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Compact Optics for High Resolution Spectroscopy of Celestial X-ray Sources

W. Cash[a], C. Lillie[b], R. McEntaffer[c], W. Zhang[d]

[a]University of Colorado, [b]Northrop-Grumman Aerospace Systems, [c]University of Iowa, [d]NASA Goddard Space Flight Center

The astronomy community has never flown a celestial source spectrograph that can resolve natural line widths in absorption the way the ultraviolet community since OAO-3 Copernicus in 1972. Yet there is important science to be mined there, and right now there are now missions on track to pursue it. We present 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 for the WHIMEx mission which was proposed as an Explorer earlier this year with the goal of detecting high temperature oxygen in the Intergalactic Medium.

Keywords: X-ray Optics; x-ray spectroscopy

1. X-ray Optics for Spectroscopy

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.

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

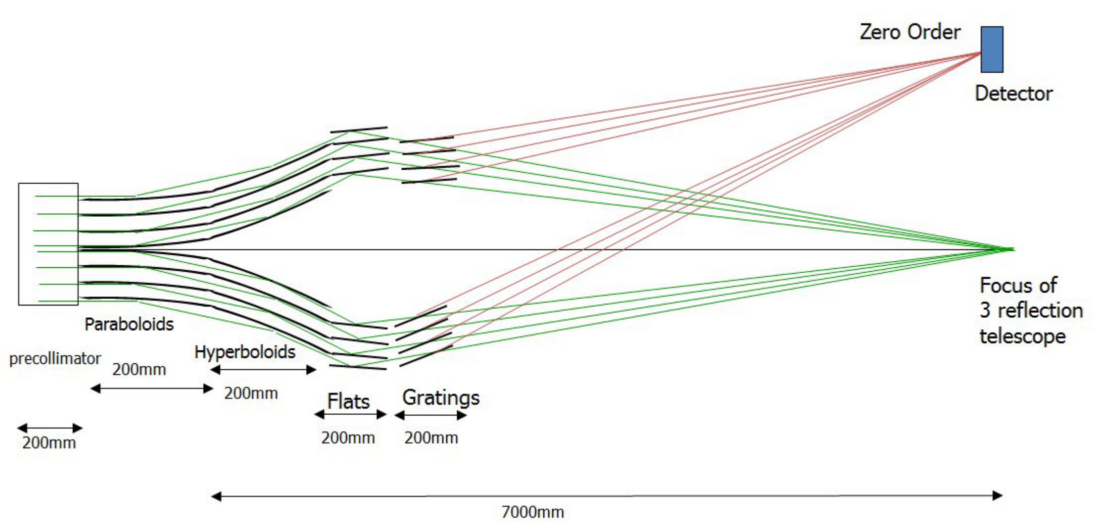

Figure 1: The basic concept behind the four reflection optic is shown. Identical paraboloid/hyperboloid telescopes are mounted in a parallel array. The output of each p-h channel is redirected by a fanned array of flat mirrors to a focus, effectively creating a three element telescope. This converging 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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various wavelengths. While the detector systems have very high quantum efficiency, they have not achieved very high spectral resolution. 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 Observatories[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]

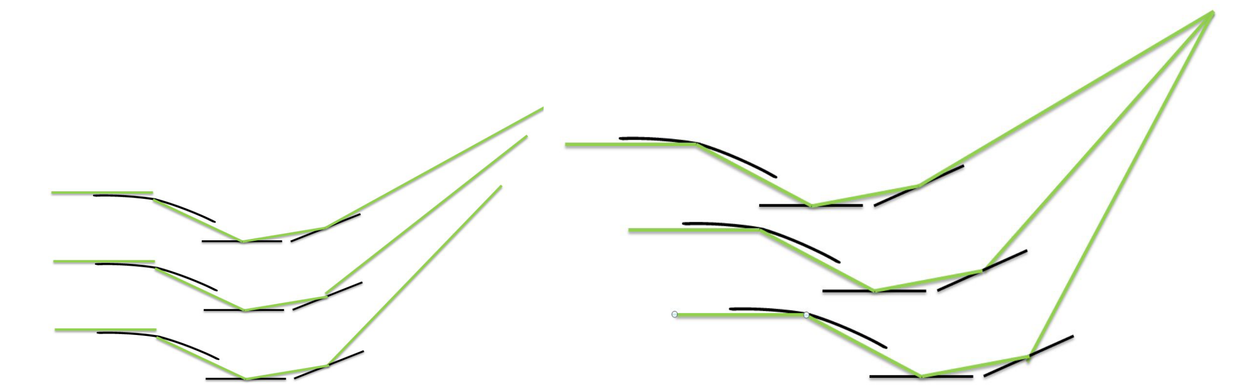

Figure 2: We show schematics of identical parallel paraboloid-hyperboloid optics. The beamlets are redirected to a common focus, but those that are subject to a higher reflection angle have a longer path to convergence plane and therefore do not focus. The solution is shown to the right. Since the channels do not have to be coherent, we simply displace the position of the first optic to compensate for the extra path length.

Yet 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 addresses how we can address the WHIM science within the limited

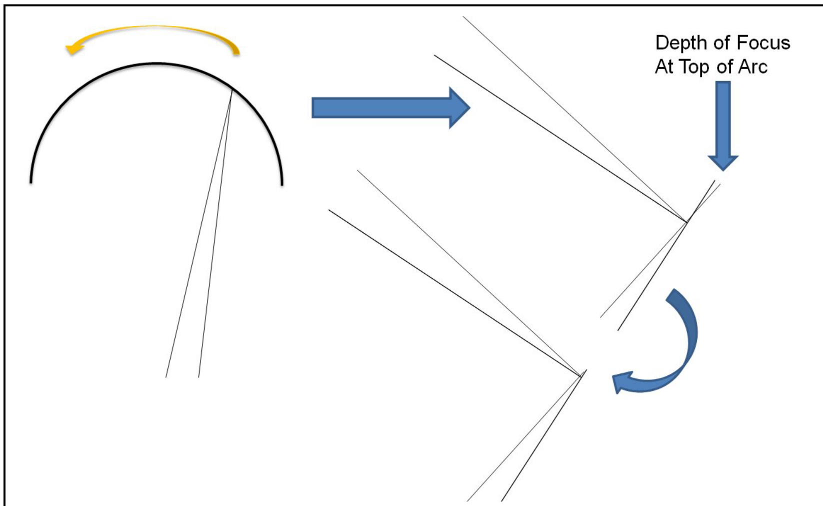

Figure 3: To the left, we point out that the spectrum is dispersed along an arc, and that the top of the arc is higher than the zero order. This leads to the beam coming in and focusing at zero order, leaving a depth of focus problem at the top of the arc as shown from the side in the upper right. Additional adjustment of the positions of the paraboloid-hyperboloids can move the convergence point to the top of the arc and remove the aberration through the critical parts of the spectrum.

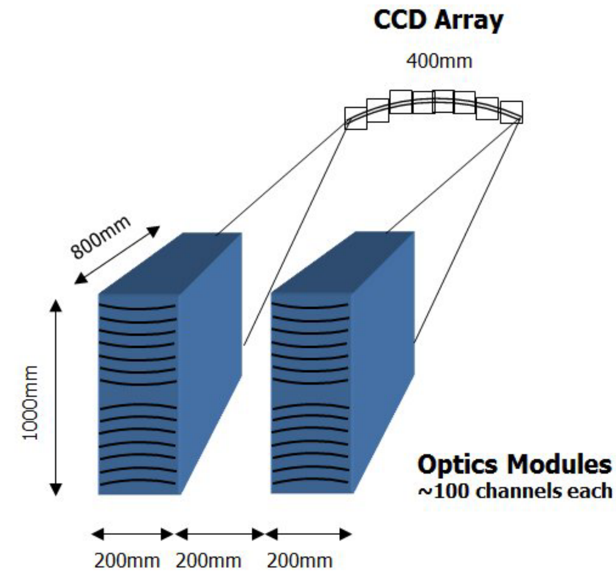

Figure 4: To maximize the effects of subaperturing, the paraboloid/hyperboloids must be narrow. Aperture is built up by stacking in the vertical direction. Multiple spectra may be placed on a single arc of CCD detectors.

cost and mass constraints of an Explorer. The key is to create highly compact x-ray optics that make the most of the available resources.

2. A New Optimization

To achieve the required resolution, the system must be dispersive, and there must be optics of appropriate resolution and a system of adequate focal length to support the dispersion. To get 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[5,6,7] 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 primary to achieve its required 1000cm^2. And second, in a dedicated Explorer, all the observing

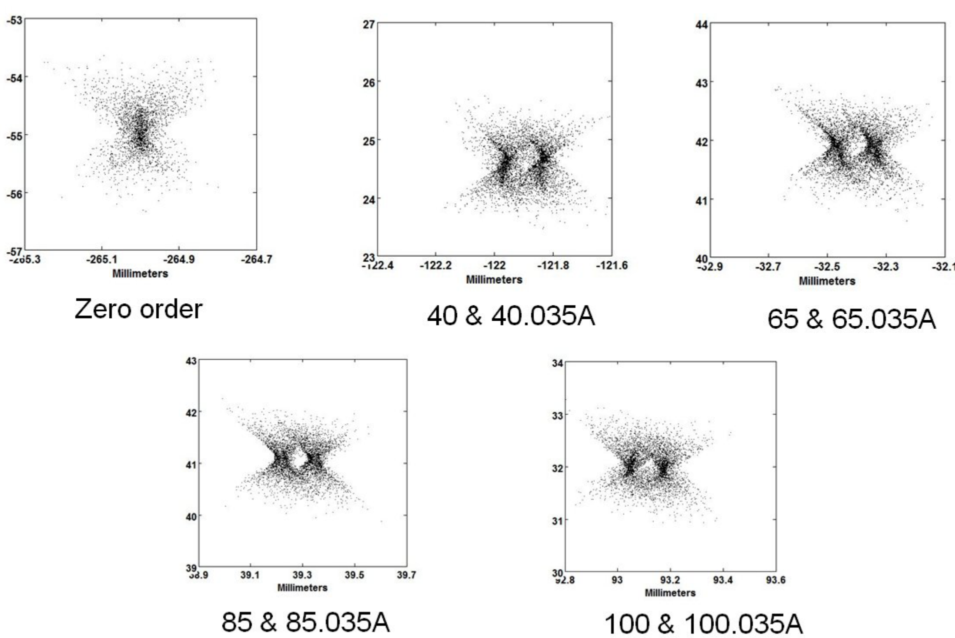

Figure 5: Pairs of wavelengths separated by 0.035Å are raytraced through a full array of channels. Resolution of 4000 is achieved near the center of the arc, where the blaze will be located.

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 5arcseconds of resolution while optics of only 10 arcseconds had been demonstrated.[8] 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.[9,10]

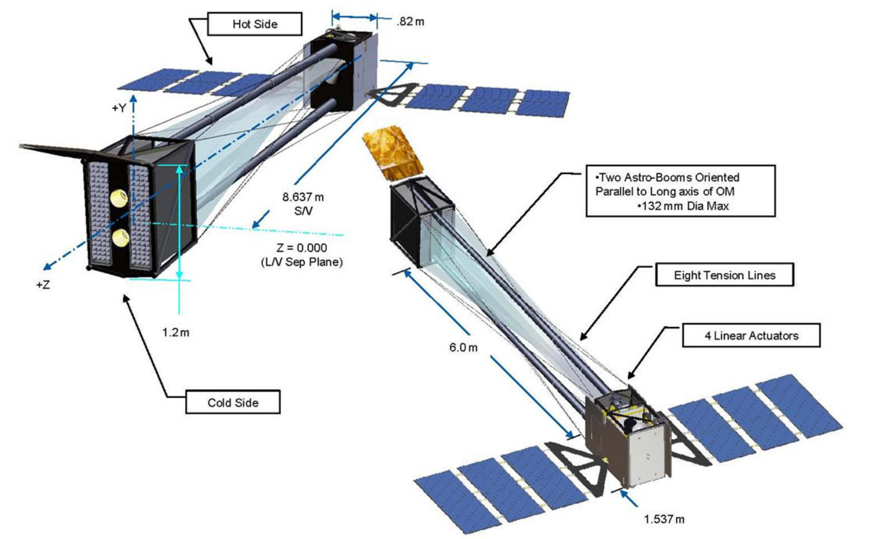

Figure 6: Preliminary CAD rendering of a spacecraft suitable for supporting the spectrograph. A boom deploys the prime optics to their 7m focal length after launch.

To achieve several hundred square centimeters of collecting area we will need to close–pack many paraboloid-hyperboloid segments. A typical size for the entrance to a channel is 0.2x10cm yield 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.

One problem that dogged the IXO and Con-X designs was the procurement of the mandrels for slumping or replication. In a standard telescope design, each p-h pair is concentric and therefore has a slightly different optical design from its adjacent pairs. These leads to a requirement for many mandrels before the first telescope module can be built. Once all the mandrels are procured, then the modules can be stamped out many times. But the cost and schedule associated with the mandrel procurement could be problematic for a low-cost, fast program like an Explorer.

We noted that, with the addition of off-plane gratings, each channel has three reflections, the final one of which is a flat. So we decided to investigate the possibility of using just one mandrel. Each p-h pair would be the very same optical design, and would be mounted parallel to its neighbors. This, of course, would lead to a separate focus for each channel, which is unacceptable. So each grating, which is a flat in zero order, would be adjusted in graze angle so that all the beams strike the focal plane at the same point. In practice this means the gratings are fanned in angle. This proved to be easy to accomplish (at least in the computer) and creates a zero order response that is undegraded from a conventional 15” telescope design.

Unfortunately, while this would work for a simple imaging application, we need to control the quality of the dispersed spectra. By fanning the grating reflection angle relative to the output of each p-h, the light incident on each grating is at a different angle in both alpha and gamma. So, while each spectrum starts at a well-controlled zero order, its arc of diffraction will diverge from the others, effectively creating a severe astigmatism. Such an aberration would severely limit the sensitivity of the system and is unacceptable.

In order to keep the incidence angle onto each grating the same, we must place fanned gratings into a beam that is already converging to a single focus. Thus, we either return to multiple mandrels, or we add another reflection as shown in Figure 1. It turns out that we can use this first, flat mirror to steer the beams to a common focus and yet have light impinge on each grating at same distance and the same gamma angle. This allows all the gratings to be identical as well, allowing us to replicate the entire grating array from a single mandrel. The price, of course, is the lowered efficiency from an extra reflection coupled with an increase in mass and complexity from the extra optic. So the value of this idea must be quantitatively analyzed to see if it represents a good trade.

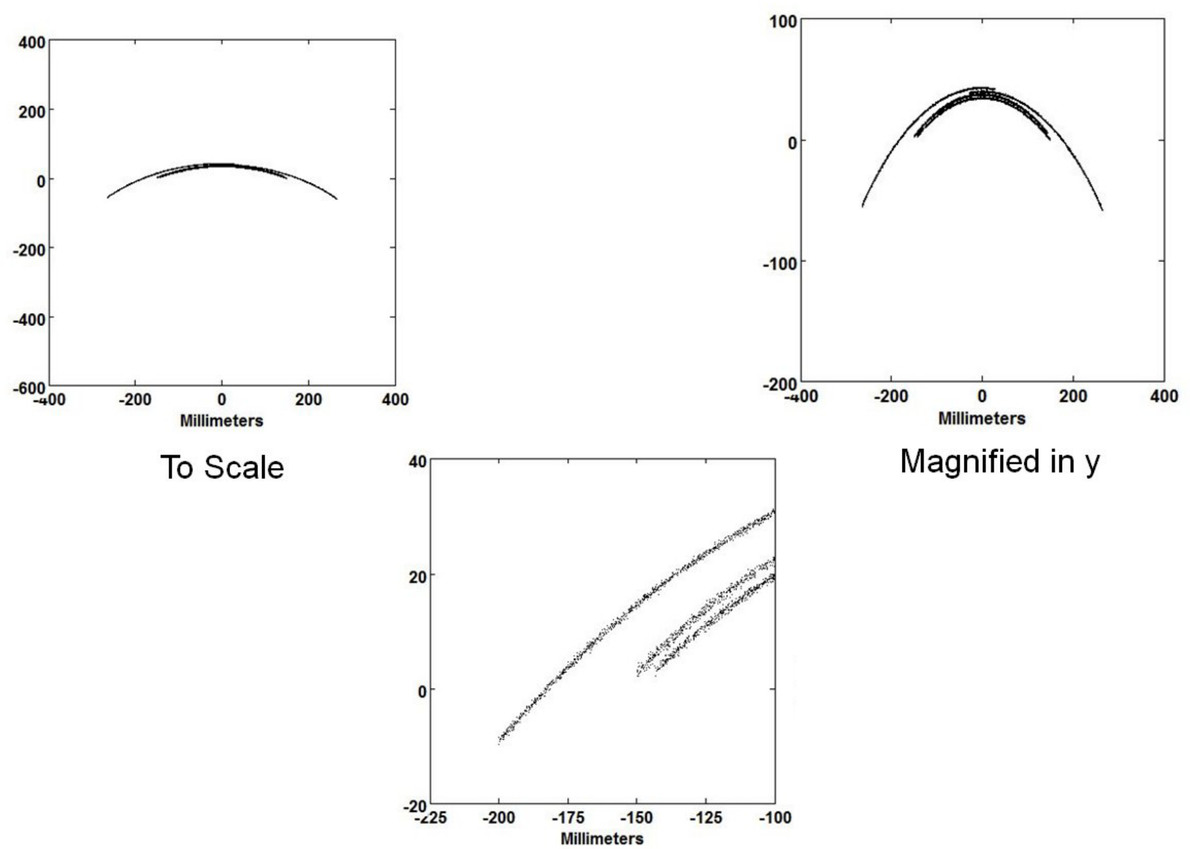

Figure 7: Raytraces of a continuum of wavelengths show the arcs of diffraction. Strategic placement of the module assemblies allows four spectra to share the same detector array.

A surprise followed. We found that the four reflection system created a very attractive packing geometry. Because all four reflections can be aligned in the same direction, one can place the channels farther off-axis, up to a factor of two, meaning that there is up to four times as much geometric area available at a given focal length, more than compensating for the reflectivity loss. Simultaneously, one can place channels right on the optic axis. In a conventional telescope, the center is always unfilled, because the graze angle there approaches zero. In the case of the four reflection optic, the steering flats allow the light from an on-axis p-h to be redirected straight down the axis. This combination of effects allows for maximum geometric collecting area, with only modest extra reflectivity loss, and turns out to be very attractive for a low cost mission.

3. New Aberrations

This new optical arrangement created some aberrations that were either missing or not apparent in the old IXO and Constellation-X designs. High resolution spectrographs always have design issues of this nature.

Figure 2 shows the first problem. Light comes off the back of the p-h's parallel. But each channel is a different distance from zero order. The solution is simple and is also shown in Figure 2. Simply stagger the z positions of the p-h's to create a common focus. Each paraboloid-hyperboloid must be the same distance along the chief ray from the focus even though the variations in graze angle on the steering flat create different paths to the focus.

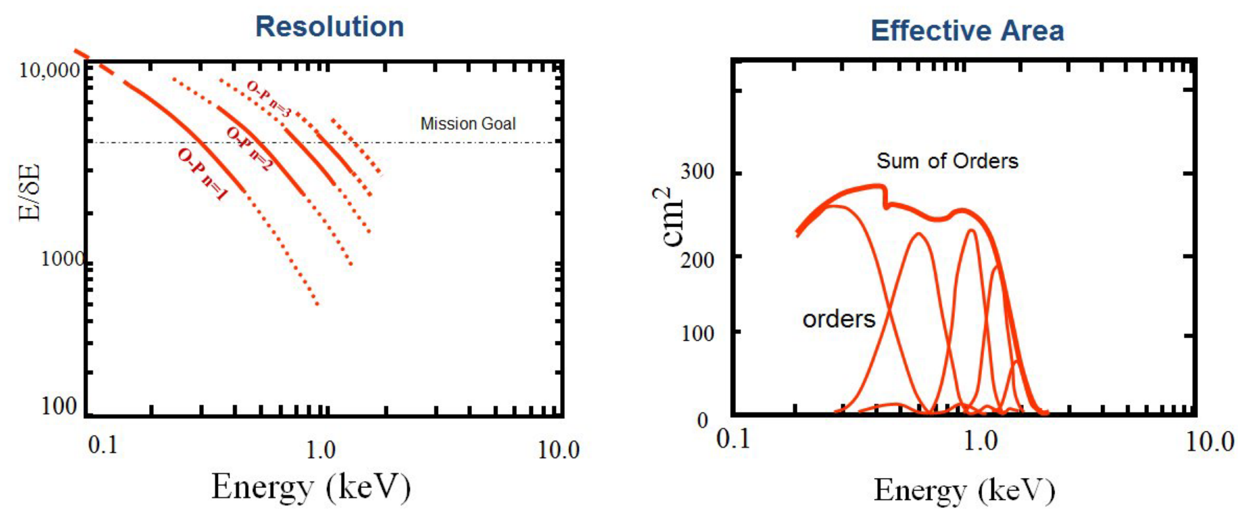

Figure 8: Estimated resolution and collecting area are shown as a function of photon energy for a full system. An average resolution of 4000 is achieved, along with hundreds of square centimeters of collecting area.

A second aberration becomes important at spectral resolutions above 1000. It turned out to be a depth of focus issue from the range of angles impinging on the detector (Figure 3). If the p-h's are arranged so that zero order is in focus, then the light goes out of focus at the top of arc as shown in Figure 5. The solution is another modification to the z positions of the p-h's, so that the beams focus is at top of arc. Once these aberrations are corrected, the system works nicely.

Raytracing was performed on an array of parallel paraboloid-hyperboloid segments that fully populate a 10x100cm box as shown in Figure 4. In Figure 5 we show some resolution pairs that substantiate that the 4000 resolution can be achieved.

4. 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 progress report and will be published later, but a few words about the scope of the mission and the optimal arrangement are in order at this point.

An early version of the WHIMEx concept is shown in Figure 6. 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 7 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. Figure 8 shows the estimated resolution and collecting area as a function of wavelength for this approach.

Finally, Figure 9 compares the WHIMEx performance to other high resolution 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.

5. Other Applications

We have developed the four reflection x-ray optic concept for support of a diffraction grating mission, but the attractive features of the approach could find application elsewhere. For example, if the gratings were to be replaced with mirrors, then we could use the optics to build telescopes that could be coupled to other kinds of x-ray instrumentation.

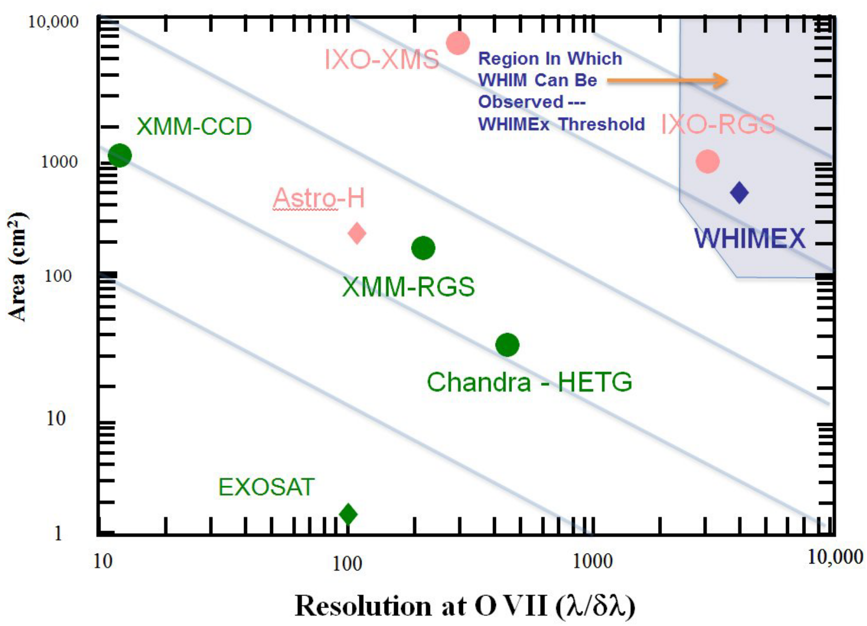

Figure 9: Spectral resolution at the critical OVII absorption line is shown versus effective collecting area for the past and present x-ray observatories in green. In pink we compare to instruments that are in study or fabrication. The diagonal lines are at constant figure of merit, which is the product 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.

For example, the prime instrument on IXO was to be a quantum calorimeter or equivalent. Such an instrument needs to be fed by a very large collecting area telescope that has substantial throughput at 6keV. The four reflection system can support this need, since the paraboloid-hyperboloid pairs have graze angles of just 0.4 degrees and thus operate efficiently at the higher energies. The use of identical p-h pairs would lower the cost and risk of the prime optic.

Then, at any given focal length, the collecting area would be substantially enhanced. By doubling the maximum angle off-axis at which the modules can be placed, a factor of four in collecting area can be achieved. Covering the center of optic should raise that factor to above five. Reflection losses can be held to about 30%, so the net improvement should be over a factor of three. The reduction in focal length will greatly reduce the cost of the mission, as will the mandrel improvement. One can start to envision a mission that can address the prime IXO science without forcing the cost into the "flagship" range.

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