Arcus - Exploring the formation and evolution of clusters, galaxies and stars

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ABSTRACT

Supermassive black holes (SMBH) interact with gas in the interstellar and intergalactic media (ISM/IGM) in a process termed “feedback” that is key to the formation and evolution of galaxies and clusters. Characterizing the origins and physical mechanisms governing this feedback requires tracing the propagation of outflowing mass, energy and momentum from the vicinity of the SMBH out to megaparsec scales. Our ability to understand the interplay between feedback and structure evolution across multiple scales, as well as a wide range of other important astrophysical phenomena, depends on diagnostics only available in soft X-ray spectra (0.1-1.5 keV). *Arcus* combines high-resolution, efficient, lightweight X-ray gratings with silicon pore optics to provide 3-10x the efficiency, 3-10x the spectral resolution, and >10x the collecting area of the *Chandra* gratings. Flight-proven CCDs and instrument electronics are strong heritage components, while spacecraft and mission operations also reuse highly successful designs.
Keywords: X-ray gratings, X-rays: Spectroscopy, Missing baryons, Explorer missions

1. INTRODUCTION

Understanding the formation and evolution of the Universe’s large scale structure (LSS) endures as a key goal of modern astronomy. While growth via the gravitational collapse of dark matter is theoretically well-modeled, characterizing the nature and distribution of baryonic matter is more challenging because its dominant component resides in the tenuous, hot, metal-enriched gas in interstellar and intergalactic media (ISM/IGM). These baryons experience shock heating, radiative cooling and feedback from black holes and star formation, all of which play critical roles in the evolution of the ISM/IGM. No current or planned mission has the ability to directly observe these “missing baryons” and determine their properties; even future microcalorimeters on *XRISM* and *Athena* lack the sensitivity needed <2 keV to detect and characterize the weak ISM/IGM spectral features. Doing so requires an X-ray grating spectrometer with a tenfold advance in 10-50Å sensitivity. This bandpass includes many diagnostic features, enabling measurements of the temperature, density, chemical abundance and ionization of the ISM/IGM, crucial to understanding how this baryonic reservoir formed and evolved.

Using a range of surveys described in Section 2, the *Arcus* mission will shed new light on how multi-scale feedback shapes the LSS, addressing multiple themes posed in the Astro2020 Decadal Survey [1] and NASA Science 2020-2024 [2] through its three science goals. The first of these is to determine how gas, metals, and dust flow into, through, and out of galaxies by measuring the distribution and properties of the gas around galaxies and clusters, including in and around our own Galaxy. The second goal is to reveal how black holes impact their surroundings, including the hot baryons in the

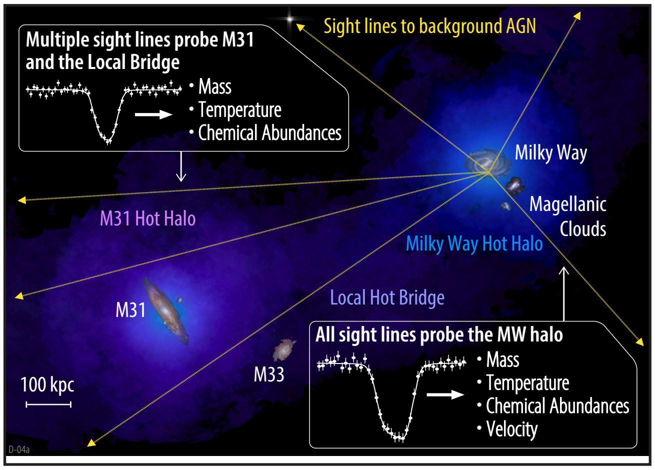

Figure 1: Every *Arcus* extragalactic sight line probes not only external galaxies, groups and clusters but also the Milky Way hot halo, providing measurements of the temperature, mass distribution and velocity of the gas. Multiple sight lines examine the M31 halo and the Local Bridge.

cosmic web. This requires measuring the mass, energy and momentum in accretion-driven winds from supermassive black holes (SMBHs). Finally, feedback can be observed on even smaller scales by probing stellar activity across the entire range of stellar types, including exoplanet hosts. *Arcus's* unique sensitivity and spectral resolution will achieve these goals by surveying a wide range of sources within and beyond the Milky Way. The mission will complement other observatories studying LSS formation and evolution, including *Athena, Vera Rubin Observatory, Euclid, ALMA, JWST* and *E-ELT/US-ELT.*

2. SCIENCE

2.1 Gas, Metals, and Dust in and around Galaxies

During structure formation, accretion shocks and feedback from supernovae (SNe) and active galactic nuclei (AGN) heat gas in galaxy groups and clusters, galactic halos and the intergalactic filaments that comprise the cosmic web [3-6]. This ISM/IGM gas (10^5-10^8 K) is thought to contain about half of all baryons and ~80% of metals in the local Universe [7-9]. Characterizing this gas constitutes a "major frontier" of Astro2020 [1]. *Arcus's* first science goal is to observe this medium and determine its fundamental properties.

Nearly all of the ion transitions useful for such observations occur in the X-ray bandpass, but most of the gas is so diffuse that its emissivity is miniscule. As such, absorption-line spectroscopy toward bright point sources is the most accessible powerful probe of the intervening ISM/IGM. Absorption by O VII, O VIII, and other X-ray lines has already been detected in gas around the Milky Way [10-13], with column densities ≥10× greater than the lower-ionization absorption lines seen in the UV (e.g., Si II through O VI; [14,15]). Beyond our Galaxy, one very deep XMM-Newton observation found such X-ray absorption, implying that most of the baryons reside in this hot, dilute phase [16]. Evidence for hot galaxy halos is corroborated by Sunyaev-Zel'dovich (SZ) stacking measurements [17,18]. However, ascertaining the origin, distribution and impact of the hot ISM/IGM gas requires an unbiased census of its mass, composition, thermal structure and dynamics. These properties are derived from the ratios and profiles of weak absorption lines that demand high spectral resolution and sensitivity only achievable with *Arcus* [19].

The *Arcus* Halo Medium and Deep Surveys (HMS, HDS) will measure the X-ray absorption of highly ionized gas in the ISM/IGM along dozens of sight lines, with ~100 detections expected in multiple ions. Simulations of structure formation predict a range of equivalent width (EW) distributions (see Fig. 2). *Arcus* will determine the cosmic density of several elements, deriving the census of metals in the ISM/IGM.

The primary absorption hosts are galaxy halos, galaxy groups and the outer parts of galaxy clusters. Galaxy halos should be the most common hosts due to their space density and because their virial temperatures align well with the X-ray absorption lines. Galaxy groups are hotter and have higher column densities, making them the likely hosts of higher ionization lines (O VIII, Fe XVII). The rarer, higher mass galaxy clusters have the highest virial temperatures, but as the temperature drops with radius, the gas near and beyond the virial radius can produce absorption lines detectable with *Arcus*. We will identify likely hosts by matching optically identified objects (with redshifts) to X-ray features. Our simulated HMS data set (based on [20]; Fig. 4) is a conservative estimate, as two absorption systems toward an AGN have now been found [16,21], lying above model expectations, e.g., [22,23]. Little

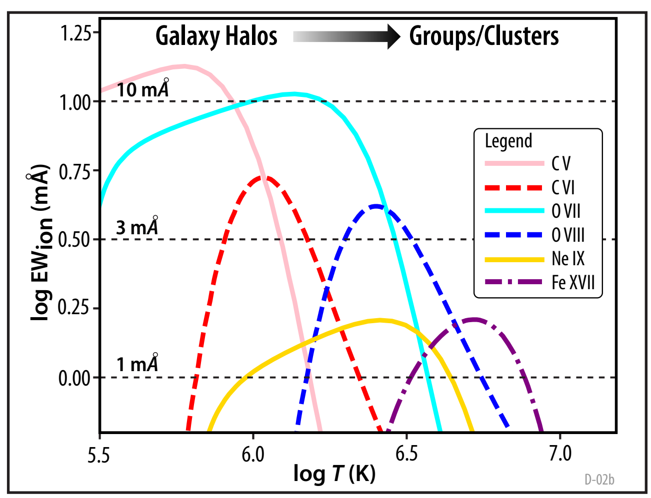

Figure 2: *Arcus* will determine the temperature distribution of halo gas in galaxies, groups and clusters. Typical galaxy halo EWs are simulated at T_{virial} and Z=0.3 Zsolar. The HMS (3 mÅ) probes oxygen and carbon species while the HDS (1 mÅ) adds hotter ions and can detect superwind feedback and cosmic web filaments.

is known about the more diffuse case probed by the HDS, but even in a conservative model *Arcus* will make multiple detections. Upcoming X-ray spectroscopy missions, such as *Athena,* only expect to detect O VII filaments down to EW ~ 5 mÅ [24].

Arcus will also observe hot gas closer to home, as the Milky Way offers unique insights into hot halo properties. Every extragalactic sight line probes the halo (see Fig. 1), and the average EW(O VII) ≥ 20 mÅ. Existing observations [25] show that *Arcus* will typically detect nine Galactic absoption lines along each sight line. Each detection encodes the gas temperature distribution and cooling rate (i.e., X-ray luminosity), even for a possible super-virial, $\sim 10^7$ K component [26].

The current uncertainty on the hot gas mass within R_{200} (~250 kpc) is ~200% [15, 27, 28], meaning that we cannot distinguish between different galaxy formation models. *Arcus* will reduce this uncertainty to just 25% through the Halo Galactic Survey (HGS), 100 lines of sight within the Galactic plane using bright background sources such as X-ray binaries. Parametric density models can be fit to the absorption columns after correcting for modest optical depth effects [29]. These models are most accurate within 50 kpc [27], but by measuring the hot gas columns to LMC/SMC targets (e.g., [12]) and comparing them with extragalactic sight lines (Fig. 1), *Arcus* will be able to extrapolate to R_{200} with improved accuracy to constrain the radial distribution of gas bound to the Milky Way.

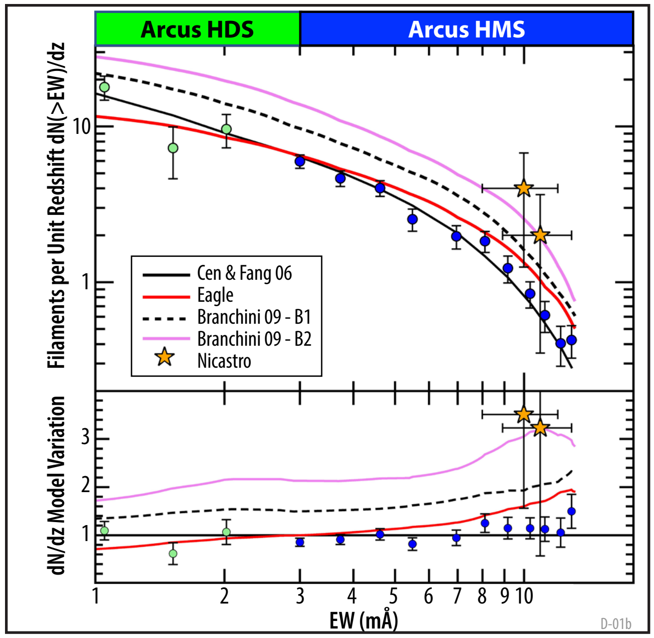

Figure 4: *Arcus* can recover an input dN/dz distribution of O VII. The data will distinguish between models with different feedback prescriptions from SNe and AGN at >99% confidence. Existing detections of O VII absorbers (gold stars; [16]) cannot differentiate between models due to their large errors (all errors are 1 sigma). The bottom panel is normalized by the input model.

2.2 AGN Wind Outflows

Astro2020 asked, "How do SMBHs form and how is their growth coupled to the evolution of their host galaxies?"[1] SMBH accretion and its associated feedback is thought to be responsible for the correlation between SMBH mass and velocity dispersion in galactic bulges [30-32], but quantitative confirmation of this link has been lacking. X-rays are particularly crucial, as X-ray winds may carry ~1000× the mass of UV outflows [33, 34], though these may be different phases of the same medium [35].

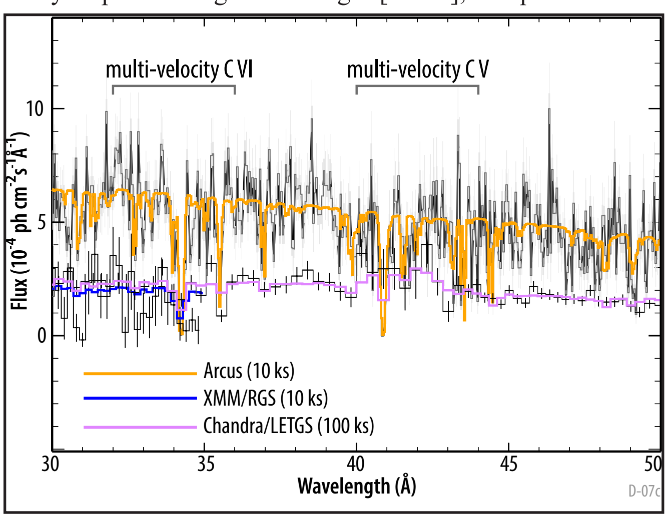

Figure 3: A simulated *Arcus* ABS spectrum (data in black, model in orange), with a typical flux of 10^{-11} erg cm^{-2} s^{-1} in the soft X-rays. In just 10 ks, *Arcus* readily detects each of the six kinematic components observed and measures velocities, column densities and ionizations with exquisite accuracy. Existing gratings data are shown for comparison. The model is based on NGC 5548.

The *Chandra* and *XMM-Newton* grating spectrometers have made important progress toward answering these questions. In the deepest exposures of the brightest AGN, accretion-driven winds are found to span a range of velocities, ionization parameters and column densities [36-38]. However, these data lack the sensitivity and resolution to measure density diagnostics that would accurately constrain launch radii and reveal mass outflow rates and kinetic power (Fig. 3).

Arcus's leap in sensitivity and resolution will transform our understanding of wind feedback from AGN. The AGN Broad, Deep and Obscured Surveys (ABS, ADS, AOS), described below will provide a set of unparalleled soft X-ray spectra that can be directly compared with archival UV and new IR and sub-mm spectra, test unified models of AGN appearance [39] and connect AGN feedback from 0.01 pc to kpc scales.

The AGN Broad Survey. The ABS is an unbiased sample of 100+ unobscured AGN. Initially selected from the *ROSAT* All-Sky Survey [40, 41] with soft X-ray fluxes in the range 3-30 x 10^{-12} erg cm^{-2} s^{-1}, it will be supplemented from *eROSITA* surveys. The mass, Eddington fraction (λ_{Edd}), and AGN type of every SMBH in the ABS have been estimated. The sample is centered on $\lambda_{Edd} = 0.3$, but spans an order of magnitude in each direction, covering the range where wind feedback is expected to matter most in the co-evolution of SMBHs and host galaxies [30, 34].

Very deep *Chandra* and *XMM-Newton* exposures of one of the brightest AGN (NGC 5548) reveal a complex wind with six components that span a broad range in velocity, column density and ionization [42]. Winds in fainter AGN may be just as complex, but such measurements are beyond the reach of current spectrometers. The ABS is designed to achieve NGC 5548-like sensitivity in every source (Fig. 3), enabling unbiased tests of wind evolution with λ_{Edd} and viewing angle.

The ABS will also reveal the demographics of wind driving mechanisms. Classical wind models based on UV outflows from AGN (radiation pressure [43]) or solar-mass black holes (thermal pressure [44]) cannot be readily applied to the complexity of AGN X-ray outflows. Magnetic wind driving has therefore been proposed as an alternative. In this scenario, the wind is launched over a large range in radius from the SMBH, creating an observable distribution of column densities as a function of the gas ionization (absorption measure distribution, AMD [45,46]). This hypothesis has been tested in only a few sources; *Arcus* will systematically test it in 100+ AGN in the ABS.

The AGN Deep Survey. The ADS is designed to demonstrate *Arcus*'s ultimate capabilities with long (~300+ks) observations of at least 5 sources, enabling the use of density-sensitive lines to obtain measurements of AGN wind feedback into host galaxies with revolutionary accuracy and precision. Mass flux and kinetic power in X-ray winds are the keys to understanding how SMBH feedback shapes host galaxies. The wind components that connect to the accretion flow on scales of 0.01 pc are seen in absorption, owing to their non-spherical nature and our viewing angle. The inability of current X-ray telescopes to measure gas density in absorption has prevented a full understanding of feedback, as the mass outflow rate is directly proportional to the gas density, whose range can span five orders of magnitude.

New atomic physics results have identified density-sensitive absorption lines from B-like and C-like charge states of sulfur and silicon in the 30-50 Å band [47]. *Arcus* is uniquely able to detect these features in deep exposures. Variability in the strengths and shapes of the absorption features presents another means by which wind density can be measured [48]. Tracking changes in the wind ionization with changes in the continuum flux tests the equilibrium time scale of the gas, and thereby its density. *Arcus* will make systematic, high-fidelity measurements with this diagnostic for the first time.

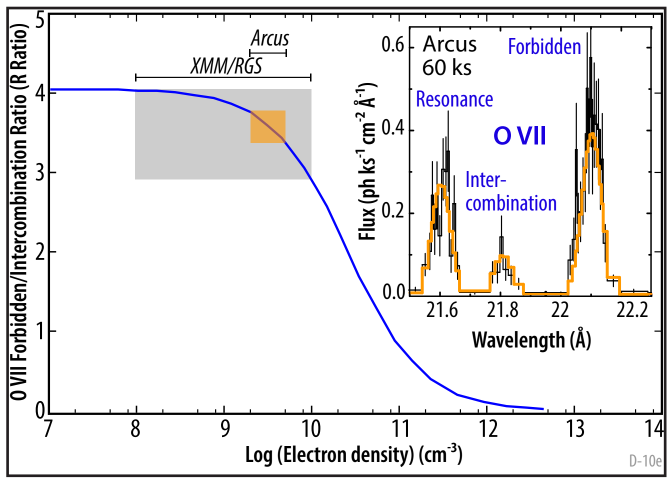

Figure 5: The O VII triplet yields strong density constraints. The inset panel shows a simulated 60-ks *Arcus* spectrum of Mrk 3, assuming n = 3x10^9 cm^{-3}. The O VII line ratios constrain the density to lie within 2-5 x 10^9 cm^{-3}, an improvement of >10x over the precision possible with current telescopes

The high resolution of *Arcus* will also separate spectral lines that are blended, and will detect velocity structure within an outflow component. In this regard, *Arcus* spectroscopy will finally connect to the velocity resolution achieved in optical and UV bands, allowing identification of X-ray outflow components that might be co-spatial with UV and optical flows with lower ionization and column density. The ADS includes unobscured Seyferts covering a range in SMBH mass and λ_{Edd} (matched to the ABS), and with variability that can be tracked accurately. Repeated observations of these targets will yield an orders-of-magnitude improvement in our measurement of the gas density in these outflows, allowing us to place the first true constraints on the amount of mass and energy they carry.

The AGN Obscured Survey. Obscured sources in the AOS provide a complementary laboratory in which to study feedback since we can measure the gas properties in emission. A notable example is NGC 1068, wherein the SMBH ejects far more hot X-ray gas (0.3 M_{sun} yr^{-1}) than the total gas required to fuel its bolometric radiative luminosity [49]. Like other Seyfert 2 AGN, the SMBH in NGC 1068 channels this gas and its radiation into a >0.1-kpc cone that coincides with the optical "narrow-line region" (NLR) of its host galaxy [50]. The strong feedback in NGC 1068 is especially clear because it is the nearest obscured AGN.The extended outflow emits numerous strong emission lines from multiple charge states of abundant elements, with strong He-like and H-like lines that permit precise density measurements. However, NGC 1068 is the only obscured AGN for which *Chandra* or *XMM-Newton* can obtain such data.

The sources in the AOS are taken from the CHRESOS sample of obscured AGN [51]. Fig. 5 shows a 60-ks *Arcus* spectrum of Mrk 3, another obscured AGN 10× fainter than NGC 1068. Even for this fainter source, *Arcus* will reduce uncertainties on the density of the gas that emits O VII lines by ≥10×. *Arcus* data will encompass a range in density diagnostics from $n=3\times10^{7}$–10^{14} cm^{-3}, yielding similar improvement in each of the sources in the sample. By obtaining unprecedented measurements of the gas density gradient within the NLR, the AOS will also rigorously test models of complex NLR physics [52].

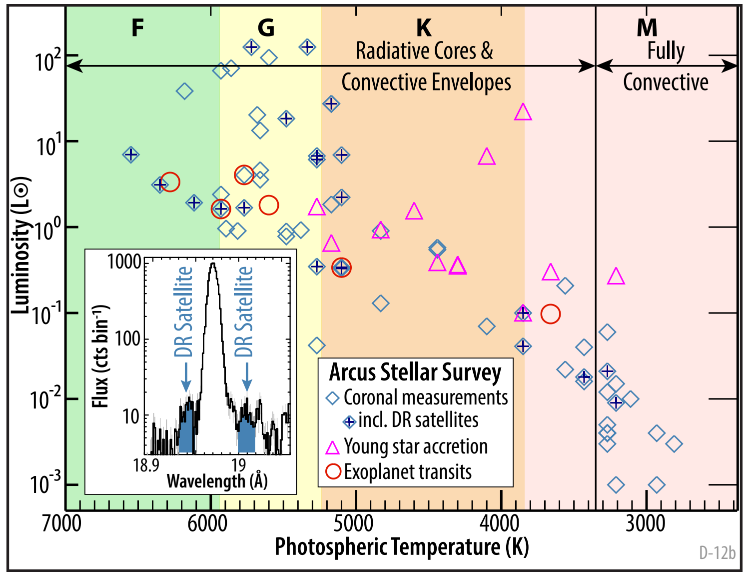

Figure 6: *Arcus* will measure the X-ray spectra of stars across the cool range of the H-R diagram to study coronae, young star accretion and exoplanet atmospheres through the SCS, SAS and EAS. For example, an 11-ks *Arcus* observation of Capella will test coronal heating models using the first robust measurements of the DR satellite lines of O VIII (inset)

2.2 Probing Stellar Activity

X-ray spectra with high resolution and sensitivity can characterize the physical conditions of stellar coronae as well as the dynamical processes driving coronal phenomena. X-ray-emitting coronae are manifestations of magnetic dynamos that operate within stellar interiors [53]. Magnetic activity can affect planetary atmospheres, in some cases removing gas faster than it can be replenished [54, 55]; stellar X-rays can also catalyze prebiotic chemistry [54]. Astro2020 prioritized this science in its "Worlds and Suns in Context" theme [1].

The *Arcus* Stellar Coronal Survey (SCS) will explore the evolution of the magnetic dynamo through measurements of coronal structure and heating for a rich sample of stars of different ages and types (Fig. 6). These studies will establish any differences in magnetic activity between main-sequence stars with solar-type dynamos and fully convective stars with turbulent dynamos. Surprisingly, no difference has been observed to date in their well-established rotation-activity relation [56-58]. The planet-hosting red dwarf Proxima Cen [59] even shows a coronal activity cycle [60]. The SCS includes ~5× more fully convective stars than the handful that have been observed to date with X-ray gratings.

Arcus can uniquely determine coronal properties using emission measure distributions (EMDs), which have so far been obtained only for the brightest, most active stellar coronae [61,62]. A tenfold increase in the number of density diagnostics, too weak or blended in existing spectra, will establish the distribution of sizes in coronal structures.

Arcus spectra can also distinguish between competing coronal heating models [63]. In nanoflare models, multiple coronal loops of magnetically confined plasma are randomly heated and ionized [64]. As each loop slowly cools, the charge state of the gas lags the local temperature, leading to a recombining plasma. Conversely, Alfvén wave heating models produce a steadily heated plasma [65] likely to be in ionization equilibrium. The flux ratios of dielectronic recombination (DR) satellite lines to their parent resonance line are highly sensitive, charge-state-independent diagnostics of temperature [66]. Existing X-ray gratings do not have the sensitivity or resolution to exploit the DR lines, nor will *XRISM* or *Athena* below 1.2 keV. *Arcus* will easily measure multiple weak DR lines, providing temperatures accurate to 10% and determining the degree of ionization equilibrium when paired with DR ratio predictions from EMD analysis.

3. INSTRUMENT & MISSION

Arcus is a photon counting spectrometer in the 10-50Å band that averages R=2500 and ~200 cm^{-2} over this bandpass. The instrument consists of four independent optical channels, each focusing photons on two detector arrays; see [67] for a recent review of the technical details and performance characteristics, which are summarized here. The optical channels combine silicon pore optics (SPOs) and Critical-Angle Tranmission (CAT) gratings. These are all in the forward assembly separated from the detectors in the rear assembly by the on-orbit deployed boom. A photon is collected and focused by an SPO and then transits a CAT grating either being diffracted or passing unaffected. The photon travels down the boom, landing on one of sixteen CCDs. This induces a pixel pattern that is identified by the Event Recognition Processor (ERP). The ERP sends the event data including time, CCD position, and energy information to the Instrument Control Unit (ICU) to be processed, combined with instrument housekeeping, and transmitted to the S/C for downlink. After downlink, images are reconstructed using photon arrival information (time, location, energy for order sorting) and observatory aspect (relative pointing and instrument deflection).

Two technologies enable *Arcus*: silicon pore optics [68, 69] developed by cosine Measurement Systems for the *Athena* mission and critical-angle transmission gratings [70,71] by Massachusetts Institute of Technology (MIT) for the *IXO*, *Arcus*, *Lynx* and other missions. The *Arcus* team of SAO and MIT has worked closely with industrial partners cosine and Media Lario (SPO alignment) over the past five years to perfect the manufacturing and alignment of the *Arcus* optical system. This culminated in several multi-SPO and CAT grating alignment tests [71, 72] conducted in X-rays to validate the process and verify performance.

5. ACKNOWLEDGMENTS

The *Arcus* team gratefully acknowledges multiple years of internal funding support from SAO, NASA/ARC, MPE, MIT, PSU, Northrop Grumman, and NASA/GSFC. Additional support for the project has come from NASA Grant 80NSSC20K0780, as well as funding from the 2017 Arcus Phase A study.

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