separates the x-ray optics from the focal plane assembly after launch. The figure shows two x-ray modules, but four can be accommodated if sufficient funding is available.

Figure 4 shows how each module creates its own arc of diffraction, about 500mm long. Four spectra can be accommodated on a single arc of CCD detectors, minimizing the detector support requirements.

4. Scientific Capability

The figure of merit for the detection of a weak (i.e. unsaturated) absorption line in an otherwise featureless continuum is the product of resolution and collecting area. Figure 5 compares the WHIMEx performance to other x-ray spectroscopy missions, past, present and under study. By applying the off-plane, four reflection geometry, WHIMEx will achieve an order of magnitude increase in both collecting area and resolution over the current state of the art in high resolution x-ray spectroscopy (Chandra). It will also be the first instrument to be able to seriously study weak absorption lines such as those generated by the intergalactic medium.

Figure 6 shows a simulation of the WHIM as observed by WHIMEx. In a million second observation very high signal-to-noise is achieved, making the stronger WHIM lines immediately apparent to the unaided eye. The detail boxes to the right show them to be broad and unsaturated. It is a great strength of an Explorer that very long observations can be made, unlike on a flagship-class mission where there are numerous, competing demands on the time. The result is that dozens of such spectra can be

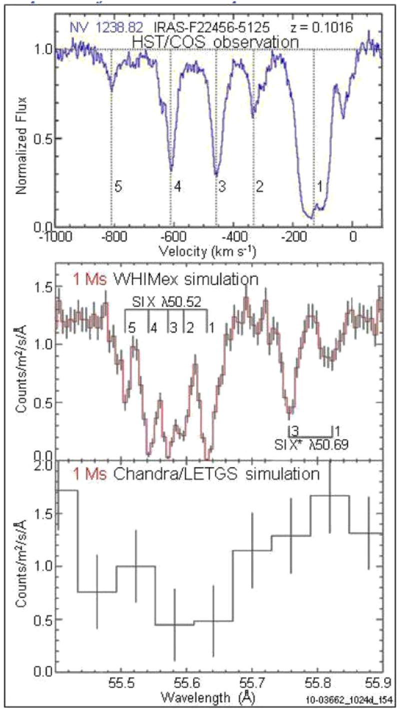


Figure 7: An actual outflow feature observed in NV is shown from COS. Simulations of an x-ray observation with both Chandra and WHIMEx show the importance of high resolution

expected in a nominal mission.

But the figure of merit tends to understate the importance of the resolution to understanding what one is observing. Figure 7 shows this effect very nicely. The upper panel shows actual data from the Cosmic Origins Spectrograph on HST. It shows a line complex of NV spread over a 1000km/s of Doppler shift. The bottom panel shows how that nitrogen complex would appear in NVI as viewed in the x-ray by the Chandra Observatory. While the complex can be detected as a whole, there is no information on outflow or the individual components. It is clear that an observer would have a very difficult time interpreting the data. In the middle panel, the same observation is simulated for WHIMEx. The high resolution brings out all of the individual components and it is clear that qualitatively different conclusions would be reached.

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