The WHIMEx Mission Concept and Lessons Learned
Response to the RFI NNH11ZDA018L
Concepts for the Next NASA X-ray Astronomy Mission

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Category of Response: Mission Concept (but of relevance to Instrument and Enabling Technologies as well)

I am willing to participate in the workshop if invited.
For the most part our information is open. Northrop-Grumman does have some competition-sensitive information about WHIMEx but would be willing to discuss those materials if needed and if proper arrangements are made.

WHIMEx (Warm Hot Intergalactic Medium Explorer) is an Explorer concept that was just submitted in the latest Explorer round. We were able to propose a mission that could do a substantial fraction of the IXO RGS science for $200M. In the small ($300-$600M) category WHIMEx would be able to achieve the high resolution spectroscopy goals envisioned for IXO and supported in the decadal review. Our top science goal is to detect the x-ray absorption lines of WHIM filaments in the spectra of AGN's.

In this response to the RFI we start with a short discussion of WHIMEx and the lessons learned in the process that may be of value to the x-ray community in planning for the coming decade. This includes a simple explanation of what we did and what resulted. The PI (Cash) also includes some personal comments on the process and suggestions as to how NASA might improve the chances of x-ray missions. These personal views are echoed by many on the team, but are not necessarily the views of the team as a whole. They are submitted in the spirit of trying to create a more productive x-ray astronomy program in the coming years. We conclude with a brief SPIE publication from this summer outlining the WHIMEx mission.

Scientific Need for High Resolution X-ray Spectroscopy

The need to perform x-ray spectroscopy at the resolution limit imposed by thermal line widths has been clear for years and in many respects forms one of the underlying arguments for IXO (and Con-X before it). For the ultraviolet band the argument was successfully made by Lyman Spitzer in the earliest days of the space program and led to a string of scientifically successful missions including OAO-2, Copernicus, IUE and HST. Yet, in the x-ray, the leading concern was imaging up to and including Chandra. While Chandra has been successful spectroscopically, neither the collecting area nor the resolution is adequate to the task of fully removing feature confusion or modeling line profiles so as to accurately measure the physical state of the matter.

The spectral resolution requirement of IXO rose from 300 in the early Con-X days to 3000 by the time of the decadal review as the results of Chandra and XMM came in and re-emphasized the need for resolution at the thermal limit. But when IXO began to stall, many of us who had been developing technology for high resolution spectroscopy began looking for low cost alternative missions. The first result of this rethinking was the WHIMEx proposal to the Explorer opportunity of 2011.

The WHIMEx Experience
In the process of the (ultimately unsuccessful) proposal effort we (the WHIMEx team members) learned a great deal about how IXO technology and science might be addressed in the near term. We here summarize a few of the lessons learned that may be of value to NASA's x-ray astronomy panel.

- *The Community Can Work Together.* Perhaps the most important thing we learned is that the entire community of those interested in high resolution x-ray spectroscopy could organize into a single team when the long-standing organization of the IXO program changed and a new, grass roots response to part of the science could develop.
- *Some IXO science can be addressed in an Explorer.* We developed a spectrograph design that could exceed the resolution requirement of IXO and approach its collecting area to within a factor of two. We simultaneously optimized for ease of fabrication. We chose the hot component of the WHIM as our marquee piece of science but showed that the majority of the IXO-XGS science goals could also be addressed in a $200M Explorer.
- *Innovative technologies remain untapped.* As NuStar and GEMS are showing, there are new technologies for x-ray astronomy that, when tapped, can give us fundamentally new views of the Universe. This is also true for x-ray optics and spectral detectors. There has not been an AO for an x-ray flagship mission since 1983, and the Con-X architecture was chosen sixteen years ago. So the WHIMEx team was able to bring together a variety of new technologies to enable a system with ten times the collecting area and ten times the resolution of Chandra in a low cost Explorer.
- *The Explorer Debrief.* In the Explorer review WHIMEx received a "below average" rating for its science. It also received a "below average" rating for technical readiness. Since this is IXO science and technology, determining why the ratings were low is of general interest to the x-ray community.

My Personal Comments and Suggestions (not necessarily speaking for the entire team)
With this new committee effort, NASA is seeking an effective path forward for x-ray astronomy. The IXO development effort was already a major improvement in organization of mission development, allowing new technologies to enter as they became available and striving to send the technology money to the places it was most needed. The instrument requirements were clearly derived from well-defined science goals.

So why did IXO come in fourth in the decadal review? It came down to concerns about costs. First, IXO would be very large, immediately implying high cost. As a community we can simplify the mission by breaking it into pieces. NuStar and GEMS are already on track to open up two of the science areas of IXO. The other three areas (high throughput spectroscopy with calorimeters, high resolution spectroscopy with gratings, and wide field imaging) can also be addressed individually, though the impact on net science needs to be quantified.

But the decadal review also had concerns about complexity, particularly in the large mirror array. This was mirrored in the WHIMEx reviews. In the era of JWST it is essential to show compelling evidence that all the details of the mission are completely understood. There can be zero doubt that all the pieces will be delivered at price on schedule. It is also essential to show that all details of system buildup, testing, calibration and operation are completely understood. And the only way to achieve those goals is to actually perform all the activities.

There are three main activities that are needed if this ultra-high burden-of-proof standard is to be reached.

1. The first one is easy to implement as a community. With WHIMEx we had to start from scratch with our science section, justifying the science goals that had already been given high priority in the decadal review. Our reviewers had a differing set of priorities, effectively creating an unknown and moving target against which to propose. If the x-ray community could articulate a set of science goals to which we instrumentalists could propose, then the review process would be better controlled. The review could quantitatively assess whether or not the proposed instrument could accomplish the goals as stated. The outcome would be more in line with the needs of the community and less subject to the vagaries of who happens to be on the committee.
2. It is clear we need to build prototypes that meet flight specifications for the mission. WHIMEx was hammered (perhaps rightly) for not having a prototype that showed we had the instrument fully under control. Yet there remains no mechanism for technology to cross that hurdle. Clearly, if the x-ray community wants to win Explorers it needs to invest in prototype equipment. These prototypes would have to be of the approximate size and quality of the proposed mission and shown to perform at the needed level if they are to be truly convincing. This would go a long way to the instruments passing muster in the technical review.
3. Science missions are chosen by scientists. The only way to convince an astronomer that a large, complex instrument is worth building is to show that astronomer exciting data taken with a smaller, lower cost instrument. So actual demonstration of the technology is essential to mission success. Small, inexpensive prototypes must perform actual astronomy that is published if committees of astronomers are to invest heavily in the concept. To provide confidence for an Explorer-class mission, a suborbital demonstration is necessary. To provide confidence for a flagship, an Explorer or Probe class mission would be needed.

Thus I am suggesting to the x-ray community that we reorganize our efforts with these thoughts in mind and perhaps improve our chances of having a productive decade and winning a flagship in the 2020 decadal review.

Our x-ray program should emphasize technology and experience base development through low cost flights. We should support suborbital demonstration of all viable and relevant technologies. These suborbital missions should be supported even if the science is not cutting edge. After suborbital demonstration, modest cost orbital flights should be supported. Ideally these could be in the form of Sounding Rockets to Orbit, as this would allow the greatest variety and flexibility in orbital missions. But, failing the start of such a program, the prototypes would need to be flown on Explorer-class missions. (This, of course, is what is already happening with calorimeters on Astro-H.) Then, we should consider building the key technologies for IXO, like the large area mirror. Starting it now would allow for some false starts but would still allow an undeniable ability to build the flight mirrors by the time of the 2020 review. These activities could be chosen through open debate and consensus within the IXO program, rather than expecting the individuals to win APRAs out of context with the program.

Partial List of Whimex Participants

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X-ray Optics for WHIMEx,
The Warm Hot Intergalactic Medium Explorer

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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

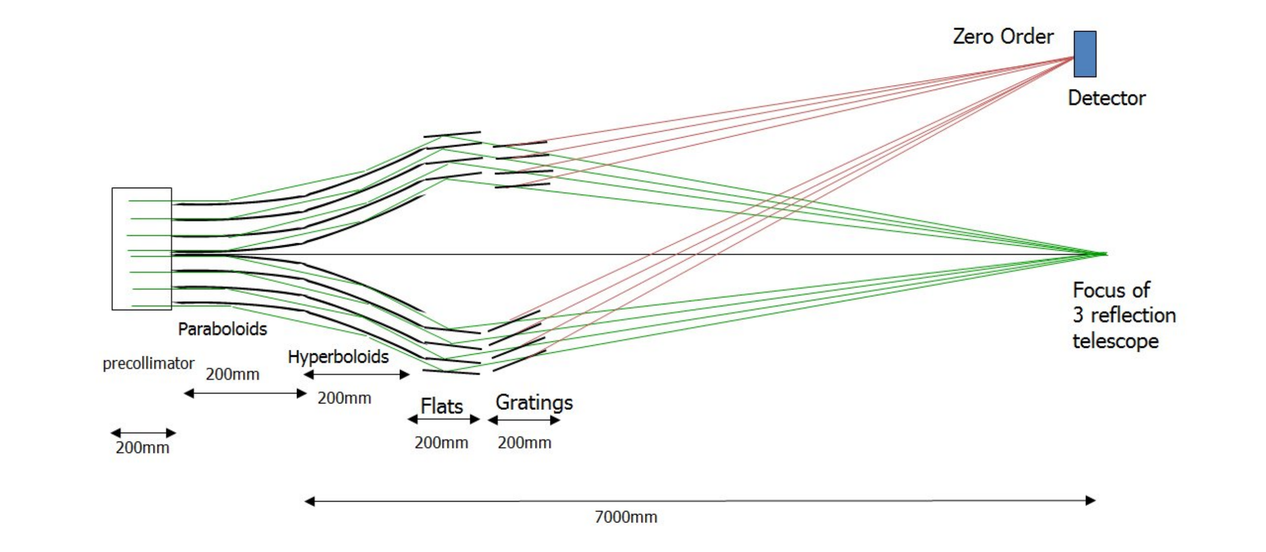

Figure 1: The basic concept behind the four reflection optic is shown. Identical paraboloid/hyperboloid telescopes are mounted in a parallel array. The output of each p-h channel is redirected by a fanned array of flat mirrors to a focus, effectively creating a three element telescope. This converging 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.

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.

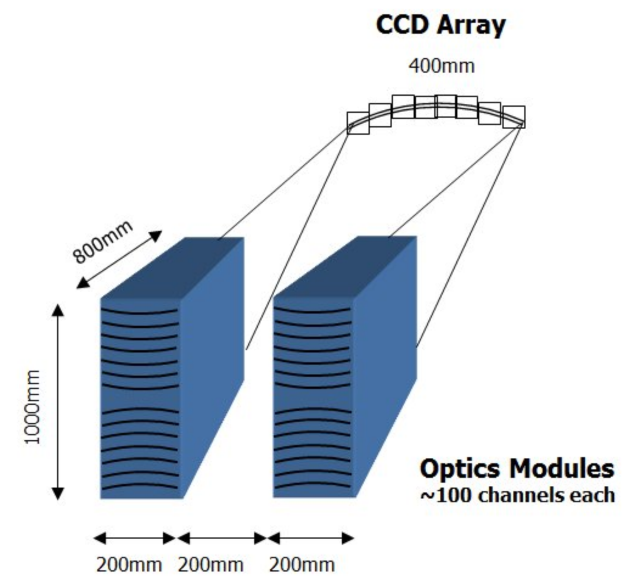

Figure 2: To maximize the effects of subaperturing, the paraboloid/hyperboloids must be narrow. Aperture is built up by stacking in the vertical direction. Multiple spectra may be placed on a single arc of CCD detectors.

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.

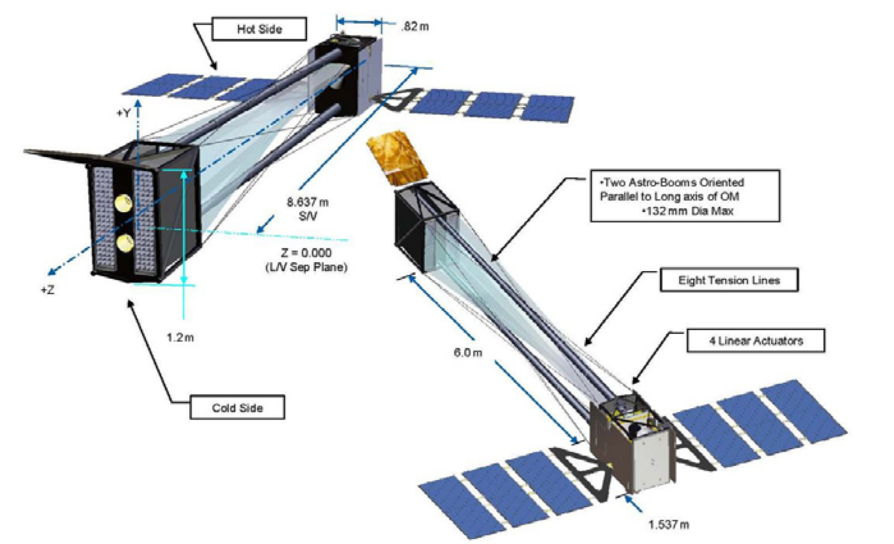

Figure 3: Preliminary CAD rendering of a spacecraft suitable for supporting the spectrograph. A boom deploys the prime optics to their 7m focal length after launch.

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

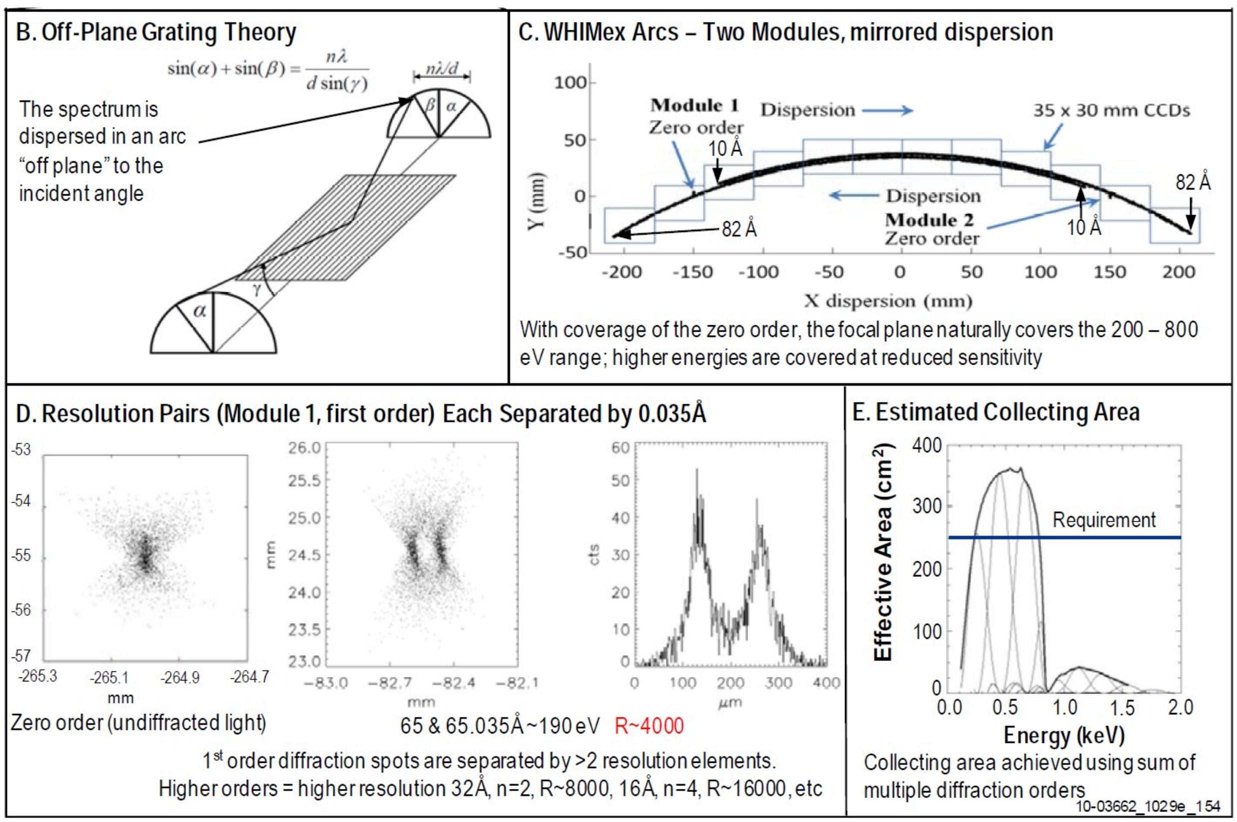

Figure 4: Estimated resolution and collecting area are shown as a function of photon energy for a full system. An average resolution of 4000 is achieved, along with hundreds of square centimeters of collecting area.

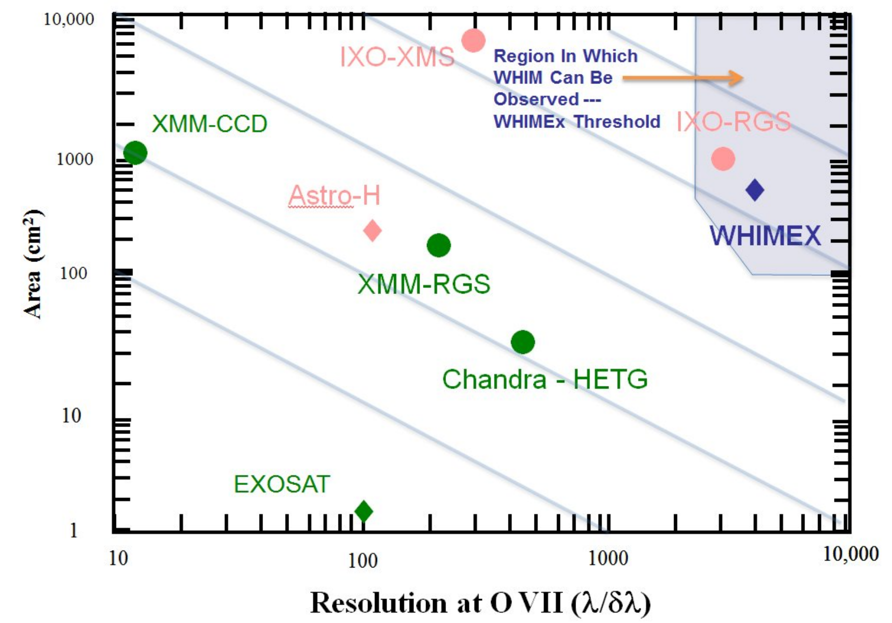

Figure 5: Spectral resolution at the critical OVII absorption line is shown versus effective collecting area for the past and present x-ray observatories. We compare instruments that are in study or fabrication. The diagonal lines are at constant figure of merit, which is the product of area and resolution. 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]

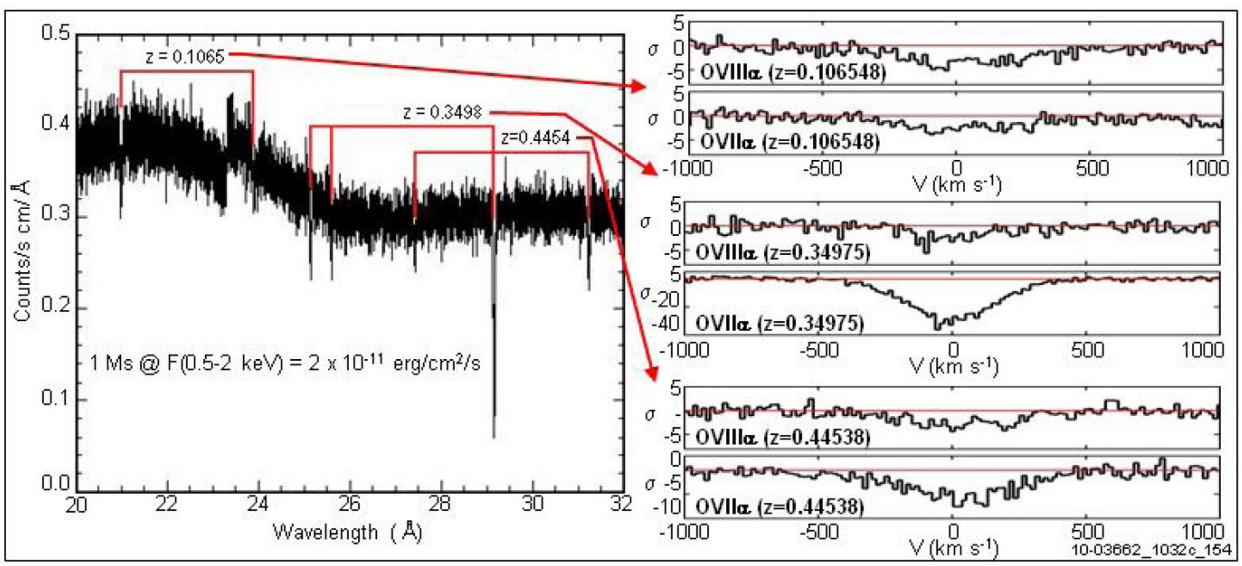

Figure 6: A simulation of a distant AGN seen through the WHIM. Strong absorption features from OVII and OVIII are clearly seen from hot filaments of gas between the galaxies.

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 expected in a nominal mission.

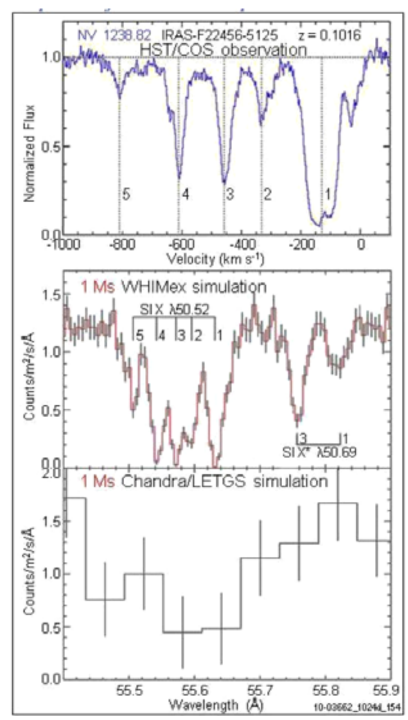

Figure 7: An actual outflow feature observed in NV is shown from COS. Simulations of an x-ray observation with both Chandra and WHIMEx show the importance of high resolution

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.

The authors would like to thank the many people who have participated in the WHIMEx concept development.

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