PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

The Arcus probe mission

Randall Smith

Randall Smith, "The Arcus probe mission," Proc. SPIE 12678, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXIII, 126780E (5 October 2023); doi: 10.1117/12.2677764

Event: SPIE Optical Engineering + Applications, 2023, San Diego, California, United States

SPIE.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023 Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

The Arcus Probe Mission

Randall Smith*[a] and the Arcus Team
[a]Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138

ABSTRACT

The *Arcus* Probe mission to be proposed to the NASA Astrophysics Probe Explorer call addresses a range of Astro 2020 Decadal Priority science areas. These include (i) exploring how supermassive black hole accretion and winds vary with luminosity, black hole mass, black hole spin and other parameters, (ii) determining how gas, metals, and dust flow into, through, and out of galaxies, and (iii) probing stellar activity across all stellar types and lifecycles, including exoplanet hosts targeted by current and future NASA habitable planet missions. These science goals, along with a robust General Observer science program, will be achieved using a mission that provides a high-sensitivity soft X-ray spectrometer (XRS) with R=3500 (R>2500 req) and an average effective area in the 12-50Å bandpass of 335 cm^2 (250 cm^2 req). It will be complemented by a co-aligned UV spectrometer (UVS) working in the 1020-1560Å band with R= 24200 (R>17000 req)and >5× the sensitivity of *FUSE* at O VI (1020Å) that observes simultaneously with the X-ray instrument. Working together, these instruments will enable astronomers to characterize warm and hot plasmas - including hydrogen, helium, and all abundant metals - throughout the Universe, from the halos of galaxies and clusters to the coronae of stars. We present the overall mission plan, including instrumentation, science, and operations for a five-year baseline mission.

Keywords: X-ray gratings, X-rays: Spectroscopy, Far-UV, UV: Spectroscopy, Probe mission

1. INTRODUCTION

The 2020 Astrophysics Decadal Survey [1] highlights understanding the nature and impact of astrophysical feedback, centering this process throughout its three main science themes: Cosmic Ecosystems, New Messengers and New Physics, and Worlds and Suns in Context. Weaving these together, it states, "Galaxies are ecosystems of their own, with further condensation of matter to form stars and planets balanced by 'feedback' from stellar winds, outflows, and supernovae that return mass and energy to the gaseous environment. The supermassive black holes that form and grow within nearly all massive galaxies also play a key role in this feedback process. Unraveling the nature of this connection is one of the key science goals of the decade." The Decadal emphasizes X-ray and UV spectroscopy as well as time-domain observations as providing the required observations to understand feedback on all scales. Furthermore, it identified the X-ray bandpass particularly as suitable for a Probe-class mission.

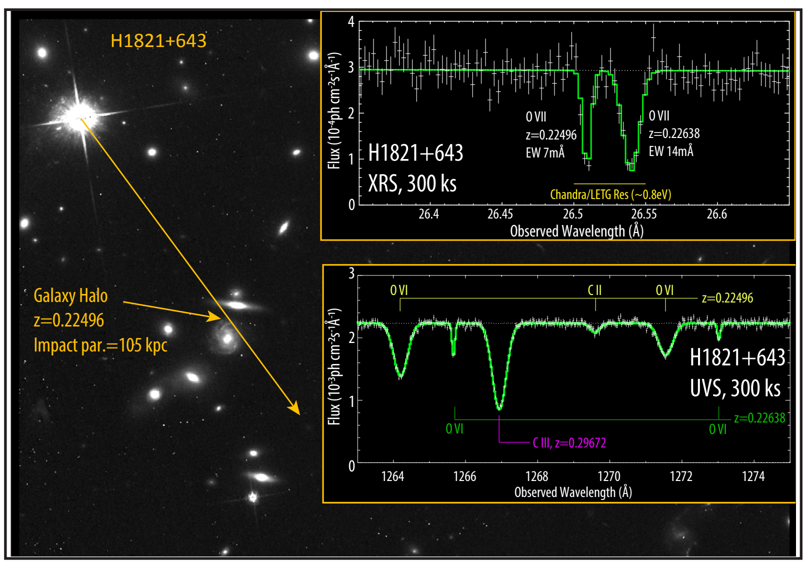

Figure 1: All Arcus observations of SMBHs will probe not only the spectrum of the AGN itself, but all intervening galaxy halos and the Milky Way halo itself. Shown here is an observation of the bright SMBH H1821+643 at the center of the cluster CL 1821+64. The observed spectrum will reveal properties of the black hole region itself, the hot cluster gas, and as shown in the insets the haloes of galaxies along the line of sight. Chandra/LETG observations (with >5× better resolution than XRISM) of this source show that there is O VII at this redshift [38], but cannot resolve if one or two galaxies are responsible for the absorption.

Multi-scale outflows of matter and energy emanate from systems as small as stars to those as large as supermassive black holes (SMBHs), representing the kinetic and radiative transfer of energy from these engines into the surrounding interstellar and intergalactic media (ISM/IGM). Tracing the flow of matter and energy from stellar to intergalactic scales and understanding the physics of feedback requires precision measurements of the properties of baryonic matter in these systems. Progress has proved elusive despite the priority placed on understanding the connections between accretion, outflows and the formation and evolution of structure

UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXIII, edited by
Oswald H. Siegmund, Keri Hoadley, Proc. of SPIE Vol. 12678, 126780E
© 2023 SPIE · 0277-786X · doi: 10.1117/12.2677764

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

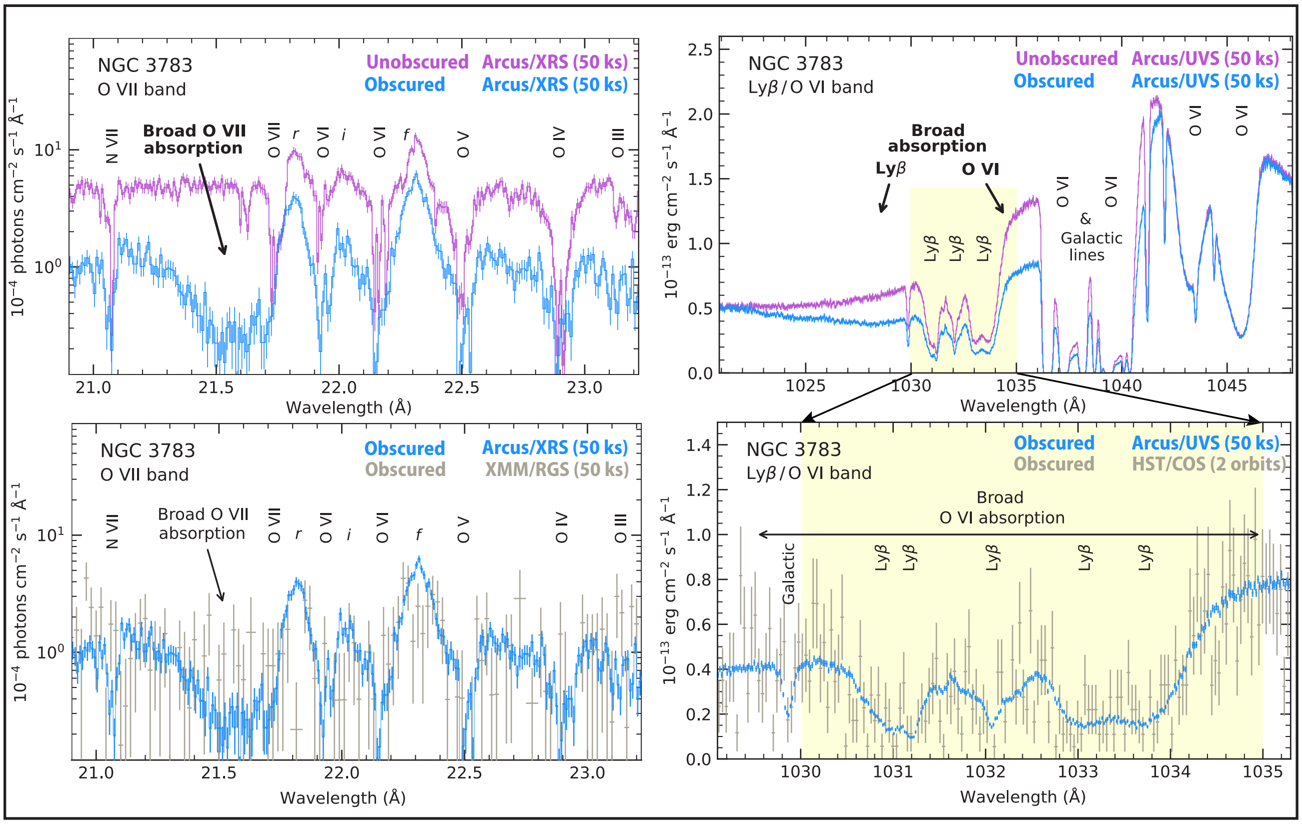

Figure 2: NGC 3783 is one of the few AGN with high-quality, simultaneous X-ray and UV data, thanks to a long, coordinated campaign with XMM-Newton and HST. The Arcus broad survey will provide hundreds of such spectra. Narrow and broad absorption lines in both the X-ray and UV bands from AGN winds are observed, with broad absorption becoming more apparent as the source moves into an obscured state (purple vs. blue data in the top panels). These features vary on time scales of hours to days. Arcus will provide higher quality spectra in a fraction of the time needed by current instruments (bottom panels), allowing us to trace this variability for the first time and to ascertain key properties of AGN winds: density, location, and energetics.

across all mass scales because current observations lack the sensitivity needed to benchmark simulations and reproduce the distribution and properties of the galaxies, clusters and intergalactic gas. Images and low-resolution spectra cannot provide the necessary data, which can only be obtained through multi-wavelength, high-resolution spectroscopy that connects data from "upstream" highly ionized outflows (dominant in the X-ray and UV bands) to "downstream" molecular reservoirs (dominant in the optical and IR bands) and beyond, into the tenuous cosmic web (also dominant in X-rays and UV). Telescopes such as *JWST* and *ALMA* provide unprecedented spectra of these cooler downstream components. Observatories such as *Chandra*, *XMM-Newton*, and *HST* have made important initial strides in characterizing upstream outflows, but these facilities lack the ability to measure their properties –or those of gas in cosmic web– with the necessary sensitivity and precision in the X-ray and UV bands.

Arcus' baseline science mission provides revolutionary data uniquely capable of answering Astro2020's most urgent science questions. The mission's science goals address the three primary themes posed in Astro2020. *Arcus'* principal goal is revealing how black holes impact their surroundings. This requires measuring the mass, energy and momentum in accretion-driven winds from supermassive black holes (SMBHs). A second goal is determining how baryonic matter flows 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. Finally, *Arcus* observes feedback on even smaller scales by probing how accretion, coronal activity and outflows influence the evolution of stellar systems over a wide range of mass and age, with an emphasis on planet-hosting stars.

2. SCIENCE

Feedback from Supermassive Black Holes: The tight correlation between SMBH mass and the stellar velocity dispersion of host galaxy bulges [2] indicates that black holes and galaxies must have co-evolved. The driver of this correlation was

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

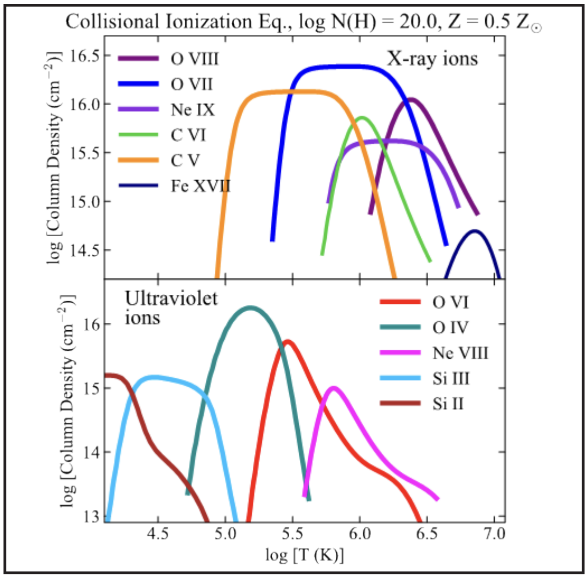

Figure 3: Column densities of selected ions observable with Arcus based on the typical total N_H and metallicity observed in the COS-Halos survey [8] and the collisional ionization equilibrium ionization models from [9]. The curves show column densities that Arcus can detect with limiting equivalent widths of 1 mÅ in the X-ray band and 10 mÅ in the UV.

revealed via foundational numerical simulations [3] that showed accretion-powered wind feedback - equivalent to just 1-5% of the radiative luminosity - can reshape host galaxies and drive co-evolution, sweeping the bulge of cold gas and preventing future star formation. For accretion-driven winds to govern the coevolution of SMBHs and host galaxies, they must also act over many orders of magnitude in physical scale, connecting regions of close to the black hole to the whole galaxy – from AU to kpc. In connecting these scales, the black hole winds will entrain additional gas and dust and eventually act over a broad range in solid angle. The total kinetic power is set in the initial outflow connected to the accreting SMBH. The central corona emits in X-rays, and the innermost disk emits in UV, therefore the innermost accretion flow and the winds it generates are best revealed by sensitive atomic spectra in these bands.

The central engines in SMBHs and the winds they launch are highly variable: the outflows are photoionized by the strong continuum radiation in AGN, which can vary on time scales of hours. This variability drives changes in the ionization state and column densities of the gas in the wind, changing the strength of both the X-ray and UV absorption lines. To accurately measure AGN feedback X-ray and UV spectra must be obtained simultaneously and in modest observing times as shown in Figure 2. To capture rapidly varying AGN phenomena such as Tidal Disruption Events (TDEs), *Arcus* will also have a 24 hour Target-of-Opportunity (ToO) capability (see §4).

The Baryon Cycle in Galaxies: "How do baryons cycle in and out of galaxies, and what do they do while they are there?" This question summarizes one of the highest science priorities of Astro2020 [1]. Most galactic baryons are in hot or "warm-hot" phases (the WHIM: 10^5 - 5×10^6 K) and reside in a circumgalactic medium (CGM) that extends to at least the virial radius (250 kpc for a Milky-Way-type galaxy). The column densities are significant but the mean density is low, and detection of these "missing baryons" through absorption, in the X-ray and far UV bands, is a powerful method for large statistical studies with many diagnostics. UV absorption studies have enabled significant progress (see [4-5]), providing evidence that halos of galaxies, groups, and clusters are filled with multiphase and metal-enriched gas clouds. However, UV observations cannot constrain the hottest phases of the CGM where most of the metals and baryons are expected to be found. *Arcus* will fill this gap, providing complementary sensitive X-ray and UV spectroscopy with the resolution required to study the physics of gas outflows and inflows as well as the volume-filling hot gas of galaxy halos and beyond.

Arcus has key advantages over current instruments or near-future ones such as the micro-calorimeters on *XRISM* and *Athena*. The three advantages that will revolutionize CGM and WHIM science are (1) A 10× sensitivity improvement compared to *Chandra*, *XMM-Newton*, or *FUSE*. (2) Spectral resolution that resolves baryon cycle flows. UV and optical studies show that typical galaxy halo sightlines detect multiple clouds with velocity spreads of ~100 - 400 km s^{-1} [6], within both UVS and XRS's capabilities but not X-ray microcalorimeters with 1-5 eV resolution (520-2600 km s^{-1} at O VII). (3) Simultaneous X-ray and UV spectroscopy along each sightline: UVS and XRS are matched so that, toward a background AGN or GRB, one will usually obtain the X-ray lines (e.g., O VII, O VIII), the adjacent UV ions (e.g., C II, Si III, O VI), and the cooler gas columns (e.g., H I), capturing all phases of the cosmic web and determining its metallicity. Further, the long slit on UVS [see 7] will record a UV emission spectrum with excellent angular resolution, while the XRS will image the field in X-rays (via zero order).

An *Arcus* census of the total column density along random lines of sight will determine the cosmological contributions from O VI, O VII, and O VIII—Ω(O VI), Ω(O VII), and Ω(O VII), shown in Figure 4 in differential form, dN(>EW)/dz. Galaxy halos, galaxy groups, and the outer parts of galaxy clusters host much of this gas. Galaxy halos are the primary absorption hosts due to their high space density and virial temperatures that align well with the X-ray absorption lines. From UV spectra, galaxy halos are known to have many metals and ionization stages [4]. 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

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

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.

Nearly all of the ion transitions useful for such observations occur in the UV and X-ray bandpasses, so both X-ray and UV spectra are needed to completely probe the baryon cycle. Absorption by O VII, O VIII, and other X-ray lines is already detected in gas around the Milky Way [18-21], and UV spectroscopy of galaxy halos has revealed pervasive lower-ionization absorption lines ranging from H I and cool metals (e.g., Si II) through O VI and Ne VIII [22-24]. X-ray and UV lines are complementary: the X-ray lines reveal the hottest, most massive, and volume-filling phases while UV transitions reveal the multiphase cool and warm-hot components due to cooling and feedback.

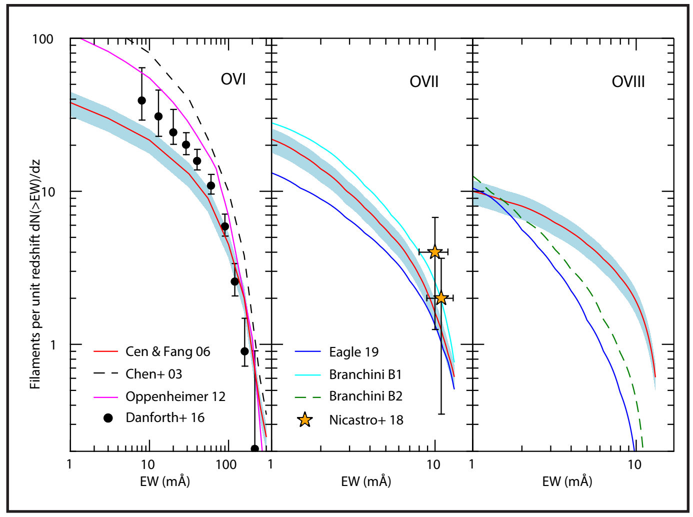

Figure 4: *Arcus* can recover the dN/dz distribution of O VI, O VII, and O VIII, determining the cosmological important cosmic densities Ω(O VI, O VII, O VIII). The data will distinguish between models with different feedback prescriptions from SNe and AGN at >99% confidence. Other than in the Milky Way, the O VIII ion remains undetected in the ISM/CGM gas, while sparse data for the O VII cannot differentiate between models due to their large errors (all data errors are 1σ). Shaded green regions show the *Arcus* 1σ error on recovering the input model [10] in all three cases. The left plot for O VI shows models [10, 15, 16] with data from [17]. The central curve for O VII shows models [11, 12] and observed data points [13] (but see [14]); the right curve shows the model curves for [10, 15, 16]; no observations yet exist for comparison.

Worlds and Suns in Context: This Decadal theme prioritizes stellar feedback science, "which captures the quest to understand the interconnected systems of stars and the worlds orbiting them, tracing them from the nascent disks of dust and gas from which they form, through the formation and evolution of the vast array of extrasolar planetary systems so wildly different than the one in which Earth resides" [1].

Arcus stellar samples will study structure and evolution over a rich array of stars of different ages and types (see Fig. 5). For example, in young stars both X-ray and UV spectra show strong emission lines formed at the accretion shock near the stellar surface [25, 26]. X-ray emission formed at the accretion shock front cools as material flows toward the chromosphere, where UV emission likely originates. Observations of a few young stars using the *Chandra* and *XMM-Newton* gratings confirm the basic accretion shock model onto the star: Ne IX and O VII diagnostic lines indicate high densities at relatively low temperatures compared with pure stellar coronae [27-29]. *HST* and *FUSE* UV spectra show strong absorption features superimposed on the line emission, believed to originate from winds, jets, and/or the disk itself, depending on the orientation to our line of sight. While HETG observations of TW Hydrae agree well with the mass accretion rate determined from optical and UV data [30], few other X-ray spectra have enough signal-to-noise to use these diagnostics. The *Arcus* Young Star Sample (YSS) consists of 20 young stars, including not only accreting systems but non-accreting systems for which the star-disk interactions can be isolated from accretion-driven processes, a goal that requires *Arcus's* capabilities. It will do so by comparing simultaneous measurements of variable mass accretion rates from UV and X-ray spectroscopic techniques, and it is the only X-ray spectrometer capable of measuring spectral profiles and velocity shifts down to 20 km s^{-1} for individual lines formed at different

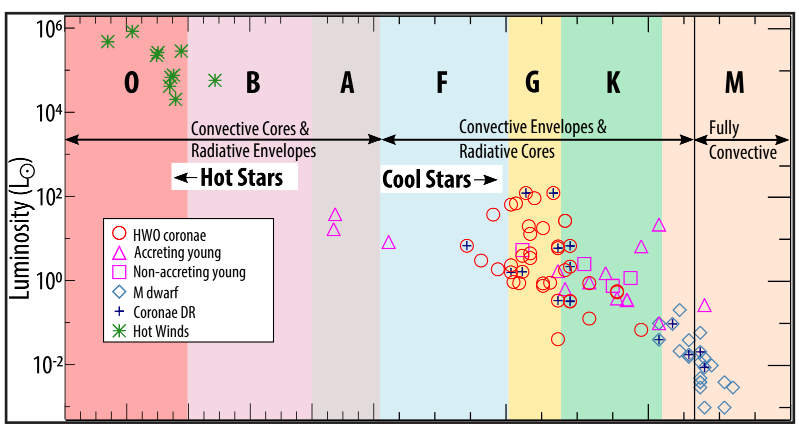

Figure 5: *Arcus* will measure the X-ray and UV spectra of stars across the H-R diagram. The *Arcus* young star sample includes non-accreting as well as accreting young stars to assess star-disk interactions. The coronal star sample (A-M) studies coronal heating, and includes a subset of HWO targets to address the role of stellar activity on exoplanet atmospheres. The hot star sample (O, B stars) measures the impact of radiatively-driven winds on the circumstellar environment.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

temperatures and densities.

The *Arcus* Coronal Star Sample (CSS) facilitates studies of coronal structure and heating for a rich distribution of stars of different ages and types (Fig. 5). The sample will include targets for the Habitable Worlds Observatory (HWO), explicitly facilitating atmospheric studies for known planets, while also expanding coronal spectral studies conducted by *Chandra*, *XMM-Newton*, *HST/COS*, *FUSE*, and other observatories. The broad coverage of elements and ionization states provided by joint X-ray and UV spectroscopy will allow us to determine emission measure distributions (EMDs) – with unprecedented simultaneous temperature sampling and for more than the brightest, most active stellar coronae [31,32] – enabling us to infer the stellar EUV environments which are the dominant drivers of atmospheric mass loss on all types of planets [33]. A tenfold increase in the number of X-ray density diagnostics, too weak or blended in existing spectra, will establish the distribution of sizes and inferred magnetic fields in coronal structures. The *Arcus* CSS also includes a set of M dwarfs, important for establishing differences in magnetic activity between main-sequence stars with solar-type dynamos and fully convective stars with turbulent dynamos. The CSS includes ~5× more fully convective stars than the handful that have been observed to date with X-ray gratings, and includes almost half of the HWO Tier A and B targets (mostly F, G, and K), plus the brightest ROSAT-detected M dwarfs to increase the sample near the transition to fully convective stars; $T_{exp} \sim 2.0$ Ms. Low-flux but strongly temperature diagnostic dielectronic recombination lines will be measured in 15 sources. If the plasma is recombining, the DR lines will be stronger than predicted and will signal the degree of non-equilibrium. These observations will yield line ratio temperature diagnostics to 5σ using the O VIII DR features. X-ray to UV line ratios will provide an additional test and ensure self-consistent analysis.

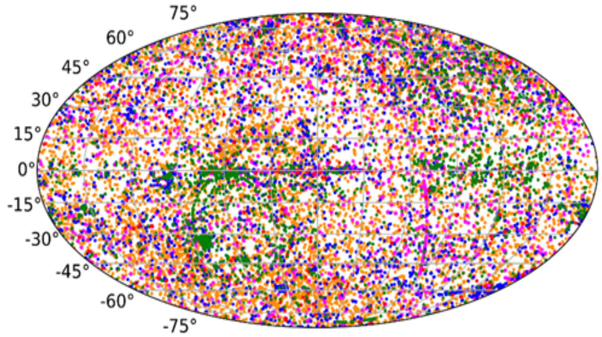

Figure 6: Arcus enables X-ray and UV studies of sight lines throughout the Milky Way and beyond. In 10-100ks, Arcus returns high-quality spectra of targets from the ROSAT all-sky survey (orange), Swift/UVOT Serendipitous Survey (magenta), XMM-Newton Serendipitous Source Catalog (blue), XMM-Newton OM Serendipitous Survey (red), and FUSE (green). Over 150,000 unique sources are observable.

Arcus also features a vibrant General Observer (GO) program that will use >70% of the available science time. GOs will be able to capitalize on data returned from the baseline science mission while exploring new areas such as galaxy emission, Type II supernovae, and the Io plasma torus. Figure 6 shows the >150,000 unique sources that *Arcus* will be able to observe by selecting from X-ray and UV catalogs that will be bright in the XRS and UVS bandpasses. At least 70% of the ToO opportunities will also be reserved for GOs. *Arcus*' regular ToO capability will enable response within 24 hours to any source within the field of regard (>50% of the full sky). A limited number of fast ToOs can be done within 4 hours, using an automated SOC response to preset ToO triggers based on *Swift* heritage. GOs will be able to follow up transient events with an unprecedented combination of sensitivity and spectral resolution simultaneously in the soft X-rays and UV, addressing the Decadal call for "...space-based observational facilities across the electromagnetic spectrum to discover and characterize the brightness and spectra of transient sources..."

3. INSTRUMENTATION

The *Arcus* instrumentation has been optimized for the scientific program described above. The Science Instrument Package (SIP) consists of a pair of simultaneously operating high-resolution spectrometers in the soft X-ray (XRS) and far ultraviolet (UVS), bandpasses that enable observations of all of the key diagnostic spectral lines from warm and hot plasmas seen both in emission and absorption (see Figure 3). To ensure maximal science return from a cost-capped mission, the instrument effective areas and spectral resolutions were carefully established. X-ray and UV instrument sensitivities are matched to ensure a 10-100ks observation achieves high S/N spectra for any of a large sample of all source classes, while the spectral resolutions were set by the underlying physics requirements. Increases to either provides limited scientific benefit unless they move the mission into flagship class. The UVS uses a standard Cassegrain design with a 0.6m primary coated with enhanced Lithium Fluoride (eLiF, a key HWO technology) to achieve high efficiency and high resolution. For more details about the UVS instrument, see [7] in this volume. The XRS, shown in Figure 6 in its deployed state, combines high-efficiency Silicon Pore Optics (SPOs), developed for ESA's *Athena* project (see [34] in this volume) with Critical-Angle Transmission (CAT) gratings (see [35] in this volume) to achieve orders-of-magnitude improvement in efficiency for soft X-ray photons at more than twice the resolution ever achieved in flight before. The raytracing and alignment details of the XRS with respect to the UVS can be found in [36], in this volume.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

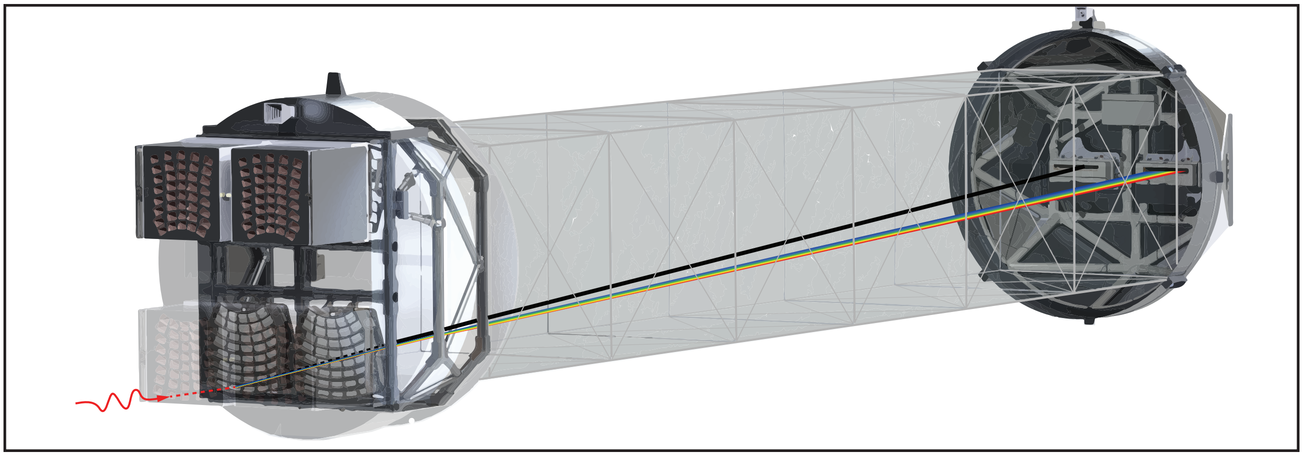

Figure 7: The XRS after deployment. At left the Front Assembly holds the four Optics Channels (OC), two of which are shown with their thermal pre-colimators (left, top) and open doors, while the other two (left, bottom) have these removed to show the SPO mounted in their petal structures. Each petal holds 40 SPO mirror modules in 8 rows, with an (unseen) CAT grating petal mounted behind this. The four OCs are mounted on a cylindrical ring that houses the focus and alignment mechanisms [see 31]. The extendable boom mounts beneath this ring and connects to the Rear Assembly that holds the CCD detectors and XRS instrument computer. The boom is wrapped with a light-tight Germanium Black Kapton® (GBK) sock to suppress stray light, and assist in controlling temperature.

4. MISSION

Arcus' deep orbit allows long continuous observations combined with a large instantaneous Field of Regard and a rapid ToO capability that enables studies of a full range of time-domain physics. A high-heritage Northrop-Grumman spacecraft (S/C) meets all instrument and mission requirements with robust technical margins. *Arcus* uses the LEOStar-3 S/C bus as its core. There have been over thirteen flown LEOStar-3 S/C, including those providing precision-pointing capability (*ICESat-2*, Landsat 9, *JPSS-2*), rapid ToO response (*Swift*), and radiation-robust designs (STPSat-6). More than four LEOStar-3 S/C currently in production continue to advance the product line. *Arcus* leverages *TESS* (LEOStar-2) design experience in a similar orbit as *Arcus* that meets the requirement for high efficiency observing from a stable platform. The design includes solar arrays qualified for long eclipses and charging environment, along with maintenance of an anti-Sun side for simplified thermal design.

The mission design enables continuous operations, with a benign radiation environment, low disturbance torques, and long-term orbit stability arising from the ~6.8-day period HEO. Science operations are simple, with long, low-jitter, inertially-pointed observations. The relative simplicity of operations in the HEO environment leads to a high observing efficiency ensuring that all science observations can be accomplished using less than 30% of the 5-year baseline science phase. Two ToOs are allowed, including a 4 hour response time that uses NASA's Near Space Network (NSN) ability to provide On-Demand Scheduling. The regular 24-hour ToO response is enabled by scheduled contacts using NASA's Lunar Exploration Ground Sites (LEGS) communication system;details can be found in [37]. NASA/ARC will host the *Arcus* Mission Operations Center (MOC) as part of the ARC Multiple Mission Operations Center (MMOC). The ARC MMOC has successfully managed mission operations for missions such as *Kepler*, *LCROSS*, *LADEE* and *IRIS*. The Smithsonian Astrophysical Observatory (SAO) provides the Science Operations Center (SOC), working closely with ARC. SAO hosts and operates multiple science operations centers ranging in scale from Explorer-sized (*Hinode*) to flagship (*Chandra*).

Arcus will serve as a long-term, invaluable resource for the entire astrophysical community. The GO program, in concert with other planned 2030 observatories, is poised to make breakthroughs in nearly every branch of astrophysics. The *Arcus* architecture and mission operations allows straightforward coordination with other ground and satellite observatories, addressing the multiwavelength focus of the Decadal, and will allow researchers to acquire a holistic view of statistically significant samples of sources and addressing the multiwavelength focus of the Decadal. Follow-up observations of transient and multi-messenger phenomena are enabled as well, including sources such as supernova explosions, tidal disruption events, gamma-ray bursts and gravitational wave detections. The mission complements other observatories studying a wide variety of astrophysical targets in the next decade, including *Athena*, *Rubin*, *Euclid*, *ALMA*, *JWST*, Roman, *E-ELT*/US-ELT and LIGO.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

5. ACKNOWLEDGMENTS

The *Arcus* team also notes internal funding support from SAO, NASA/ARC, MPE, MIT, PSU, Northrop Grumman, and NASA/GSFC. Thanks to team members Jay Bookbinder, Laura Brenneman, Joel Bregman, Nancy Brickhouse, Casey DeRoo, Adam Foster, Moritz Günther, Ed Hertz, David Huenemoerder, Missagh Mehdipour, Pasquale Temi, and Lynne Valencic for input to this presentation. Special thanks go to Kevin France for stepping in to give the presentation at the last minute after the author was unable to attend due to Hurricane Hilary.

6. REFERENCES

[1] National Research Council, "New Worlds, New Horizons in Astronomy and Astrophysics" (2010). http://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics.

[2] Ferrarese, L., and Merritt, D., “A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies”, The Astrophysical Journal, vol. 539, iss. 1, p. L9 (2000).

[3] Di Matteo, T., Springel, V., and Hernquist, L., "Energy input from quasars regulates the growth and activity of black holes and their host galaxies”, Nature, vol. 433, iss. 7026, p. 604 (2005).

[4] Tumlinson, J., Peeples, M. S. & Werk, J. K., "The Circumgalactic Medium", ARA&A, 55, 389 (2017)

[5] Péroux, C. & Howk, J., "The Cosmic Baryon and Metal Cycles", ARA&A, 58, 363 (2020)

[6] Tumlinson, J., et al., "The Large, Oxygen-Rich Halos of Star-Forming Galaxies Are a Major Reservoir of Galactic Metals", 2011, Science, 334, 948 (2011)

[7] France, K. et al., "Far-ultraviolet spectroscope on the Arcus X-ray probe", SPIE, 12678-22 (2023)

[8] Prochaska, J. et al., "The COS-Halos Survey: Metallicities in the Low-redshift Circumgalactic Medium", ApJ, 837, 169 (2017)

[9] Oppenheimer, B. & Schaye, J., "Non-equilibrium ionization and cooling of metal-enriched gas in the presence of a photoionization background", MNRAS, 434, 1043 (2013)

[10] Cen, R & Fang, T., "Where are the Baryons? III. Nonequilibrium Effects and Observables", ApJ, 650, 573 (2006)

[11] Branchini, E. et al., "Studying the Warm Hot Intergalactic Medium with Gamma-Ray Bursts", AJ, 697, 328 (2009)

[12] Wijers, N. et al., "The abundance and physical properties of O VII and O VIII X-ray absorption systems in the EAGLE simulations", MNRAS, 488, 2947 (2019)

[13]Nicastro, F. et al., " Observations of the missing baryons in the warm-hot intergalactic medium", Nature, 558, 406 (2018)

[14] Gatuzz, E. et al., "Searching for the warm-hot intergalactic medium using XMM-Newton high-resolution X-ray spectra", MNRAS, 521, 3098 (2023)

[15] Oppenheimer, B., et al., "The intergalactic medium over the last 10 billion years - II. Metal-line absorption and physical conditions", MNRAS, 420, 829 (2012)

[16[Chen, X. et al., "X-Ray Absorption by the Low-Redshift Intergalactic Medium: A Numerical Study of the Λ Cold Dark Matter Model", ApJ, 594, 42 (2003)

[17] Danforth, C. et al., "An HST/COS Survey of the Low-redshift Intergalactic Medium. I. Survey, Methodology, and Overall Results", ApJ, 817, 111 (2016)

18] Nicastro, F., et al., “Chandra Discovery of a Tree in the X-Ray Forest toward PKS 2155-304: The Local Filament?”, ApJ, 573, 157 (2002)

[19] Rasmussen, A., Kahn, S. M., and Paerels, F., “X-ray IGM in the Local Group”, Astrophysics and Space Science Library, p. 109 (2003).

[20] Wang, Q. D., et al., “Warm-Hot Gas in and around the Milky Way: Detection and Implications of O VII Absorption toward LMC X-3”, ApJ, 635, 386 (2005).

[21] Miller, M. J., and Bregman, J. N., “The Structure of the Milky Way's Hot Gas Halo”, ApJ, 770, 118 (2013).

[22] Fox, A. J., et al., “Multiphase High-Velocity Clouds toward HE 0226-4110 and PG 0953+414”, ApJ, 630, 332 (2005)

[23] Wakker, B. P., et al., “Characterizing Transition Temperature Gas in the Galactic Corona”, ApJ, 749, 157 (2012)

[24] Burchett, J. et al., " The COS Absorption Survey of Baryon Harbors (CASBaH): Warm-Hot Circumgalactic Gas Reservoirs Traced by Ne VIII Absorption", ApJ, 877, 20 (2019)

[25] Schneider, P., Guenther, H. M., France, K., " The UV Perspective of Low-Mass Star Formation
", Galaxies, 8, 27 (2020)

[26] Hartmann, L., Herczeg, G., Calvet, N., "Accretion onto Pre-Main-Sequence Stars", ARA&A, 54, 135 (2016)

[27] Drake, J. J., “Trouble on the shock front: TW Hydrae, X-rays and accretion”, 13th Cambridge Workshop on Cool

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Stars, Stellar Systems and the Sun, 560, 519 (2005)
[28] Feigelson, E., et al., “X-Ray Properties of Young Stars and Stellar Clusters”, Protostars and Planets V, p. 313 (2007).
[29] Brickhouse, N., et al., “A Deep Chandra X-Ray Spectrum of the Accreting Young Star TW Hydrae”, ApJ, 710, 1835 (2010)
[30] Brickhouse, N., et al., “X-Ray Determination of the Variable Rate of Mass Accretion onto TW Hydrae”, ApJ, 760, L21 (2012)
[31] Testa, P., Drake, J. J., and Peres, G., “The Density of Coronal Plasma in Active Stellar Coronae”, The Astrophysical Journal, vol. 617, iss. 1, p. 508 (2004)
[32] Brickhouse, N. S., et al., “Coronal Structure and Abundances of Capella from Simultaneous EUVE and ASCA Spectroscopy”, The Astrophysical Journal, vol. 530, iss. 1, p. 387 (2000)
[33] Tian, F. et al., "Transonic Hydrodynamic Escape of Hydrogen from Extrasolar Planetary Atmospheres", ApJ, 621, 1049 (2005)
[34] Girou, D. et al., "Silicon pore optics: a mature and adaptable x-ray mirror technology", SPIE, 12679-4 (2023)
[35] Heilmann, R. et al, "Soft x-ray performance and fabrication of flight-like blazed transmission gratings for the X-Ray Spectrometer on Arcus Probe", SPIE, 12679-21 (2023)
[36] Guenther, H. M et al., "Ray-tracing Arcus for performance and alignment tolerances", SPIE, 12678-48(2023)
[37] Foster, A. et al., "The Arcus operations simulator: a general tool for observation planning", SPIE, 12678-53(2023)
[38] Mathur, S. et al., "Probing the hot circumgalactic medium of external galaxies in X-ray absorption II: a luminous spiral galaxy at $z \approx 0.225$", MNRAS, 525, 11 (2023)

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 25 Oct 2023
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use