An X-ray Grating Spectroscopy Probe

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In the discussion of the International X-ray Observatory (IXO) in New Worlds, New Horizons, two key instrumental capabilities were identified for meeting the scientific objectives. These were an X-ray calorimeter array and an X-ray grating spectrometer. ESA's Athena mission incorporates a calorimeter with capabilities comparable to those planned for IXO, but it is lacking a grating spectrometer. While an Explorer class grating mission (effective area ~500 cm^2, $\lambda/\Delta\lambda \sim 2500$) can address many of the IXO science objectives, an X-ray Grating Spectroscopy Probe (XGS-P) providing higher spectral resolving power ($\lambda/\Delta\lambda > 5000$) and higher throughput (effective area > 1000 cm^2) in the soft X-ray band (5-50 Å) could fully achieve and go beyond the IXO science objectives. A partial list of key science questions, along with how XGS-P can address them follows:

1. ***What is the role of matter and energy feedback from supermassive black holes in the evolution of galaxies?***
   a. XGS-P would be capable of exploring the full range of ionization states and density characteristics of SMBH accretion disk winds on recombination timescales of thousands of seconds, thus sensitively probing time variation in these winds. Furthermore, current grating studies under-resolve the spectral complexity of ionized absorbers, which is evident at other wavelengths, but not yet realized for X-rays. The >5 factor of improvement over existing observatories in spectral resolving power can study absorption line profiles in depth to uncover wind dynamics. Such studies can occur on hundreds of AGN over many absorption lines such as the K-shells of C, N, O, and Ne, as well as the L-shells of Si and Fe while only a small number of bright AGN on longer time scales would be possible with the capabilities in an Explorer mission.
   b. Studying density-sensitive lines such as Fe XX, XXI, and XXII can accurately trace the launching radius of the wind which is currently unknown and key to understanding the physical mechanisms of this feedback.
   c. Emission lines of the Fe L-shell will probe the relativistic inner disk conditions in some of these systems and provide insights into the environments adjacent to the central supermassive black hole.
   d. Resolving down to the thermal limit (~ 50 km/s) for photoionized plasmas would open new diagnostics for the physics of outflows driven from black hole systems.
2. ***What is the distribution of hot baryons?***
   A significant fraction of baryonic matter and metals in the Universe are thought to exist in hot (10^{6-7} K) gas in the outskirts of galaxies and clusters, comprised of both infalling material that never formed into dense structures as well as material expelled via outflows from supermassive black holes, although the relative strength and importance of each process remains uncertain. Only a grating spectrometer can detect the metals in this hot gas via absorption lines of C and O to determine how the gas density and temperature vary with galactocentric (or cluster-centric) radius. With XGS-P, equivalent widths down to below 2 mÅ could be measured, enabling measurements of multiple ions along each line of sight, constraining both abundances and temperatures.
3. ***What are the basic characteristics of our hot Galactic halo?***
   a. Using X-ray absorption spectroscopy, XGS-P can measure the abundances of C, N, O, and Ne, along with the heavier elements Si, S, and Fe. These relative abundances will determine SN type progenitors which is key to determining the halo's origin.
   b. Measurements of C V absorption will be possible for the first time, which, when combined with O and N measurements, will determine the temperature distribution of the halo.
   c. The high spectral resolving power of XGS-P will allow derivation of a rotation model for the halo and characterize the angular momentum distribution. The radial dependence on rotation provides information on the origin of the halo and its interaction with Galactic fountains.
4. ***What are the characteristics of the solid phase of material along the line-of-sight to extragalactic sources?***
   a. Soft X-ray absorption spectroscopy can concurrently address both gas and dust abundances unlike any other wavelength band. Absorption and scattering fine structure at the O-K, C-K, and Fe-L edges can be compared to laboratory dust analogs to determine grain compositions and properly constrain dust grain models. The details in these features can only be seen through the combination of spectral resolving power and effective area offered by XGS-P.
   b. Such studies are crucial to understanding foreground linear polarization in CMB measurements, the dust torus intrinsic to AGN, and extragalactic dust in the foreground to XGS-P sightlines.
5. ***How do young stars accrete?***
   High spectral resolving power is necessary to separate contributions from coronal emission, accretion processes, and outflows. Only when combined with large effective areas, such as those offered by XGS-P, can

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a complete study of line ratios be performed on a substantial sample of young stars. Accessing He-like triplets such as Mg XI, Ne IX, OVII, and, for the first time, CV will provide necessary constraints on accretion models.

6. ***What are the dynamics of hot star winds?***
   XGS-P will be able to resolve structure present in the strong emission lines from C, N, O, Ne, Mg, and Fe. This structure evolves on the timescale of hours and produces broad lines with distinct profiles. The line profile structure is affected by inhomogeneities in the wind and acceleration of the plasma, while being dependent on the radius of formation. Fully resolving this structure in a wealth of lines will allow determination of where X-ray emitting shocks are formed, characterizing the dynamics within these winds.
7. ***How do extreme events in our Universe evolve over time?***
   a. LIGO's first detection of gravitational waves (GW) opened a new door of scientific discovery. Typical GW sources are expected to be mergers of two neutron stars which should generate a gamma ray burst and possibly emission from magnetar-powered ejecta. The XGS-P would be sensitive to the faint spectral features in the spectrum of either the direct or scattered X-rays during the afterglow of the source, thus allowing characterization of this GW counterpart.
   b. X-ray flares in galaxies can be attributed to tidal disruption of a star by the central supermassive black hole. These tidal disruption events can be observable for months to years. The XGS-P can perform detailed spectroscopy to measure the temperature, abundance, velocity, and ionization state of this plasma and do so over multiple observations to trace the evolution of the disrupted stellar material.

A concept probe study for a Notional X-ray Grating Spectrometer (N-XGS) was completed earlier this decade and is included in the NASA X-ray Mission Concepts Study Project Report, August 2012 (http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php). The optical design of XGS-P would be very similar to that of N-XGS, but could also take advantage of recent developments in X-ray mirror, grating, and detector technologies.[1] The instrument suite would likely consist of two or more independent, objective grating spectrometers operating in parallel. The telescope would have a modular design with several azimuthal sectors contributing to the total collecting area. Each sector would feed an array of gratings that disperse the spectrum onto an array of CCDs. The modular design maximizes spectral resolving power by only sampling a fraction of the total telescope PSF (subaperturing) while also allowing for increased effective area through the incorporation of multiple independent spectrometers.

The performance requirements for XGS-P ($\lambda/\Delta\lambda > 5000$, effective area > 1000 cm^2, bandpass <2 keV) could be realized in the near future through existing technologies. X-ray telescope technologies are rapidly advancing, and methods such as those using slumped glass optics are capable of fabricating and aligning mirrors to reliably produce Wolter-I telescopes with PSFs < 10", HEW. Slumped glass optics from GSFC are at a TRL of 4 and would be a feasible and technically sound choice for XGS-P. Furthermore, two grating technologies – off-plane reflection gratings and critical angle transmission gratings – are also being developed through PCOS programs, clearing a TRL of 4 with a clear path to TRL 5. The detectors would be composed of CCDs and electrical subsystems similar to those used on previous X-ray missions and are already at a high TRL as a result. System level tests incorporating these technologies are already planned and will reduce the most critical technical risk for a Probe mission. Even though developments are currently being made in all the key areas for a grating spectroscopy probe, mission specific developments to reach TRL 6 would still take time given the different focal length, module size requirements, alignment budgets, etc. that will be specific to the final design and unique from what is currently being developed.

A proper study of an XGS-P capable of achieving the science goals listed above is necessary to accurately assess cost and spacecraft requirements. This study should be performed after a conceptual design is formulated using the state-of-the-art for the various spectrometer technologies. However, a rough order of magnitude cost and estimate of mission requirements for XGS-P can be based upon the previous N-XGS study, which had similar optical designs and spacecraft demands. Costs drivers such as mass, power, and launch vehicle are similar and the cost study performed for N-XGS can be used as a basis for XGS-P. This cost came out to be $784M, including reserves. This is dominated by the Payload (~$166M), Spacecraft (~$229M), and Launch Vehicle ($140M) with the remainder divided between the other various WBS elements. The N-XGS basis for spacecraft requirements includes a mass of 828 kg, power of 646/1451 W (observing/peak), 10 Mbps downlink, and 58 Gbit of storage. These numbers include 30% contingency. The prime mission would have a lifetime of 3 years and a goal of 5 with an orbit at L2 after being delivered by a Falcon 9 vehicle. Pointing requirements include control of 45" over 200 ks, knowledge of 1.3" (3σ, per axis), and jitter of 0.2" RMS for frequencies above 15 Hz.