The Arcus Probe Mission

Randall Smith*[a], Jon Arenberg[b], Marshall Bautz[c], Ehud Behar[d], Dolon Bhattacharyya[e], Jay Bookbinder[f], Joel Bregman[g], Laura Brenneman[a], Nancy Brickhouse[a], G. Esra Bulbul[h], Vadim Burwitz[h], Joseph Bushman[b], Peter Cheimets[a], Elisa Costantini[i], Casey DeRoo[j], Benjamin D. Donovan[b], Abraham Falcone[k], Brian Fleming[e], Adam Foster[a], Kevin France[e], Peter Friedrich[h], Luigi Gallo[l], Catherine E. Grant[c], H. Moritz Günther[c], Daryl Haggard[m], Ralf K. Heilmann[c], Sarah Heine[c], Butler Hine[f], David Huenemoerder[c], Jelle Kaastra[i], Igor Kreykenbohm[n], Sibasish Laha[o], Pamela Marcum[f], Herman Marshall[c], Randall McEntaffer[k], Missagh Mehdipour[p], Eric D. Miller[c], Jon M. Miller[g], Kirpal Nandra[h], Nicholas Nell[e], Michael Nowak[q], Frits Paerels[r], Katya Poppenhaeger[s], Andrew Ptak[t], Agata Rozanska[u], Jenna Samra[a], Jeremy Sanders[h], Mark L. Schattenburg[c], Norbert S. Schulz[c], Leroy Mark Sparr[t], Pasquale Temi[f], Todd M. Tripp[v], Lynne Valencic[w], Joern Wilms[n], Stephen Walker[f], David Wilson[e], Scott Wolk[a]

[a] Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, [b] Northrop Grumman, Dulles, VA & Goleta CA USA, [c] Massachusetts Institute of Technology, Cambridge, MA USA, [d] Technion, Haifa, IL, [e] Laboratory for Atmospheric and Space Physics, Boulder, CO, USA, [f] NASA Ames Research Center, Moffet Field, CA USA, [g] University of Michigan, Ann Arbor, MI USA, [h] MPI für extraterrestrische Physik, Garching, DE, [i] SRON / Netherlands Institute for Space Research, Leiden, NL, [j] University of Iowa, Iowa City, IA USA, [k] Pennsylvania State University, University Park, PA USA, [l] Saint Mary's University, Halifax, CA, [m] McGill University, Montreal, CA, [n] FAU Erlangen-Nuernberg, Bamberg, DE, [o] University of Maryland, College Park, MD USA, [p] Space Telescope Science Institute, Baltimore, MD USA, [q] Washington University, St. Louis, MO USA, [r] Columbia University, New York, NY USA, [s] Leibniz Institute for Astrophysics, Potsdam, DE, [t] NASA Goddard Space Flight Center, Greenbelt, MD USA, [u] Nicolaus Copernicus Astronomical Center, Warsaw, PL, [v] University of Massachusetts Amherst, Amherst, MA USA, [w] Johns Hopkins University, Baltimore, MD USA

ABSTRACT

The *Arcus Probe* mission addresses a wide range of Astro2020 Decadal and NASA Science Mission Directorate Priority science areas, and is designed to explore astrophysical feedback across all mass scales. Arcus' three baseline science goals include: (i) Characterizing the drivers of accretion-powered feedback in supermassive black holes, (ii) Quantifying how feedback at all scales drives galaxy evolution and large-scale structure, including the tenuous cosmic web, and (iii) Analyzing stellar feedback from exoplanetary to galactic scales, including its effects on exoplanet environments targeted by current and future NASA missions. These science goals, along with a robust General Observer program, will be achieved using a mission that provides a high-sensitivity soft (10-60Å) X-ray spectrometer (XRS), working simultaneously with a co-aligned UV spectrometer (UVS; 970-1580Å). Arcus enables compelling baseline science and provides the broader astronomy community a revolutionary tool to characterize the full ionization range of warm and hot plasmas - including hydrogen, helium, and all abundant metals - in the Universe, from the halos of galaxies and clusters to the coronae of stars.

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

1. INTRODUCTION

Understanding astrophysical feedback, from the intergalactic down to individual stars was a cornerstone of the 2020 Astrophysics Decadal Survey [1; hereafter Astro2020] and a part of all three of its science themes: Cosmic Ecosystems, New Messengers and New Physics, and Worlds and Suns in Context. Astro2020 emphasizes X-ray and UV spectroscopy as well as time-domain observations are needed to understand feedback on all scales. *Arcus Probe* (hereafter *Arcus*) uses these to address three big questions are (1) What powers the black hole winds that impact galaxies and clusters? (2) How does

Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray, edited by Jan-Willem A. den Herder, Shouleh Nikzad, Kazuhiro Nakazawa, Proc. of SPIE Vol. 13093, 1309326

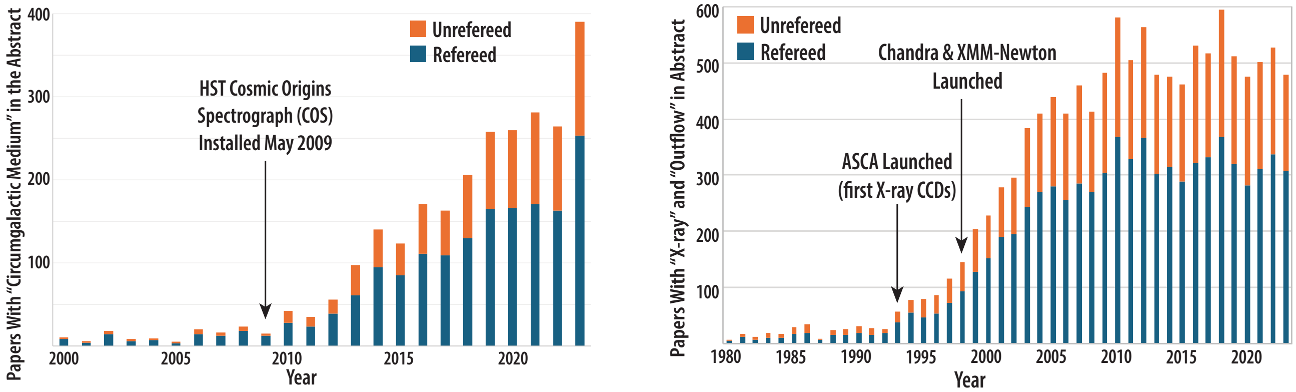

Figure 1: Astro2020 noted that "In the next decade, spectroscopy will be the dominant discovery tool for astronomy." This is not a new observation; new spectroscopic capabilities can create entirely new fields. On the [Left] is a histogram of papers with 'circumgalactic medium' in the abstract as a function of time, with the installation of the HST's Cosmic Origins Spectrograph (COS) marked. On the right is a histogram of papers on X-ray Outflows as a function of time. A small rise is seen with the first X-ray CCDs on ASCA, but it was only with the grating spectrometers on Chandra and XMM-Newton that the field reached hundreds of papers per year.

matter cycle in and out of galaxies, and finally (3) How do stars and circumstellar disks form, evolve, and die?
The challenge to making progress on these questions has primarily been obtaining adequate data. As Figure 1 shows, new capabilities can create (or invigorate) entire new fields. Interest in the intergalactic medium was certainly high before COS was installed on *HST*, but UV observations with earlier spectrometers (STIS, GHRS) were simply too time-consuming to allow sufficient data to be collected. With COS observations, however, results flowed rapidly. X-ray outflows (Figure 1[Right]) showed a similar pattern after *Chandra* and *XMM-Newton* launched. *Arcus*' dramatic improvement in soft X-ray spectral sensitivity over existing facilities can be seen in Figure 2, which compares the figures of merit for detecting absorption and emission lines for *Arcus* against the three high-resolution X-ray spectrometers currently in orbit.

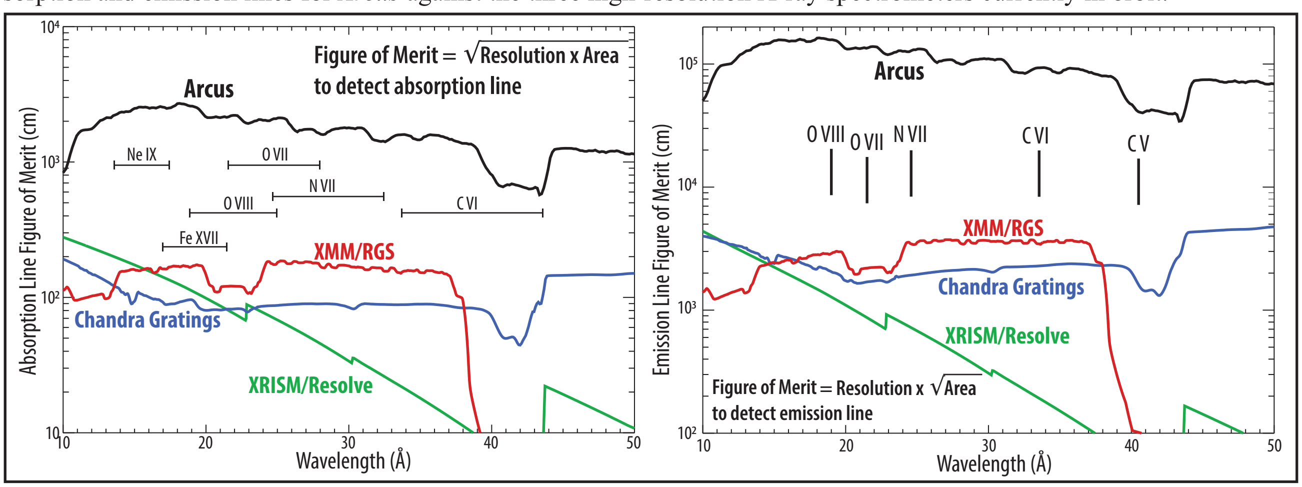

Figure 2: Figures of Merit for detecting absorption [Left] or emission [Right] lines as a function of wavelength for a range of wavelengths. The XRISM/Resolve figure assumes an open Be Gate Valve as the closed value would not appear on this figure. The Chandra gratings figure assumes the highest value obtained, at launch, for either the ACIS-S or HRC-S detectors and either the HETG or LETG gratings. In the emission line figure the vertical bars mark key emission lines; in the absorption line figure, the horizontal bars mark line features from z=0-0.3

2. SCIENCE

The *Arcus* mission and science case is presented in [2], and reviewed in detail in the forthcoming JATIS special issue. We focus here on topics that were only briefly mentioned in [2], such as time-domain science and opportunities for the General Observer (GO) program. For example, the first science goal is to characterize the drivers of accretion-powered feedback in supermassive black holes, much of which has been done assuming a stable accretion process. However, time-domain

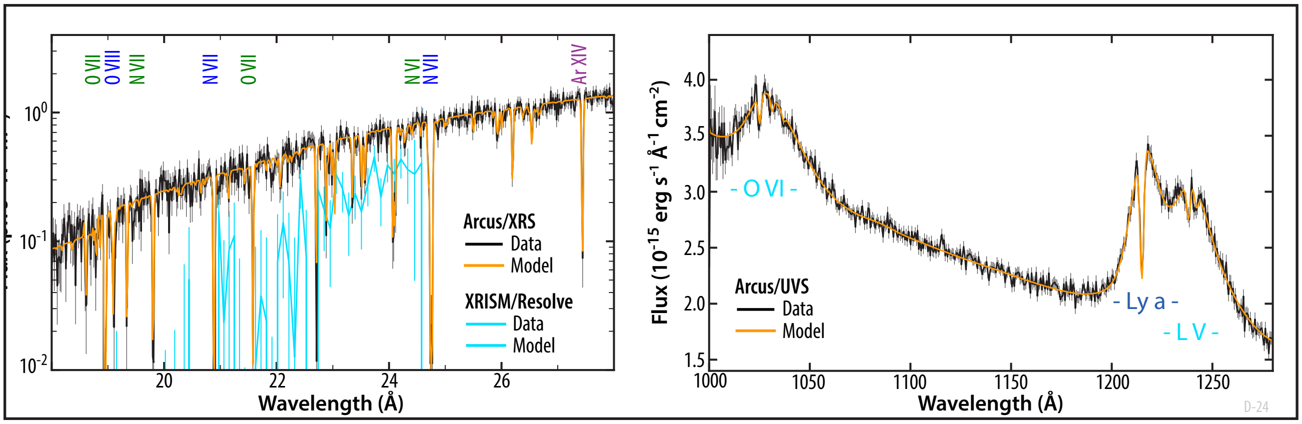

Figure 3: Arcus will provide the first high-resolution, simultaneous X-ray/UV spectra of TDEs. Shown here are simulated 100-ks XRS (left; shown vs. XRISM/Resolve) and UVS (right) spectra, based on Chandra, XMM-Newton, and HST/STIS spectra of ASASSN-14li [27, 37] at 10% of its flux. The UV spectrum is dereddened and interstellar lines are removed; both spectra are binned for clarity. High-resolution X-ray spectroscopy is currently impossible at this flux level, even with microcalorimeters. The X-ray spectra are characterized by a thermal continuum and strong absorption lines blueshifted by 300 km s-1, while the UV spectra are composed of broad AGN-like emission lines (2200 km s-1) and narrow absorption lines that correspond to the X-ray wind. Selected ions are noted: H-like (blue), He-like (green), Li-like (cyan), Be- and B-like (purple).

studies of SMBHs are poised to explode in the near future as *Rubin, SKA, SVOM, ULTRASAT* and the *Einstein Probe* come online, as well as *UVEX*. *Arcus* provides a missing spectroscopic facet of time-domain studies, responding to ToO triggers from such missions as quickly as 4 hours (“fast” ToOs).

Tidal disruption events (TDEs) are an important discovery space to which *Arcus* is ideally suited. Following a stellar disruption by a massive black hole, a phase of hyper-Eddington accretion is predicted to last for days or weeks [3]. This mode of accretion is extremely rare among SMBHs in the local universe [4], but was likely very important in building the first SMBHs in the early Universe [5-8]. TDEs are also the only laboratories wherein the formation and evolution of an accretion disk, winds, and jets in SMBHs can be observed in real time. Unfortunately, the majority of TDEs are too faint for current spectrometers.

Simultaneous X-ray and UV spectroscopy with *Arcus* taken within ~24 hours of a ToO trigger are needed to answer key questions about accretion and outflows in the super-Eddington regime, measure the time scale for disk formation, measure the spins of previously dormant black holes, and more [9]. Triggers could come from, e.g., *Rubin*, then be confirmed as X-ray and/or UV bright by high energy missions referenced above. *UVEX* expects to discover ~500 UV-selected TDEs per year, while *ULTRASAT* expects ~250 over three years. The recently-launched *Einstein Probe* will observe 30-100 TDEs per year above a soft X-ray flux detectable by *Arcus*/XRS [10,11]. Figure 3 shows simulated 100-ks *Arcus* spectra of a TDE assuming the wind spectrum observed in ASASSN-14li [12], but with an X-ray flux ~10× lower at 10^{-12} ergs cm^{-2} s^{-1}. *Arcus* will still achieve 1σ errors of 25%, 3%, and 4% on N_H, ξ and v_{out}, respectively, revealing their physical nature and the impact of feedback from these sources on the surrounding ISM.

Obscurers are winds with high column densities and complex stratification that can partially obscure the soft X-ray band for weeks [13, 14]. Coordinated UV and X-ray observations have only been able to provide broad characterizations of obscurers [13, 15, 16]. Using ToO observations, *Arcus* will be able to follow the evolution of the ionization, covering factor and outflow velocity in both the X-ray and UV bands at different time scales, revealing their densities and impact on feedback.

Changing-state AGN (CSAGN) are a subclass wherein changes to the accretion flow geometry cause the observed source type (broad – or narrowline emission components) to flip over a period of months or years. The advent of high-cadence, all-sky surveys in optical bands has greatly enhanced the detection rate of these events (3-5 per year, currently), and rates will increase even more in the *Rubin* era. Owing to the pointing and sensitivity limitations of current instrumentation, simultaneous high-resolution X-ray and UV spectroscopy of CSAGN has not been possible. Some CSAGN may be triggered by a TDE reshaping the inner accretion flow [17, 18]; other CSAGN may arise through instabilities in the accretion disk [19]. Numerous models predict different consequences for the X-ray and UV continua, for the broad line region, and for winds. Intra-day soft X-ray variability has been reported [20]; *Arcus* standard ToO observations and subsequent monitoring are needed to disambiguate these models, and to begin unlocking the true nature of CSAGN.

General Observer Potential

The six Astro2020 science panels prioritized 24 critical questions across astrophysics. *Arcus* data address 11 of these (Table 1). The nominal GO program shown here is based on discussions with the community together with the scientific priorities identified in Astro2020 and the 2023 Planetary survey [21]. Table 1 shows a range of possible GO studies. GOs will be able to follow up transient events in <4 hrs, addressing the Astro2020 call for "...space-based observational facilities across the electromagnetic spectrum to discover and characterize the brightness and spectra of transient sources..." Over 150,000 potential targets could return high-quality X-ray/UV spectra in <100-ks observations.

Accretion in Compact Objects

Table 1: Arcus Probe General Observer Science

	Decadal Science Goals	Potential GO Science Objectives	Physical Parameters
Cosmic Ecosystems	Explore how SMBH spectra and winds vary with luminosity, black hole mass, black hole spin and other parameters (Decadal science panel questions B-Q4, D-Q3).	Identify the location, size, and structure of coronae in AGN.	Time delays between UV seed photons from the disk and reprocessed X-rays from the Compton corona reveal disk-corona geometry. Uses XRS zero-order X-rays from 2-10 keV.
		Understand transition of radiatively efficient to inefficient accretion flows in AGN.	Separate obscuration and wind-related features by measuring time-dependent X-ray and UV spectra.
Unveiling the Drivers of Galaxy Growth	Determine how gas, metals, and dust flow into, through, and out of galaxies (Decadal science panel questions D-Q2, D-Q3, D-Q4).	Determine the distribution and metal abundance of all phases of gas in our galaxy.	Use background AGN to measure the composition of the hot gas within *Fermi/ eROSITA* bubbles.
			Measure the composition of ISM dust as a function of position within the Galaxy, correlated with H_2 and other molecules.
		Determine the distribution and metal abundance of all phases of gas in galaxies to the ir virial radii and beyond.	Measure emission from warm and hot gas in distant compact clusters and groups.
			Measure warm and hot gas emission lines (O VI, Hβ) as a function of galactic position.
Worlds and Suns in Context	Explore stellar feedback and how the star-planet interaction influences atmospheric properties over all time scales and the range of potentially habitable environments around different types of stars (Decadal science panel questions E-Q4, F-Q1, G-Q1, GQ-3, G-Q4).	Measure the thermodynamic properties of transient events in stars and their impact on their surroundings.	Determine X-ray and UV flare frequency distribution from coronal stars as a function of stellar mass and age, especially exoplanet hosts.
			Observe the evolution of long-duration flares in X-ray and UV from giant stars.
			Measure centroids, line widths and line profiles from Type II supernovae shock wave overrunning circumstellar winds.
			Observe exoplanet transits to measure oxygen absorption depths of 2.5% to 3σ accuracy.
New Messengers and New Physics	Probe physics of stellar-mass compact objects and the associated accretion disks (Decadal science panel questions B-Q1, B-Q2).	Determine what drives the super-Eddington accretion seen in Ultraluminous X-ray Sources.	Reveal time-dependent accretion and outflow signatures by measuring X-ray and UV spectra within 24 hours after optical outburst trigger.
		Measure the physical properties of transient gravitational wave sources.	Search for signatures of r-process elements by measuring the X-ray and UV spectra within 24 hours of a NS-NS kilonova detection.
		Measure both steady and transient accretion events onto white dwarfs.	Observe the UV and X-ray spectral evolution of novae over a period of months
			Use high-res X-ray and UV spectra to measure electron temperature, density, velocity, and elemental abundances in WD systems.
		Probe formation and feedback of winds in stellar mass black holes.	Measure density-sensitive lines in black hole systems as a function of viewing angle, accretion state, and feeding mechanism.
Planetary Decadal: Solar System Science	Origins: Probe the composition of cometary bodies.	Observe the X-ray and UV spectra of comets to measure the composition of both the solar wind and cometary matter.	Measure cometary abundances and compositions using a combination of X-ray charge exchange features from the solar wind together with UV fluorescence lines.
	Worlds & Processes: Probe the properties and dynamics of solid body atmospheres and exospheres, including material loss to space.	Observe Moon-Earth interactions via X-ray and UV lines, including mapping the positions of the emission in the UV.	Measure Sun-Moon-Earth interactions in the Earth's geotail as the Moon moves between day and night phases using X-ray absorption toward bright background sources as well as UV imaging, driven both by solar photon flux and interactions with the solar wind.
	Worlds & Processes: What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?	Determine what combination of solar X-ray flux and the energetic particles from the Io Plasma Torus create X-ray and UV emission.	Time- and space-dependent X-ray and UV spectral emission line diagnostics to separate the different formation processes.

Arcus' simultaneous X-ray and UV spectroscopy over long, uninterrupted observations across multiple visits to stellar mass black holes – highly dynamic sources – facilitates numerous GO programs. The formation and feedback of winds in stellar mass BHs remains a puzzle. Among the first evidence for such winds was X-ray absorption from H-like and He-like Fe near 7 keV [22]. Since then, high-resolution, soft-X-ray spectra have proven crucial; e.g., density-sensitive lines with measured blueshifts have been used to argue for magnetic driving of BH winds [23], although this is still hotly debated [24-26]. Arcus GO studies will elucidate the combination of mechanisms at play in all BH systems, disentangling the roles of viewing angle, accretion state, and feeding mechanism in determining both wind-launching mechanisms and observability (e.g., [27]).

Arcus GOs can explore not only how coronae, jets, and winds interact with their environments, but also how they illuminate them. Winds/atmosphere of the secondary absorb X-rays and UV from the primary, while emission lines arise from the secondary's atmosphere. Studies of Vela X-1 [28] and Cyg X-1 [29] have begun to reveal the role that stellar winds play in the evolution of massive stars [30,31]. Given the surprisingly massive stellar BHs observed as LIGO sources, *Arcus* GO science is crucial for filling in the "gaps in the understanding of stellar winds …[that] leads to large uncertainties in which massive stars become black holes and which become neutron stars." [1].

Ultra-luminous X-ray sources (ULXs) promise to be an exciting new class of GO targets for Arcus, strongly motivated by the Astro2020 question, "When and How are Transients Powered by Neutron Stars or Black Holes?" Super-Eddington accretion onto a neutron star [32] must power many ULXs, and relativistic wind outflows with complex signatures in both X-ray and UV spectra are expected [33]. CCD and gratings spectra have hinted at time-dependent soft X-ray line structure [33,34]. Currently, the spectra require extremely long integration times, however, making it difficult to discern any spectral/temporal dependencies in wind outflows [35,36]. GO programs using the vastly improved *Arcus* resolution, effective area and ToO response time (e.g., triggered by *Rubin* optical monitoring) can systematically attack these issues.

GOs can extend SMBH science as well. Time delays between UV (seed photons from the disk) and X-ray (Compton corona reprocessed) emission encode the location, size, and structure of AGN coronae [37]. This requires simultaneous UV and X-ray observations on the ~10-ks time scales of coronal variability and, with repeated pointings over months or years, the `reverberation mapping' time scales of the broad line region. NGC 5548 is the only source so far with high-fidelity reverberation mapping results in the UV [38, 39], but such studies could become commonplace with *Arcus*.

GO studies will be crucial for understanding the physics behind the putative transition from radiatively-efficient to radiatively-inefficient accretion flows as AGN change from high luminosities to low luminosities. Such studies required 300-ks observations with *Chandra*/HETG for the low-luminosity AGN M81* [40, 41]. Subsequent observations showed intriguing line variations with luminosity over the course of a year, but were limited by the S/N of the 50-ks observations [42]. *Arcus* allows a much broader exploration of the differences among the underlying accretion mechanisms in the various classes of AGN, obtaining higher-resolution X-ray spectra in a fraction of the time currently needed.

Probing the Physics of Reionization

Understanding the cosmological transition from an entirely neutral universe to a highly ionized universe – the "Epoch of Reionization" – is one of the foremost science goals in Astro2020 and cosmology in general. JWST has opened the floodgates for directly observing high-redshift galaxies during this epoch, but has two insurmountable deficiencies for understanding the galactic physics of reionization: (1) the galaxy distances preclude detailed mapping of the multiphase gas, and (2) the H I Lyman continuum escaping from the galaxies cannot be directly observed (it is also attenuated by the Lyα forest from the foreground IGM). To investigate the physics that governs reionization, *Arcus*/UVS can overcome both of these deficiencies by observing low-z analogs of the various types of galaxies and AGN that may have reionized the universe. With wavelength coverage extending to 970Å (observed), the UVS can directly measure the ionizing Lyman continuum flux leaking out of galaxies at z>0.06. This can be studied as a function of galaxy mass, metallicity, morphology, AGN presence, orientation within the galaxy, etc. By working at low-z, the UVS can obtain spatially resolved UV emission maps for comparison to locations of ionized chimneys/channels and phases of the ISM (from, e.g., H II regions, 21-cm and dust emission maps, and X-rays). In addition, the UVS can map the related H I Lyα emission. Lyα emission can be observed at high redshifts, but its distribution and properties depend on complicated resonant scattering that is not well understood. With detailed maps in space and velocity, UVS can provide invaluable constraints for Lyα radiative transfer models, and the insights gained can then be applied to the extensive Lyα emission observations now being obtained at high-z. While HST/COS has done similar observations, it has only scratched the surface, and it is not practical to fully map galaxies with COS because of its small slit (2"). With a 6'-long slit, UVS can obtain such maps, providing an exciting opportunity for GO studies related to reionization.

The Interplay Between Dust and Molecules in the Milky Way's Ecosystem

Arcus spectra will reveal the dust composition of the MW ISM, greatly improving CMB studies and addressing the "missing oxygen problem" in the disk. Comparing Arcus' X-ray spectra to laboratory-measured spectra of dust analogs reveals ISM dust grain composition [43,44]. CMB studies rely on removing foreground dust emission to extract the polarized CMB. Current CMB analyses approximates dust emission as a modified blackbody, but future advances [45-49] will require a realistic emission spectrum that includes grain composition, size, and geometry [50-52]. Additionally, even small amounts of magnetic inclusions – detectable with the XRS – affect the CMB emission [53, 54].

Arcus will also uncover the mysterious "oxygen sinks" in the ISM—which current grain models are unable to reproduce—by distinguishing between different types of oxygen-bearing grains and ices. Studies may imply the presence of water ice in the diffuse ISM [55], and laboratory experiments show that hydrated silicates can exist in that environment [56]. Arcus will detect even small amounts of solid-phase oxygen. A detection of water ice well below current upper limits for the diffuse ISM, (N_{H2O}=4x10^{16} cm^{-2}; [57]) can be achieved in 200 ks toward a bright X-ray source.

White Dwarf Studies

White dwarfs (WDs) are the most ubiquitous end point for stellar evolution. Short-period WD binaries will be significant sources for LISA gravitational wave measurements [58, 59]. However, Astro2020 noted that "detailed photometric and spectroscopic electromagnetic observations spanning infrared through X-ray wavelengths, coupled with gravitational wave measurements and attention from theory, [is needed to] elucidate these multiple pathways." *Arcus* GO programs combining X-ray spectra to study the physics of accretion flow and UV spectra to model mass transfer will be key for fully understanding these systems.

In the WD binary systems that will become LISA calibrators/detections, evolution is driven by a combination of angular momentum losses due to gravitational radiation and outflowing winds, and mass transfer from the companion. WD atmosphere modeling of UVS spectra, coupled with Gaia distance measurements, will constrain the mass of and accretion rate onto the WD (e.g., [60, 61]). Current studies indicate a "missing component" of angular momentum loss in many such systems [62]. Identifying such components requires better models of the mass and momentum loss in WD binary system outflows, along with higher-resolution XRS spectra to test such models.

Cataclysmic Variables and symbiotic novae are both candidates for type Ia SNe progenitors with poorly understood evolutionary pathways. As material transfers from the donor to the recipient, a hydrogen-rich layer is formed which becomes degenerate and undergoes thermonuclear fusion, causing an outburst (nova) lasting from days to months. The shocks resulting from this explosion have speeds of up to 7000 km s^{-1} and temperatures up to tens of keV, and are an important source of stellar-scale feedback into the surrounding ISM [63]. Understanding the characteristics and evolution of these outbursts (e.g., metal content, shock velocity, structure) is vital to fully characterizing the different classes of novae and understanding their roles in spreading metals throughout the ISM. Arcus' high-resolution X-ray and UV spectral coverage will measure the chemical yields for a wide range of elements, and will provide line diagnostics to constrain the electron temperature, density, velocity, and elemental abundances of the gas in these systems [64-66].

Early X-ray/UV Spectra of Type II SNe

Multiwavelength data on Type II SNe explosions show rapid spectral evolution, demonstrating the importance of fast response times; however, early optical spectra are notably featureless. X-ray and UV spectra provide a wealth of lines, but are more difficult to obtain early after the explosion, owing to the *HST* and *Chandra* ToO response times. Only 3 SNe have been observed in the FUV less than one week after the explosion [67], while no high-resolution spectra exist in the X-rays. The UV features may come from elements in the outer envelope of the star or the close-in circumstellar medium (CSM), and will help determine the physical conditions (temperature, density, composition) in these regions. As the SN expands into the CSM, changes in spectral line profiles reveal characteristics of the progenitor during the final years of its life. Arcus will measure variable centroids, line widths and line profiles from Type II SNe shock waves overrunning the CSM within 24±3 hours of the SN using standard ToOs. Revisiting the targets on timescales from days to months will probe further back into the CSM and thus late-phase stellar winds.

Solar System Science

The *Arcus* GO program can address questions posed by the 2023 Decadal review of Planetary science [21], such as "How and when did cometary bodies orbiting beyond the giant planets form?" and what was "the nature and evolution of [planetary building blocks]?" Only *Arcus* can provide both X-ray and UV spectra of charge exchange emission (CXE) between escaping cometary gases and the solar wind. *Chandra* [69] and *Rosetta* [68] data have made the first inroads here, but *Arcus* GOs will approach these questions with vastly improved tools, testing CXE models based on comet composition and solar wind types – fast and cold polar wind vs. a warm equatorial wind [70-72].

With *Europa Clipper* due to arrive in 2030 and *JUICE* in 2031, the Jovian system will have been the subject of astronomical investigation for over 500 years. Chandra observations have detected unresolved soft X-ray emission of unknown origin from the Io Plasma Torus (IPT) and from Europa and Io (perhaps due to surface bombardment by H, S, and O ions from near the IPT) [73]. The surface composition of Europa has been studied via *HST*/STIS FUV spectroscopy [74]. *Arcus* GO observations can provide higher-quality, simultaneous X-ray and UV data to help determine what combination of the solar X-ray flux and the energetic particles from the IPT drives the observed emission processes.

3. CONCLUSIONS

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*.

4. ACKNOWLEDGMENTS

The *Arcus Probe* team also notes internal funding support from SAO, LASP, NASA/ARC, MPE, MIT, PSU, Northrop Grumman, and NASA/GSFC.

5. 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] Smith, R. and the Arcus Team, "The Arcus Probe Mission", SPIE, 126780E (2023)
[3] Rees, M. J., "Tidal disruption of stars by black holes of 10^6-10^8 solar masses in nearby galaxies", Nature, vol. 333, iss. 6173, p. 523 (1988).
[4] Lodato, G., and Natarajan, P., "Supermassive black hole formation during the assembly of pre-galactic discs", Monthly Notices of the Royal Astronomical Society, vol. 371, iss. 4, p. 1813 (2006).
[5] Hickox, R. C., et al., "Host Galaxies, Clustering, Eddington Ratios, and Evolution of Radio, X-Ray, and Infrared-Selected AGNs", The Astrophysical Journal, vol. 696, iss. 1, p. 891 (2009).
[6] Madau, P., and Dickinson, M., "Cosmic Star-Formation History", Annual Review of Astronomy and Astrophysics, vol. 52, iss. 1, p. 415 (2014).
[7] Mayer, L., and Bonoli, S., "The route to massive black hole formation via merger-driven direct collapse: a review", Reports on Progress in Physics, vol. 82, iss. 1, p. 016901 (2018).
[8] Woods, T. E., et al., "Titans of the early Universe: The Prato statement on the origin of the first supermassive black holes", Publications of the Astronomical Society of Australia, vol. 36, p. e027 (2019).
[9] Komossa, S., "Tidal disruption of stars by supermassive black holes: Status of observations", Journal of High Energy Astrophysics, vol. 7, p. 148 (2015).
[10] Yang, H. K., et al., "The Fermi Bubbles: Supersonic Active Galactic Nucleus Jets with Anisotropic Cosmic-ray Diffusion ", The Astrophysical Journal, vol. 761, iss. 2, p. 185 (2012).
[11] Crocker, R. M., et al., "Steady-state Hadronic Gamma-ray Emission from 100-myr-old Fermi Bubbles ", The Astrophysical Journal, vol. 791, iss. 2, p. L20 (2014).
[12] Miller, J. M., et al., "Flows of X-ray gas reveal the disruption of a star by a massive black hole", Nature, vol. 526, iss. 7574, p. 542 (2015).
[13] Kaastra, J. S., et al., "A fast and long-lived outflow from the supermassive black hole in NGC 5548", Science, vol. 345, iss. 6192, p. 64 (2014).
[14] Mehdipour, M., et al., "Chasing obscuration in type-I AGN: discovery of an eclipsing clumpy wind at the outer broad-line region of NGC 3783", Astronomy & Astrophysics, vol. 607, p. A28 (2017).

[15] Kara, E., et al., "AGN STORM 2. I. First results: A Change in the Weather of Mrk 817", The Astrophysical Journal, vol. 922, iss. 2, p. 151 (2021).
[16] Mao, J., et al., "Multiwavelength Observations of the Obscuring Wind in the Radio-quiet Quasar MR 2251-178", The Astrophysical Journal, vol. 940, iss. 1, p. 41 (2022).
[17] Chan, C., et al., "Tidal Disruption Events in Active Galactic Nuclei", The Astrophysical Journal, vol. 881, iss. 2, p. 113 (2019).
[18] Ricci, C., et al., "The 450 Day X-Ray Monitoring of the Changing-look AGN 1ES 1927+654", The Astrophysical Journal Supplement Series, vol. 255, iss. 1, p. 7 (2021).
[19] Noda, H., and Done, C., "Explaining changing-look AGN with state transition triggered by rapid mass accretion rate drop", Monthly Notices of the Royal Astronomical Society, vol. 480, iss. 3, p. 3898 (2018).
[20] Ricci, C., et al., "The Destruction and Recreation of the X-Ray Corona in a Changing-look Active Galactic Nucleus", The Astrophysical Journal, vol. 898, iss. 1, p. L1 (2020).
[21] Committee on the Planetary Science and Astrobiology Decadal Survey, et al., "Origins, Worlds, and Life" (2023).
[22] Kotani, T., et al., "ASCA Observations of the Absorption Line Features from the Superluminal Jet Source GRS 1915+105", The Astrophysical Journal, vol. 539, iss. 1, p. 413 (2000).
[23] Miller, J. M., et al., "The magnetic nature of disk accretion onto black holes", Nature, vol. 441, iss. 7096, p. 953 (2006).
[24] Neilsen, J., and Homan, J., "A Hybrid Magnetically/Thermally Driven Wind in the Black Hole GRO J1655-40?", The Astrophysical Journal, vol. 750, iss. 1, p. 27 (2012).
[25] Neilsen, J., and Degenaar, N., "High-Resolution Spectroscopy of X-ray Binaries", arXiv e-prints, arXiv:2304.05412 (2023).
[26] Tomaru, R., Done, C., and Mao, J., "What powers the wind from the black hole accretion disc in GRO J1655-40?", Monthly Notices of the Royal Astronomical Society, vol. 518, iss. 2, p. 1789 (2022).
[27] Ponti, G., et al., "Ubiquitous equatorial accretion disc winds in black hole soft states", Monthly Notices of the Royal Astronomical Society: Letters, vol. 422, iss. 1, p. L11 (2012).
[28] Fürst, F., et al., "X-ray variation statistics and wind clumping in Vela X-1", Astronomy and Astrophysics, vol. 519, p. A37 (2010). DOI: 10.1051/0004-6361/200913981
[29] Hanke, M., et al., "Chandra X-Ray Spectroscopy of the Focused Wind in the Cygnus X-1 System. I. The Nondip Spectrum in the Low/Hard State", The Astrophysical Journal, vol. 690, iss. 1, p. 330 (2008).
[30] Giménez-García, A., et al., "Measuring the stellar wind parameters in IGR J17544-2619 and Vela X-1 constrains the accretion physics in supergiant fast X-ray transient and classical supergiant X-ray binaries", Astronomy & Astrophysics, vol. 591, p. A26 (2016).
[31] Neijssel, C. J., et al., "Wind Mass-loss Rates of Stripped Stars Inferred from Cygnus X-1", The Astrophysical Journal, vol. 908, iss. 2, p. 118 (2021).
[32] Bachetti, M., et al., "An ultraluminous X-ray source powered by an accreting neutron star", Nature, vol. 514, iss. 7521, p. 202 (2014).
[33] Fürst, F., et al., "Long-term pulse period evolution of the ultra-luminous X-ray pulsar NGC 7793 P13", Astronomy & Astrophysics, vol. 651, p. A75 (2021).
[34] Middleton, M. J., et al., "Broad absorption features in wind-dominated ultraluminous X-ray sources?", Monthly Notices of the Royal Astronomical Society: Letters, vol. 438, iss. 1, p. L51 (2013).
[35] Pinto, C., Middleton, M. J., and Fabian, A. C., "Resolved atomic lines reveal outflows in two ultraluminous X-ray sources", Nature, vol. 533, iss. 7601, p. 64 (2016).
[36] Middleton, M. J., et al., "Diagnosing the accretion flow in ultraluminous X-ray sources using soft X-ray atomic features", Monthly Notices of the Royal Astronomical Society, vol. 454, iss. 3, p. 3134 (2015).
[37] Pinto, C., et al., "XMM-Newton campaign on ultraluminous X-ray source NGC 1313 X-1: wind versus state variability", Monthly Notices of the Royal Astronomical Society, vol. 492, iss. 4, p. 4646 (2020).
[38] Chiang, J., "EUVE/ASCA/RXTE observations of NGC 5548", AIP Conference Proceedings, vol. 599, p. 578 (2001).
[39] Williams, P. R., et al., "Space Telescope and Optical Reverberation Mapping Project. XII. Broad-line Region Modeling of NGC 5548", The Astrophysical Journal, vol. 902, iss. 1, p. 74 (2020).
[39] Horne, K., et al., "Space Telescope and Optical Reverberation Mapping Project. IX. Velocity-Delay Maps for Broad Emission Lines in NGC 5548", The Astrophysical Journal, vol. 907, iss. 2, p. 76 (2021).

[40] Young, A. J., et al., “High-Resolution X-Ray Spectroscopy of a Low-Luminosity Active Galactic Nucleus: The Structure and Dynamics of M81*”, The Astrophysical Journal, vol. 669, iss. 2, p. 830 (2007).
[41] Markoff, S., et al., “Results from an Extensive Simultaneous Broadband Campaign on the Underluminous Active Nucleus M81*: Further Evidence for Mass-scaling Accretion in Black Holes”, The Astrophysical Journal, vol. 681, iss. 2, p. 905 (2008).
[42] Miller, J. M., et al., “Exploring Accretion and Disk-Jet Connections in the LLAGN M81*”, The Astrophysical Journal, vol. 720, iss. 2, p. 1033 (2010).
[43] Lee, J. C., and Ravel, B., “Determining the Grain Composition of the Interstellar Medium with High-Resolution X-Ray Spectroscopy”, The Astrophysical Journal, vol. 622, iss. 2, p. 970 (2005).
[44] Lee, J. C., et al., “Condensed Matter Astrophysics: A Prescription for Determining the Species-specific Composition and Quantity of Interstellar Dust Using X-rays”, The Astrophysical Journal, vol. 702, iss. 2, p. 970 (2009).
[45] Hensley, B. S., and Bull, P., “Mitigating Complex Dust Foregrounds in Future Cosmic Microwave Background Polarization Experiments”, The Astrophysical Journal, vol. 853, iss. 2, p. 127 (2018).
[46] Planck Collaboration, “Planck 2018 results. XI. Polarized dust foregrounds”, Astronomy & Astrophysics, vol. 641, p. A11 (2020).
[47] Mangilli, A., et al., “Dust moments: towards a new modeling of the galactic dust emission for CMB B-modes analysis”, Astronomy & Astrophysics, vol. 647, p. A52 (2021).
[48] Abazajian, K., et al., “CMB-S4 Science Case, Reference Design, and Project Plan”, arXiv e-prints, arXiv:1907.04473 (2019).
[49] Sugai, H., et al., “Updated Design of the CMB Polarization Experiment Satellite LiteBIRD”, Journal of Low Temperature Physics, vol. 199, iss. 3-4, p. 1107 (2020).
[50] Guillet, V., et al., “Dust models compatible with Planck intensity and polarization data in translucent lines of sight”, Astronomy & Astrophysics, vol. 610, p. A16 (2018).
[51] BeyondPlanck Collaboration, “BEYONDPLANCK. I. Global Bayesian analysis of the Planck Low Frequency Instrument data”, Astronomy & Astrophysics, vol. 675, p. A1 (2023).
[52] Draine, B. T., and Hensley, B., “Magnetic Nanoparticles in the Interstellar Medium: Emission Spectrum and Polarization”, The Astrophysical Journal, vol. 765, iss. 2, p. 159 (2013).
[53] Draine, B. T., and Hensley, B. S., “The Dielectric Function of "Astrodust" and Predictions for Polarization in the 3.4 and 10 μm Features”, The Astrophysical Journal, vol. 909, iss. 1, p. 94 (2021).
[54] Draine, B. T., and Hensley, B., “Magnetic Nanoparticles in the Interstellar Medium: Emission Spectrum and Polarization”, The Astrophysical Journal, vol. 765, iss. 2, p. 159 (2013).
[55] Poteet, C. A., Whittet, D. C. B., and Draine, B. T., “The Composition of Interstellar Grains toward ζ Ophiuchi: Constraining the Elemental Budget near the Diffuse-dense Cloud Transition”, The Astrophysical Journal, vol. 801, iss. 2, p. 110 (2015).
[56] Potapov, A., et al., “Dust/ice mixing in cold regions and solid-state water in the diffuse interstellar medium”, Nature Astronomy, vol. 5, iss. 1, p. 78 (2020).
[57] Whittet, D. C. B., et al., “Infrared Spectroscopy of Dust in the Diffuse Interstellar Medium toward Cygnus OB2 No. 12”, The Astrophysical Journal, vol. 490, iss. 2, p. 729 (1997).
[58] Kupfer, T., et al., “LISA verification binaries with updated distances from Gaia Data Release 2”, Monthly Notices of the Royal Astronomical Society, vol. 480, iss. 1, p. 302 (2018). DOI: 10.1093/mnras/sty1545 http://dx.doi.org/10.1093/mnras/sty1545
[59] Kupfer, T., et al., “LISA Galactic binaries with astrometry from Gaia DR3”, arXiv e-prints, arXiv:2302.12719 (2023).
[60] Pala, A. F., et al., “Effective temperatures of cataclysmic-variable white dwarfs as a probe of their evolution”, Monthly Notices of the Royal Astronomical Society, vol. 466, iss. 3, p. 2855 (2016).
[61] Pala, A. F., et al., “Constraining the evolution of cataclysmic variables via the masses and accretion rates of their underlying white dwarfs”, Monthly Notices of the Royal Astronomical Society, vol. 510, iss. 4, p. 6110 (2021).
[62] Pala, A. F., et al., “Constraining the evolution of cataclysmic variables via the masses and accretion rates of their underlying white dwarfs”, Monthly Notices of the Royal Astronomical Society, vol. 510, iss. 4, p. 6110 (2021).
[63] Orio, M., et al., “Chandra High Energy Transmission Gratings Spectra of V3890 Sgr”, The Astrophysical Journal, vol. 895, iss. 2, p. 80 (2020).
[64] Nelemans, G., et al., “The chemical composition of donors in AM CVn stars and ultracompact X-ray binaries: observational tests of their formation”, Monthly Notices of the Royal Astronomical Society, vol. 401, iss. 2, p. 1347 (2010).

[65] Strohmayer, T. E., "Detection of Nitrogen and Neon in the X-Ray Spectrum of GP Comae Berenices with XMM/Newton", The Astrophysical Journal, vol. 608, iss. 1, p. L53 (2004).
[66] Ramsay, G., et al., "XMM-Newton observations of AM CVn binaries", Astronomy & Astrophysics, vol. 440, iss. 2, p. 675 (2005).
[67] Bostroem, K. A., et al., "SN 2022acko: The First Early Far-ultraviolet Spectra of a Type IIP Supernova", The Astrophysical Journal Letters, vol. 953, iss. 2, p. L18 (2023).
[68] Feldman, P. D., et al., "FUV Spectral Signatures of Molecules and the Evolution of the Gaseous Coma of Comet 67P/Churyumov-Gerasimenko", The Astronomical Journal, vol. 155, iss. 1, p. 9 (2017).
[69] Bodewits, D., et al., "Spectral analysis of the Chandra comet survey", Astronomy & Astrophysics, vol. 469, iss. 3, p. 1183 (2007).
[70] Schwadron, N. A., and Cravens, T. E., "Implications of Solar Wind Composition for Cometary X-Rays", The Astrophysical Journal, vol. 544, iss. 1, p. 558 (2000).
[71] Kharchenko, V., and Dalgarno, A., "Variability of Cometary X-Ray Emission Induced by Solar Wind Ions", The Astrophysical Journal, vol. 554, iss. 1, p. L99 (2001).
[72] Bodewits, D., et al., "Catching Some Sun: Probing the Solar Wind with Cometary X-Ray and Far-Ultraviolet Emission", The Astrophysical Journal, vol. 606, iss. 1, p. L81 (2004).
[73] Elsner, R. F., et al., "Discovery of Soft X-Ray Emission from Io, Europa, and the Io Plasma Torus", The Astrophysical Journal, vol. 572, iss. 2, p. 1077 (2002).
[74] Becker, T. M., et al., "The Far-UV Albedo of Europa From HST Observations", Journal of Geophysical Research (Planets), vol. 123, iss. 5, p. 1327 (2018).