Astro2020 APC White Paper

Supporting Archival Research with Euclid and SPHEREx Data

Thematic Areas: An Enabling Foundation for Research

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Abstract (optional):

Archival research greatly increases the scientific return on NASA missions. Robust funding for archival research through the NASA Astrophysics Data Analysis Program (ADAP) has been a successful and vital investment for NASA. In the mid-2020s, the largest projects for ADAP research will be the new infrared missions, Euclid and SPHEREx. Additional ADAP funding will be required to fully exploit this flood of new infrared data. In this white paper, we provide an overview of the science focus of research with Euclid and SPHEREx, the synergy between their data and those from other missions, and estimate the needed increase in funding to support the U.S. community's increased archival research effort.

1. Introduction

Archival research greatly increases the scientific return on NASA missions. For observatories, the number of archival papers can exceed the number published by General Observers[1,2], and for dedicated experiments the number of community papers can exceed the number from the Science Team. Robust funding for archival research through the NASA Astrophysics Data Analysis Program (ADAP) is thus a vital investment for NASA.

In the mid-2020s, there will be a wealth of archival research opportunities, resulting from the operating NASA missions, including: JWST, Hubble, Chandra, SOFIA, WFIRST, Euclid, SPHEREx, IXPE, and TESS. The strategic missions (JWST, Hubble, Chandra, WFIRST) will have their own archival research programs, but support for the others comes from ADAP. In the mid-2020s, the largest projects for ADAP research will be the new infrared missions, Euclid[3] (Laureijs et al. 2011; Racca et al. 2016) and SPHEREx[4] (Bock et al. 2018; Dore et al. 2018). Additional ADAP funding will be required to fully exploit this flood of new infrared data without starving the archival research using other archival data sets. Current infrared missions in ADAP (Spitzer, WISE/NEOWISE) will cease operations in 2020 and researchers will need less support for using those data. However, SPHEREx alone will need those archival resources given its scope and unique capabilities and data products as an all-sky spectral survey. Thus, to guarantee the science return of NASA's investment in Euclid, ADAP will need to be augmented (see Section 6).

In this white paper, we provide an overview of the science focus of research with Euclid and SPHEREx, the synergy between their data and those from other missions, and estimate the needed increase in funding to support the U.S. community's increased archival research effort. Throughout, we reference relevant Astro2020 White Papers from the Science (SWP) and APC (APCWP) calls.

2. Euclid Overview

Euclid is an European Space Agency (ESA) M-class mission to study the geometry and nature of the dark universe. The mission is the second medium-class mission (M2) in the Cosmic Vision program (2015-2025). Euclid was adopted by ESA's Science Program Committee (SPC) in June 2012, and is slated for launch in June, 2022. Euclid will consist of a 1.2m Korsch space telescope with two instruments: VIS: 550-900 nm band imager with 36 4k x 4k CCDs, covering 0.5 deg^2 with 0.1 arcsecond pixels; and NISP: near-infrared (NIR) slitless spectrograph and imager, with 16 2k x 2k detectors, covering 0.5 deg^2 with 0.3 arcsecond pixels. Imaging data will be obtained in the Y, J, and H bands. Spectroscopy will mostly use the red grism, covering 1.25-1.85 microns, at R~380 for a compact object (0.5 arcseconds).

The Euclid mission will conduct two surveys to meet its cosmology objectives: the Wide

[1] https://irsa.ipac.caltech.edu/docs/biblio/bibliography.html
[2] https://archive.stsci.edu/hst/bibliography/pubstat.html
[3] http://sci.esa.int/euclid/
[4] http://spherex.caltech.edu/

Survey: 15,000 deg^2 of the extra-galactic sky; galactic latitude |b| > 30 deg; and the Deep Survey[5]: approximately 2 magnitudes deeper than the wide survey, total area of approximately 40 deg^2 in patches of 10 and 20 deg^2 (see also SWP Capak et al.). Calibration fields also cover an additional ~7 square degrees around existing deep multi-wavelength areas. Additional surveys will almost certainly be conducted in an extended mission (e.g., SWP Penny et al.). Euclid data will be made public within about two years of acquisition. Euclid will provide a Petabyte-scale dataset, having observed more than a trillion spatial resolution elements in the wide survey.

Euclid will survey the least reddened ~40% of the sky, and will provide highly refined, uniform data products with exquisitely characterized systematics, as required for the Dark Energy objectives. The Wide Survey depth will vary from 24.5 AB mag (10sigma) in the VIS band for a typical galaxy, and almost a magnitude deeper for a point source, to 24 AB mag (5sigma) for the H band, making the Euclid data set an essential astronomical resource, whose value will be enhanced by synergy with LSST, SPHEREx and WFIRST data.

The Euclid mission has been optimized for the measurement of two primary probes sensitive to Dark Energy: (1) Weak Gravitational Lensing, for which Euclid will image ~1.5 billion galaxies to infer the growth of structures that cause tiny distortions in observed galaxy shapes; and (2) Galaxy Clustering, for which Euclid will obtain grism redshifts of ~30 million galaxies to measure the cosmic expansion history through baryonic acoustic oscillations (BAO).

Archival research with Euclid data will complement and augment the research published by the Euclid Consortium (EC)[6], which will have proprietary access to the data before public release. The scope of Euclid's data set suggests that even the large number of EC members will only scratch the surface of the science to be extracted from Euclid's survey of the extragalactic sky, with additional potential discoveries offered by the combination with other wide-area surveys. Euclid has been referenced in more than 60 science white papers for Astro2020.

Quick (Q) and Data Releases (DR)	Timeline w.r.t. nominal mission start	Estimated Date (about December of each year)	Area
Q1	14 months	2023	50 deg^2
DR1	2 years + 2 months	2024	2,500 deg^2
Q2	3 years + 2 months	2025	50 deg^2
DR2	4 years + 2 months	2026	7,500 deg^2
Q3	5 years + 2 months	2027	50 deg^2
Q4	6 years + 2 months	2028	50 deg^2
DR3	7 years + 2 months	2029	15,000 deg^2

[5] http://sci.esa.int/euclid/61403-three-dark-fields-for-euclid-deep-survey/
[6] http://www.euclid-ec.org/

2.1 Euclid Data Products

Euclid will produce a Petabyte-scale dataset. The data release schedule (Table 1) includes four minor releases (each 50 deg^2) and three major releases (each covering thousands of square degrees). Data products will be a combination of data obtained by the Euclid instruments onboard the spacecraft and supporting data obtained from ground-based observatories. Euclid data products will include:

- Basic calibrated Euclid data: single VIS and NISP exposures with detector effects removed and calibration applied,
- Euclid Mosaics: combinations of Euclid exposures within standard field of view,
- "Euclidized" ground-based data (release policy is TBD): ground-based data processed for optimal use in combination with Euclid data,
- Spectra: one-dimensional spectra extracted from grism exposures,
- Catalogs: object catalogs extracted from Euclid+ground data,
- Higher level science products: the EC also plans to release higher level products to enable community science.

2.2 Science with the Euclid Archive

The breadth of Euclid science is too vast to cover in detail here. Instead, we provide a few representative investigation topics to indicate the variety of archival research that the US community will conduct. Additional benefits of public Euclid data are discussed in Astro2020 Science White papers (e.g., SWP Mantz et al.; SWP Pisani et al., SWP Simon et al.)

2.2.1 Tracing Galaxy Evolution via Emission-Line Galaxies

Euclid's slitless spectroscopic survey of the extragalactic sky will provide an unprecedented resource for the study of galaxy evolution. Euclid will measure emission lines for over 30 million galaxies, inferring their redshift and star-formation properties. By tracing the global density of these sources, Euclid will provide a fundamental measurement of cosmic star-formation density. Archival researchers will have the opportunity to study many aspects of galaxy evolution in the Euclid spectroscopic database, including:

- <u>Extinction</u>: In certain redshift ranges, Euclid will be sensitive simultaneously to the H-alpha and H-beta emission lines, especially in the deep fields where the blue grism is available. Large samples of Balmer emission lines will enable the study of extinction as a function of other galaxy properties. Previous studies (e.g., Dominguez et al. 2013) have demonstrated the power of grism data for this kind of investigation.

- Galaxy pairs: Mergers are an important stage in the evolution of some massive galaxies. Current merger samples at comparable redshift are limited to small sample sizes, but there is some indication that major-merger rates do not decline with cosmic time as originally predicted (e.g. Rodriguez-Gomez et al. 2015, Man et al. 2016). Euclid will identify the most strongly star-forming galaxy pairs at z>1, that is those in which both merger components have emission line(s) from on-going star-formation.
- Extreme emission line galaxies: Euclid will discover thousands of low-mass, low-metallicity galaxies from their very strong emission lines. These extreme emission-line galaxies (EELGs; Atek et al. 2011) contribute significantly to the global star-formation rate at the peak epoch of star formation (Atek et al. 2014). They are also likely analogous to the sources of Reionization at higher redshift.

2.2.2 Linking Stellar Mass To Dark Matter Via Clustering Statistics

Statistical methods such as abundance matching and 2-point clustering studies allow us to link galaxies to their underlying dark matter halos if sufficient areas and numbers of galaxies are measured (e.g. Berlind & Weinberg 2002, Leauthaud et al. 2012). For instance, the mass function and clustering of passive galaxies are known to differ strongly from the overall galaxy population (Hartley et al. 2010, Williams et al. 2009, Ilbert et al. 2009). By z~2 these massive galaxies already form a 'red sequence' of strongly clustered galaxies (Ilbert et al. 2010, Brammer et al. 2011, McCracken et al. 2010, Williams et al. 2009) in which the last star formation episodes occurred >1-2 Gyr earlier (i.e. z~3-6, Toft et al. 2012). In addition, the feedback models used to quench star formation in the z~2 passive systems imply that high redshift large scale structure should include quasars, but this connection has yet to be observed at z>3 (Overzier et al. 2009, Banados et al. 2013). The clustering properties of luminous z >3 galaxies may suggest a link to the z~2 passive galaxies (Hildebrandt et al. 2009, Ouchi et al. 2004, McCracken et al. 2010, Williams et al. 2009), but finding a definitive connection between these populations requires linking galaxies to their dark matter haloes as a function of stellar mass and redshift, something only a survey with the statistical power of Euclid can do definitively.

2.2.3 The most luminous LBGs at high redshift

The most massive (a few M*, z>7 Lyman Break Galaxies; LBGs) at high redshift are expected to be the signpost of the first over-dense regions in the Universe. The global ionizing output of galaxies in these regions is expected to carve large ionized bubbles in the neutral intergalactic medium (IGM), thus allowing Lyα from these objects to escape freely (Bauer et al. 2015; Furlanetto et al. 2017; D'Aloisio et al. 2018). Simulations suggest that these bubbles are 0.2-3 degrees across depending on the epoch when reionization started, thus a large area is crucial to characterize these structures well enough to differentiate models (Springel et al. 2005, Overzier et al. 2009, Bauer et al. 2015). The Euclid spectroscopic data (especially in the deep fields where the blue grism will be used) will identify Lyα emitters at z>7, providing a tracers of the ionized IGM (e.g. SWP Cuby et al.). The deep optical and IR imaging will enable the selection of LBGs, providing tracers of the mass distribution. . Furthermore, Spitzer has invested heavily in observing Euclid Deep fields in its final cycles to ensure estimates of stellar mass are available for galaxies found by Euclid. This combination of data alone ensures a large number of ADAP proposals will be be written to analyze the joint Euclid Spitzer data in the deep regions.

2.2.4 Quasars at High- and Low-z

Understanding the parallel evolution of galaxies and supermassive black holes is one of the major questions of astrophysics, with several connections to open key problems such as the origin of the first massive black holes, the evolution of their accretion rate, the co-evolution with the host galaxies and the establishment of the present-day scaling relations between the black hole and galaxy bulge masses. Euclid will identify QSOs at a range of redshifts, including some of the luminous and most distant (e.g. SWP Fan et al.), which will provide important follow-up targets for JWST and other facilities.

2.2.5 Community Cosmology Investigations: Improved Knowledge of Galaxy Properties will Improve Dark Energy Measurements

Euclid anticipates the measurement of two billion galaxies with photometric redshifts, more than 30 million grism-based redshifts, a thousand multiply-imaged quasars, and $3x10^4$ strongly lensed galaxies.

By better understanding the galaxy population we will significantly improve the understanding of systematics in dark energy measurements, improving confidence in DE results. Both Euclid and WFIRST rely on near-infrared ~1-2μm grism spectroscopy to make the BAO measurement. The majority of objects in these surveys will contain only one emission line that must be identified as either H-alpha, H-beta, [OII], or [OIII] (or possibly a less common line). Spitzer and WISE data over these deep fields will provide key constraints on the 1.6μm photometric feature at z>1 and GALEX data constrains the 0.09μm Lyman-limit and 0.12 μm Lyman-alpha break at z<0.7, better differentiating the different lines and improving the statistical correction (e.g. Sawicki 2002).

WL tomography measurements are critically sensitive to knowledge of the redshift distribution of galaxies in each of the tomographic bins. Improved knowledge of these systematics rapidly improves the constraint on dark energy (Huterer et al. 2006). In practice this is done by obtaining high-quality spectroscopy in regions with high-quality photometry (deep fields) to create a map from the observed survey photometry to redshift space. This mapping is then used by (or used to correct) "photometric redshifts" methods to obtain unbiased redshift distributions (Newman et al. 2013, Bordoloi et al. 2010, Masters et al. 2015).

Multi-wavelength data are particularly valuable in controlling three key systematics in this mapping: extinction due to dust in objects, characterizing the Active Galactic Nuclei (AGN) that systematically bias photometric redshifts (Masters et al. 2012), and differentiating stars, galaxies and AGN. In addition, the multi-wavelength data improves the confidence in the spectroscopic redshifts used to calibrate these surveys for the same reasons it improves the BAO surveys.

Intrinsic extinction within galaxies is known to correlate with photometric redshift bias. This bias correlates with observables such as galaxy type and ellipticity and can be used to statistically correct photometric redshifts if an independent measure of extinction is available (e.g.

Kriek & Conroy 2013). Spitzer, WISE, and Herschel data provide this independent measurement by spanning a long-wavelength range that is nearly independent of extinction. These measurements must be made with statistically significant samples of galaxies with spectroscopic redshifts - hence coverage of deep fields is crucial.

Active galactic nuclei are known to both bias and increase the scatter in photometric redshifts, but are easily selected with X-ray, Spitzer, and WISE data (e.g. Donley et al. 2012, Masters et al. 2012, Salvato et al., 2011,2018). In addition to AGN, multi-wavelength data also pick out other classes of objects including heavily dust obscured sources and strong emission line galaxies (e.g. Donley et al. 2012).

3. SPHEREx Overview

SPHEREx, formally the "Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer", is a recently-selected NASA Medium Explorer mission. SPHEREx will conduct the first all-sky near infrared (0.75 to 5 microns) spectroscopic survey during its planned two year mission, with launch likely in late 2023.

SPHEREx has a 20cm mirror, enabling observations of 3.5x11 deg^2 field of view. Spectra will be obtained by a high-throughput linearly variable filter (LVF) spectrometer that employs six detectors (three in transmission and three in reflection) with no moving parts. Complete spectra are built up over multiple exposures by scanning the spacecraft. SPHEREx will conduct four complete sky surveys to obtain low resolution spectra (96 photometric bands) of every 6.2x6.2 arscsecond pixel on the sky. SPHEREx spectral resolution will be: R=41 between 0.75 and 2.42 microns; R=35 between 2.42 and 3.82 microns; R=110 between 3.82 and 4.42 microns; and R=130 between 4.42 and 5.00 microns. SPHEREx will reach AB~19 mag (5sigma) per spectral/spatial resolution element, obtaining high significance spectra for every isolated source in the 2MASS Point Source Catalog (Skrutskie et al. 2006) and spectra with S/N>3 per frequency element for the faintest sources in WISE (Wright et al. 2010). In addition to the all-sky survey, SPHEREx will observe deep fields of about 100 square degrees at the ecliptic poles, reaching more than 2 magnitudes deeper.

SPHEREx is optimized for investigations of three primary science areas:

- Cosmic Inflation: SPHEREx will measure the correlation of peaks in the matter density across very large scales in order to understand the non-Gaussianity of the primordial universe and constrain the physics of inflation
- Interstellar and Circumstellar Ices: SPHEREx will study the origin of water in the early phases of planetary system formation by measuring ice abundance and composition via absorption spectra
- Extra-Galactic Background Light: Observing fluctuations in the infrared background light, which results from the total light produced by all galaxy populations, will enable SPHEREx to study the evolution of the large scale structure and investigate the history of galaxy formation.

3.1 SPHEREx Data Products

SPHEREx data will be available via the NASA/IPAC Infrared Science Archive (IRSA)[7]. Basic calibrated data will be released within 2 months of acquisition. Major data releases will follow the completion of each full sky survey and will include higher level products. At the completion of the prime mission, SPHEREx will release the full Galaxy Catalog (based on positional priors) and Ices Catalog, together with mosaics of the deep fields.

SPHEREx will provide a unique dataset by offering the first all-sky infrared spectral survey. More than a billion spectra of known objects will be obtained, in the survey that will take spectra in more than a trillion spatial resolution elements (Table 2). Basic calibrated spectral images (exposures of each detector through the LVF) will be offered in FITS format, but will have wavelength varying across the image. Software to extract 1D spectra, spectral maps, and data cubes from the basic images will be offered at the archive. The SPHEREx high-level data products will rely on positional priors for spectral extraction, but the archive will offer a discovery tool to search for additional sources based on user-defined criteria. SPHEREx will also collect a wealth of data on moving objects, and specialized tools will be provided.

Table 2: SPHEREx All-Sky Survey	
Galaxy spectra	> 1 billion
High Quality redshifts	> 100 million
Stellar spectra	> 100 million
Ice Absorption spectra	> 100 thousand
QSO spectra	> 1 million
Asteroid spectra	> 10 thousand
Spectral-spatial elements per sky survey	1.3 trillion
	Table from Doré et al. (2018)

3.2 Science with the SPHEREx Archive

The SPHEREx data set will provide an enormous legacy for research in many areas of astrophysics, well beyond the focused investigation by the Science Team. With more than a billion galaxy spectra, SPHEREx will offer an unprecedented opportunity for new investigations. In 2016 and 2018, the SPHEREx proposal team held a community workshop to discuss the legacy benefits of the mission and the synergies between SPHEREx and other astronomical projects. The results of these workshops are summarized in Dore et al. (2016, 2018) and provide

[7] irsa.ipac.caltech.edu

an important (but not exhaustive) guide to the archival research that SPHEREx will enable.

4. Synergy with other missions

Euclid and SPHEREx will provide critical information on the redshift and classification of sources that are only accessible from the optical and NIR. While other wide-field space missions provide measurements of the physical parameters of galaxies (e.g. GALEX, 2MASS, WISE/NEOWISE, Spitzer, Planck, Herschel), to be fully realized they need the redshifts estimates and parameter constraints that will be provided by Euclid and SPHEREx. Furthermore, Euclid will be more sensitive and have higher spatial resolution (0.1-0.4" vs 1.5-30") than most of the previous space based large-area multi-wavelength data. To get the most information from the low-resolution data sets the community has settled on "priors-based" extraction as the preferred method for measuring photometry from space data (e.g. Laigle et al. 2016, Mehta et al. 2018, Lang et al. 2016). This has several advantages over blind detection followed by catalog matching. First, it overcomes the confusion limit, allowing for deeper extraction (e.g. Hurley et al. 2017). Second, it enables optimal model fit photometry even for extended galaxies (e.g. Lang et al. 2016, Laidler et al. 2007). Finally, it provides a unique SED linked to a fixed sky position for each identified object. In addition, the residual maps provided after the model fit is subtracted can be used to search for sources not present in the optical and IR catalogs. However, it also means the analysis need to be re-done and improved when the deep high-resolution data are improved. Euclid will provide such deep high-resolution data for the entire extragalactic sky, so it is possible that a large fraction of prior investigations will be re-visited with the addition of the Euclid data.

Euclid data will also be used together with other mission data from the 2020s to conduct cosmological investigations that are not possible with any single project (e.g. SWP Rhodes et al.; SWP Chary et al).

5. Science Platforms

The immense Euclid and SPHEREx datasets – individually and in combination with other space- and ground-based data— will require advanced techniques to manage analysis of the Petabyte-scale data volume. Some science questions will focus on a small subset of the data and will use traditional techniques. Others will require the analysis to touch large subsets of the data and will relay on "big data" solutions. In these cases, the data will be too large for most institutions to handle at reasonable cost, and so the archive will provide the capability for "analysis near the data." This resource will be a combination of common analysis software (e.g. Tractor, R, SExtractor) and the ability for users to submit their own algorithms to run on archive infrastructure (subject to suitable security and authentication). Science Platforms within the US Astrophysics Archives are discussed in detail in the APC White Paper by Desai et al.

6. Estimated Impact on ADAP

The U.S. community interest in SPHEREx and Euclid archival data will translate into more effort invested, requiring more support and increasing the proposal pressure on ADAP. We estimate the additional resources needed to provide that support, and discuss possible impacts.

Spitzer and WISE each accounted for about 40% of ADAP proposals in the years those data sets were first eligible for ADAP support. Even today, about 40% of ADAP proposals use infrared data (often in combination with data at other wavelengths). We expect that demand for support for Spitzer- and WISE-focused proposals will decline a few years after the end of operations in 2020. At about that time SPHEREx data will become available. Given its scope and complexity, funding pressure for SPHEREx will easily match or exceed that for the release of WISE, accounting for the newly available resources.

Euclid data will generate comparable interest to the original release of Spitzer and WISE, but more sustained because of the gradual roll-out. Euclid data begin to go public in 2023 and will therefore be eligible for ADAP proposals to be funded in FY24. So ADAP funds need to be augmented to account for this activity.

There are multiple drivers for additional funding in the era of peta-byte scale data sets. First, all-sky or very large area coverage to much greater sensitivity and a spectral dimension enables more research topics and questions, thus motivating more teams and proposals. Second, the manipulation of very large data sets is more demanding, requiring more sophisticated tools and therefore more workforce or access to specialize astroinformatics skills. Moreover, the investigators are required to publish their resulting data products, which will in turn be larger and more complex, requiring more work to generate and validate. Finally, the ADAP program funding level will need augmentation just to maintain its effective scope against inflation.

Total ADAP funding is about $20 million (in 2019), supporting 120 investigations with an average award of about $143k each. Such an award typically supports a postdoc or a graduate student in addition to partial support for the advisor.

We estimate the additional resources needed to support Euclid archival research in two ways. During peak years, 200-500 US-based researchers in 30-50 teams will likely be actively using Euclid data at a level of commitment requiring funding. This amounts to an increase of one third in the scope of effort under ADAP. This estimate of 30-50 teams is derived from the wide range of science investigations described above. A similar growth in scope results from the amount of new data brought into the archives by Euclid.

As this peak activity on Euclid occurs in the second half of the twenties, a sustained ADAP budget increase of 7% per year starting in 2022 would reach the estimated one third growth by 2027. Alternatively, an injection to fund Euclid research of $2-3M in FY24 followed by additional annual injections would achieve the target increase of $7M by 2027.

7. Summary

Robust funding for ADAP research provides a significant return on NASA's investment. In the mid-2020s, SPHEREx and Euclid archival data will offer unprecedented opportunities for astrophysics research over a broad range of research areas. The addition of these two missions will require current ADAP funding levels to be augmented. The required augmentation is estimated at about one third growth in the ADAP budget, or about $7M by FY2027.

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ASTRO2020 APC White Papers (APCWP)

Desai et al.

ASTRO2020 Science White Papers (SWP)

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