Arcus: Exploring the Formation and Evolution of Clusters, Galaxies and Stars

Randall K. Smith[1], R. Allured[1], M. Bautz[2], J. Bookbinder[3], J. Bregman[4], L. Brenneman[1], N. Brickhouse[1], D. Burrows[5], V. Burwitz[6], P. Cheimets[1], E. Costantini[7], C. DeRoo[8], R. DeRosee[3], A. Foster[1], C. Grant[2], R. Heilmann[2], E. Hertz[1], D. Huenemoerder[2], J. Kaastra[7], R. McEntaffer[8], E. Miller[2], J. Miller[4], R. Mushotzky[9], K. Nandra[6], M. Nowak[2], R. Petre[10], K. Poppenhager[11], A. Ptak[10], J. Sanders[6], M. Schattenburg[2], N. Schulz[2], A. Smale[10], L. Valencic[10,12], R. Willingale[13], J. Wilms[14], S. Wolk[1]
[1]Smithsonian Astrophysical Observatory, [2]MIT, [3]NASA/Ames, [4]U. Michigan, [5]Penn State University, [6]MPE, [7]SRON, [8]U. Iowa, [9]U. Maryland, [10]NASA/GSFC, [11]Queens University Belfast, [12]JHU, [13]U. Leicester, [14]FAU

We present the design and scientific motivation for Arcus, an X-ray grating spectrometer mission to be proposed to NASA as a MIDEX in 2016. This mission will observe structure formation at and beyond the edges of clusters and galaxies, feedback from supermassive black holes, the structure of the interstellar medium and the formation and evolution of stars. Key mission design parameters are R~3000 and ~500 cm² of effective area at the crucial O VII and O VIII lines, with the full bandpass going from ~10-50Å. Arcus will use the silicon pore optics proposed for ESA's Athena mission, paired with off-plane gratings being developed at the University of Iowa and combined with MIT/Lincoln Labs CCDs.

SCIENCE GOALS	SCIENCE OBJECTIVES	SCIENTIFIC MEASUREMENT REQUIREMENTS		INSTRUMENT REQUIREMENTS	BASELINE REQUIREMENT	PROJECTED PERFORMANCE	MARGIN ON BASELINE
		Physical Parameters	Observables	Parameter	Value	Value	
G1: Determine how baryons cycle in and out of galaxies	Measure the radial profiles of hot gas at and beyond the virial radii of galaxies and clusters, and all phases of gas in our Galaxy	G1-1. Column density of absorber as a function of radial distance from nearest cluster center	Observe 20 lines of sight to yield 40 detections of OVII Kα (at 21.6Å, z=0) of > 4 mÅ EqW spanning a total summed redshift range (Σzi) of 8	**G1-1(a):** Spec. Res (21.6-25Å) **G1-1(b):** A_{eff}(21.6-25Å) (avg) **G1-1(c):** Background @ 24Å	λ/δλ=2000 400 cm² <0.015 cts/s	2770 640 cm² 0.006 cts/s	39% 60% 150%
		G1-2. Column density of absorber as a function of radial distance to nearest galactic center	Measure OVII, OVIII lines with >3.5 mÅ EqW for Milky Way & M31 to yield 30 detections using 20 lines of sight for LSS above, plus 5 additional targets	**G1-2(a):** A_{eff}(16-21.6Å) (avg) **G1-2(b):** Spec. Res. (16-21.6Å) **G1-2(c):** Rel. A_{eff} cal in res. elem.	200 cm² λ/δλ=1500 ±10%	593 cm² 2260 ±5%	196% 51% 100%
		G1-3. Column density of neutral and ionized absorbers along Milky Way line of sight	Observe 21 lines of sight with K-shell absorption lines from C, N, O, Ne plus L-shell Fe lines >3.5 mÅ EqW using bright XRBs	**G1-3(a):** Bandpass **G1-3(b):** Min Spec Res (9-51Å) **G1-3(c):** CCD energy res.	9-51Å λ/δλ=1000 250 eV	9-51Å 1550 100 eV	By design 55% 150%
G2: Determine how black holes grow and influence their surroundings	Measure the mass, energy, and composition of outflowing winds from the inner regions of black holes	G2-1. Centroids, column densities, and line profiles of warm absorbers near SMBHs as a function of time	Measure 90 K-shell absorption lines from C, N, O, Ne plus L-shell Si, Fe lines towards 5 AGN; resolve v>100 km/s	**G2-1(a):** Wavelength cal. **G2-1(b):** Absolute A_{eff} cal.	<0.4mÅ ±20%	0.3mÅ ±10%	33% 100%
		G2-2. Centroids, column densities, and line profiles of warm absorbers near XRBs as a function of time	Measure 30 K-shell absorption lines from C, N, O, Ne plus L-shell Si, Fe lines towards 5 XRBs; resolve Δv>100km/s on disk dynamical times (10s)	**G2-2(a):** Time Resolution	10 s	1 s	1000%
		G2-3. Column densities of many elements to reveal abundance ratios and distributions in galaxy cores	Measure at least one absorption line with >3.5 mÅ EqW for each element C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe and Ni towards AGN	As above	As above	N/A	
G3: Understand how stars, circumstellar disks, and exoplanet atmospheres form and evolve	Observe material accreting onto young stars along with stellar coronae from young and main sequence stars; also observe exoplanet transits	G3-1. For young stars, map the electron temperature, electron density and turbulent velocity of the shock and absorption column density of pre-shock gas	Measure emission line flux, velocity, width of C, N, O, Ne, Fe for sample of 14 classical and weak-lined TTauri, Herbig AeBe stars with Δv>100 km/s	**G3-1(a):** Bandpass **G3-1(b):** Min Spec Res (9-51Å) **G3-1(c):** A_{eff}(9-51Å) (avg)	9-51Å λ/δλ=1000 200 cm²	9-51Å 1550 518 cm²	By design 55% 159%
		G3-2. For stellar coronae, determine EMD using wealth of strong lines; measure weak temperature-sensitive lines	Measure emission line flux of C, N, O, Ne, Fe and line ratios to 5s using 6 dielectronic recombination satellite lines of O VIII for 20 stars	As above	As above	N/A	
		G3-3: Measure the X-ray transit depth of an exoplanet as function of energy	Make 10 transit observations of one exoplanet, duration 30 ks/each, to measure X-ray depth of 12% to 5s accuracy	**G3-3(a):** A_{eff}(19Å)	200 cm²	261 cm²	31%

EXPLORING MATTER AT THE EDGES OF GALAXIES

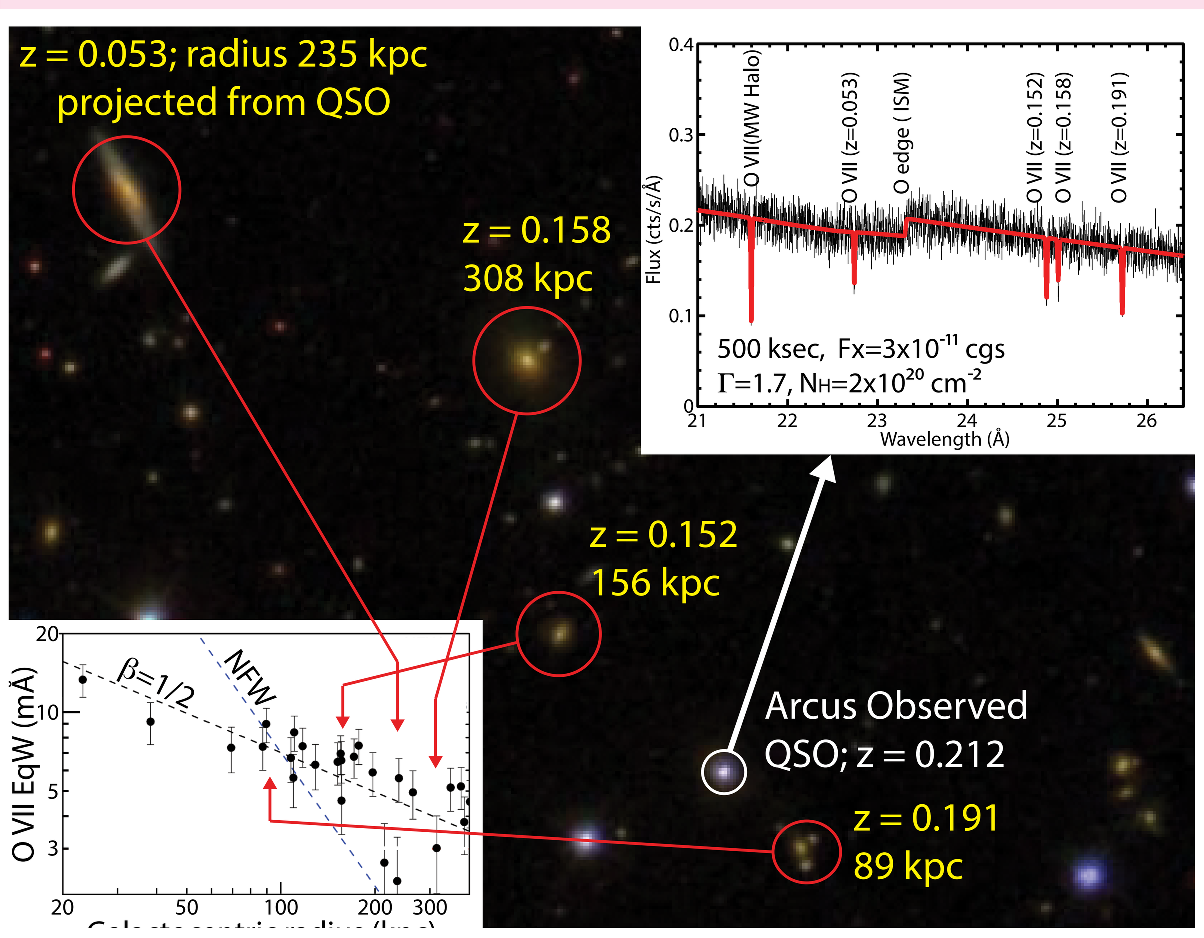
Bright background sources illuminate material at and beyond the edges of clusters and galaxies. Combined with spectra of Milky Way sources, Arcus will allow us to create a complete picture of the formation and cycling of metals in and out of galaxies and clusters. Multiple lines of sight exist that will allow us to map the location, motion, and temperature of hot gas around galaxies, groups, and clusters, revealing its origin and destiny.

FEEDBACK FROM SUPERMASSIVE BLACK HOLES

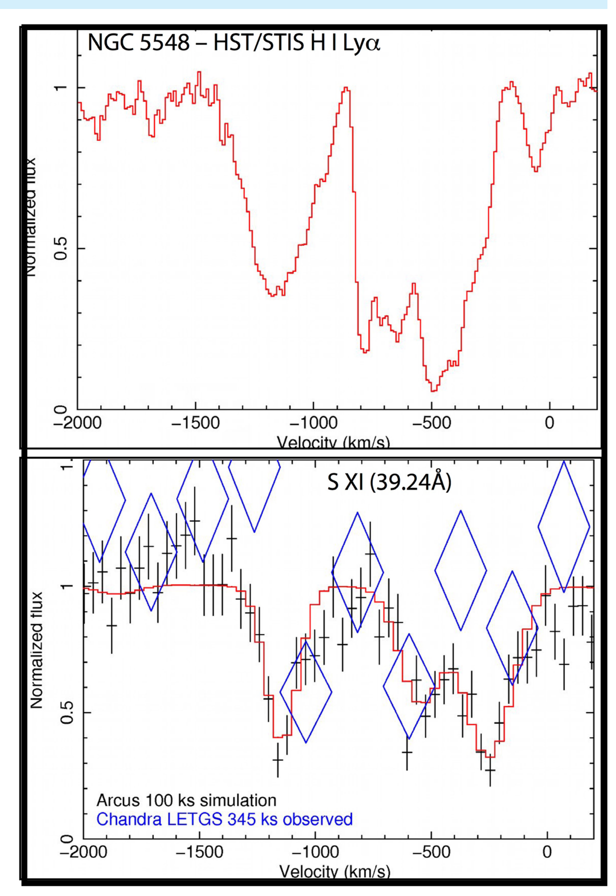
Exploring how physics behaves at the extremes of space and time near a black hole and learning how supermassive black holes have formed and evolved requires X-ray spectra. Observing on timescales of a few ksec requires a large effective area combined with resolution over a broad bandpass to measure spectral changes that reveal the ionization state, density, and total mass flux in outflowing material near the black hole. Arcus detects nearly every iron ion, allowing far more sensitive studies of absorption than other observatories.

THE BIRTH AND EVOLUTION OF STARS

Accretion from a protoplanetary disk drives the final stage of star formation, during which planets are also formed. Accreting young stars are spinning too slowly, given that they are still adding mass and contracting. Does the accretion drive a wind that removes angular momentum? Similarly, young stars show high levels of magnetic activity relative to their main sequence counterparts. How do the accretion streams interact with the stellar magnetic fields? High-resolution X-ray spectra are the only way to diagnose these highly-energetic processes.



Arcus will observe the end products of structure formation in the form of hot gas beyond the virial radius of galaxies and clusters, as well as detecting filaments in the IGM itself via absoprtion to background AGN. In the case shown at right, a single AGN observation can reveal absorption features from multiple galaxies to map the distribution of hot gas around typical galaxies with ease. Arcus will allow us to identify features in hot gas outflow that match cooler gas detected by HST (see right). Hot gas is thought to carry most of the energy of the outflow, but diagnosing their mass requires using density-sensive lines that are not resolvable with existing missions or even Astro-H.



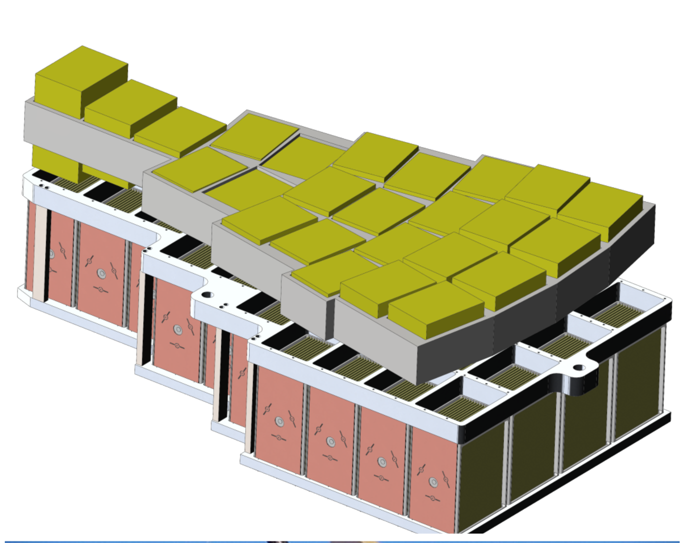
Conclusions

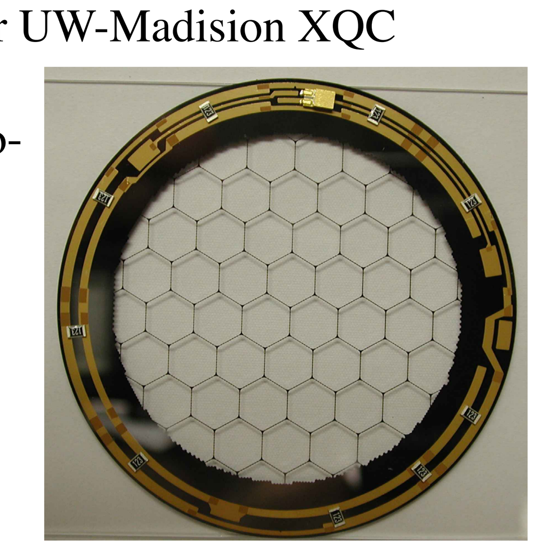
The Arcus science goals were highly regarded both by NASA and by the community, as reflected by their mention in the 2010 New Worlds, New Horizons Decadal Survey. With ESA's decision to launch Athena in 2028 as their L2 mission, the grating science remains an exciting opportunity.
The challenge has been to achieve those goals in a timely fashion and an affordable cost.

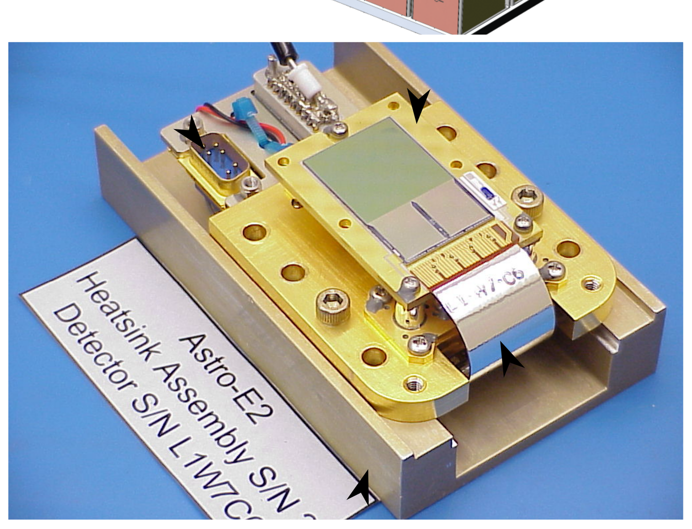
Arcus will address significant aspects of the scientific recommendations of the 2010 Decadal Survey at the cost of a MIDEX mission, with observatory capability thereafter.

Arcus Optical & Detector Layout

- Uses 3 'petals' packed with silicon pore optics (SPO) to achieve at least 500 cm² area at O VII
- X-rays diffracted by off-plane grating (OPG) modules
- 12 m focal length, same as Athena
- Each petal has a focal plane detector for dispersed light and for zero order.
- Uses Suzaku-type back-illuminated CCD shown at right
- Reuses filters developed and demonstrated for UW-Madision XQC sounding rocket program

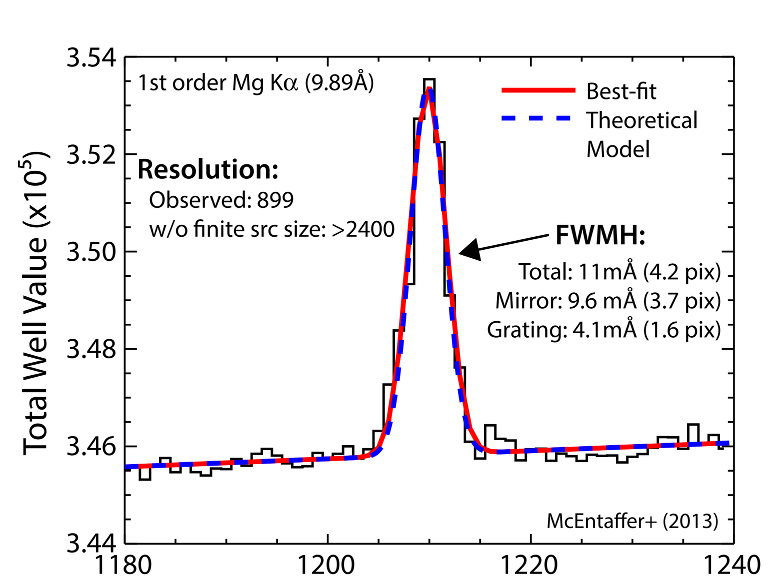


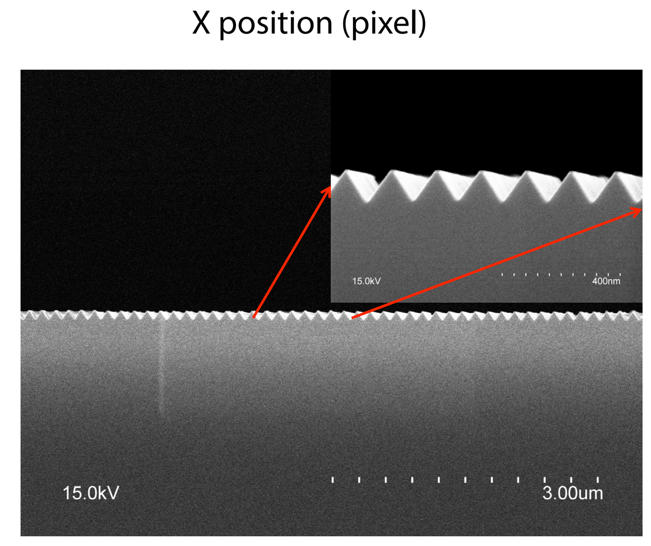




Off-Plane Grating (OPG) Arrays

- Leverages NASA's investment in OPGs for Con-X and IXO.
- Demonstrated at the NASA/MSFC stray light facility to reach R = λ/Δλ > 1000, limited by the finite source size.
- Recent tests at PANTER for Arcus show multiple gratings can be co-aligned.
- Blazed off-plane gratings have been demonstrated at U. Iowa, as shown in the SEM at right
- Gratings will be housed in modules that will be paired to the silicon pore optics modules, simplifying assembly and alignment.





Silicon Pore Optics (SPO)

- Leverages ESA's substantial investment in SPOs.
- Subapertures the optic to disperse along the narrow "transverse" PSF
- The data shown here at right find a 1.6" FWHM in the transverse PSF
- The probe beam has a divergence of 1", so a 1" image is the geometrical limit.
- **While under active development, the current silicon pore optics meet the Arcus requirement.**